

This is a self-archived version of an original article. This version may differ from the original in pagination and typographic details.

Author(s): Laird, Alison Monica; Lugaro, Maria; Kankainen, Anu; Adsley, Philip; Bardayan, Dan; Brinkman, Hannah; Cote, Benoit; Deibel, Catherine; Diehl, Roland; Hammache, Fairouz; den Hartogh, Jacqueline; Jose, Jordi; Kurtilgil, Deniz; Lederer-Woods, Claudia; Lotay, Gavin; Meynet, George; Palmerini, Sara; Pignatari, Marco; Reifarth, Rene; de Séréville, Nicolas; Sieverding, Andre;

Title: Progress on nuclear reaction rates affecting the stellar production of 26AI

Year: 2023

Version: Published version

Copyright: © 2023 the Authors

Rights: CC BY 4.0

Rights url: https://creativecommons.org/licenses/by/4.0/

Please cite the original version:

Laird, A. M., Lugaro, M., Kankainen, A., Adsley, P., Bardayan, D., Brinkman, H., Cote, B., Deibel, C., Diehl, R., Hammache, F., den Hartogh, J., Jose, J., Kurtilgil, D., Lederer-Woods, C., Lotay, G., Meynet, G., Palmerini, S., Pignatari, M., Reifarth, R., . . . Mengoni, A. (2023). Progress on nuclear reaction rates affecting the stellar production of 26Al. Journal of Physics G: Nuclear and Particle Physics, 50(3), Article 033002. https://doi.org/10.1088/1361-6471/ac9cf8

TOPICAL REVIEW • OPEN ACCESS

Progress on nuclear reaction rates affecting the stellar production of $^{26}\mathrm{AI}$

To cite this article: A M Laird et al 2023 J. Phys. G: Nucl. Part. Phys. 50 033002

View the article online for updates and enhancements.

You may also like

- <u>A next-generation liquid xenon</u> observatory for dark matter and neutrino physics
- J Aalbers, S S AbdusSalam, K Abe et al.
- <u>Roadmap on Li-ion battery manufacturing</u> research Patrick S Grant, David Greenwood, Kunal
- Patrick S Grant, David Greenwood, Kunal Pardikar et al.
- <u>Black holes, gravitational waves and</u> <u>fundamental physics: a roadmap</u> Abbas Askar, Chris Belczynski, Gianfranco Bertone et al.

IOP Publishing

J. Phys. G: Nucl. Part. Phys. 50 (2023) 033002 (59pp)

https://doi.org/10.1088/1361-6471/ac9cf8

Topical Review

Progress on nuclear reaction rates affecting the stellar production of ²⁶Al

A M Laird^{1,*}, M Lugaro^{2,3,4}, A Kankainen⁵, P Adsley^{6,7}, D W Bardayan⁸, H E Brinkman^{2,9}, B Côté^{2,3,10,11},

C M Deibel¹², R Diehl¹³⁽¹⁾, F Hammache¹⁴

J W den Hartogh^{2,11}, J José¹⁵, D Kurtulgil¹⁶, C Lederer-Woods¹⁷, G Lotay¹⁸, G Meynet¹⁹, S Palmerini^{20,21}, M Pignatari^{2,8,11,22}, R Reifarth¹⁶, N de Séréville¹⁴, A Sieverding^{23,24}, R J Stancliffe^{11,22,25}, T C L Trueman^{2,22}, T Lawson^{2,22}, J S Vink²⁶, C Massimi²⁷ and A Mengoni²⁸

¹ Department of Physics, University of York, Heslington, York, YO10 5DD, United Kingdom

Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Eötvös Loránd Research Network (ELKH), Konkoly Thege Miklós út 15-17, H-1121 Budapest, Hungary

³ ELTE Eötvös Loránd University, Institute of Physics, Budapest 1117, Pázmány Péter sétány 1/A, Hungary

School of Physics and Astronomy, Monash University, VIC 3800, Australia

⁵ Department of Physics, University of Jyvaskyla, P.O. Box 35 (YFL), FI-40014 University of Jyvaskyla, Finland

⁶ School of Physics, University of the Witwatersrand, Johannesburg 2050, South Africa

⁷ iThemba Laboratory for Accelerator Based Sciences, Somerset West 7129, South Africa

⁸ Physics Department, University of Notre Dame, Notre Dame, IN-46556, United States of America

⁹ Graduate School of Physics, University of Szeged, Dom tér 9, Szeged, 6720 Hungary ¹⁰ Joint Institute for Nuclear Astrophysics, Center for the Evolution of the Elements, Michigan State University, 640 South Shaw Lane, East Lansing, MI 48824, United States of America

¹¹ NuGrid Collaboration, nugridstars.org

¹² Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803, United States of America

¹³ Max Planck Institut für extraterrestrische Physik, D-85748 Garching, Germany

¹⁴ Université Paris-Saclay, CNRS/IN2P3, IJCLab, F-91405 Orsay, France

¹⁵ Department of Physics, Technical University of Catalonia (UPC), Barcelona, Spain

¹⁶ Goethe-Universität Frankfurt, D-60323 Frankfurt am Main, Germany

¹⁷ School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3FD, United Kingdom

¹⁸ Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom

¹⁹ Department of Astronomy, University of Geneva, Switzerland

²⁰ Department of Physics and Geology, University of Perugia, via A. Pascoli, I-06125 Perugia, Italy

²¹ I.N.F.N. sezione di Perugia, via A. Pascoli, I-06125 Perugia, Italy

²² E. A. Milne Centre for Astrophysics, Department of Physics and Mathematics,

²³ School of Physics and Astronomy, University of Minnesota, Minneapolis, MN-55455, United States of America

²⁴ Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, United States of America

²⁵ H. H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, United Kingdom

²⁶ Armagh Observatory and Planetarium, College Hill, Armagh BT61 9DG, United Kingdom

²⁷ Department of Physics and Astronomy—University of Bologna and INFN,

Bologna, I-40146, Italy

²⁸ ENEA Bologna and INFN sezione di Bologna, V.le Berti Pichat, 6 I-40146, Italy

E-mail: alison.laird@york.ac.uk, maria.lugaro@csfk.org and anu.kankainen@ivu.fi

Received 26 November 2021, revised 14 September 2022 Accepted for publication 24 October 2022 Published 28 February 2023



Abstract

The radioisotope ²⁶Al is a key observable for nucleosynthesis in the Galaxy and the environment of the early Solar System. To properly interpret the large variety of astronomical and meteoritic data, it is crucial to understand both the nuclear reactions involved in the production of ²⁶Al in the relevant stellar sites and the physics of such sites. These range from the winds of low- and intermediate-mass asymptotic giant branch stars; to massive and very massive stars, both their Wolf-Rayet winds and their final core-collapse supernovae (CCSN); and the ejecta from novae, the explosions that occur on the surface of a white dwarf accreting material from a stellar companion. Several reactions affect the production of ²⁶Al in these astrophysical objects, including (but not limited to) ${}^{25}Mg(p, \gamma){}^{26}Al, {}^{26}Al(p, \gamma){}^{27}Si$, and ²⁶Al($n, p/\alpha$). Extensive experimental effort has been spent during recent years to improve our understanding of such key reactions. Here we present a summary of the astrophysical motivation for the study of ²⁶Al, a review of its production in the different stellar sites, and a timely evaluation of the currently available nuclear data. We also provide recommendations for the nuclear input into stellar models and suggest relevant, future experimental work.

Keywords: nucleosynthesis, radioisotope, nuclear reaction rate

(Some figures may appear in colour only in the online journal)

Author to whom correspondence should be addressed.



Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

University of Hull, HU6 7RX, United Kingdom

1. Introduction

The radioactive nucleus ²⁶Al²⁹ has gained significant attention in the past decades within several fields of astronomy and planetary science. Its half-life is 0.717(24) Myr [1], which corresponds to a mean lifetime of 1.035 Myr. This value allows the ²⁶Al produced in stars and supernovae, to live, on the one hand, long enough to allow us to trace its abundance back to its creation events, on the other hand, short enough to provide us snapshots of the Galaxy at very specific times, such as today and when the Solar System formed, 4.6 Gyr ago [2]. The fact that its decay produces high-energy γ photons at 1.8 MeV ensures that this radioactive process is observationally accessible via the γ -ray spectrometry performed by satellite observatories (section 1.1). Furthermore, the high-energy γ photons emitted by the decay of ²⁶Al produce a significant amount of heat within rocks that incorporate ²⁶Al at their formation. This is relevant for the first planetesimals that formed in the early Solar System, and potentially for extrasolar planetary systems (section 1.3). Interestingly, we have the samples and the laboratory tools to be able to detect and measure the abundance of ²⁶Al both 'alive' today in the Galactic interstellar medium, as it was potentially deposited inside Earth samples by nearby stellar sources within the past few Myr (section 1.2 [3]), as well as 'extinct', i.e. already fully decayed into ^{26}Mg . In fact, from the measured $^{26}Mg/^{24}Mg$ ratio and its correlation with the ²⁷Al/²⁴Mg ratio inside a mineral sample, we can infer the amount of ²⁶Al that was initially present in solid samples that formed at the time when the Sun was formed 4.6 Gyr ago (section 1.3). We can even measure the initial abundance of ²⁶Al in stardust recovered in meteorites and produced around stars and supernovae that exploded before the formation of the Sun, between roughly 5 and 7 Gyr ago (section 1.4).

Due to these rich and far-reaching implications, the production and distribution of ²⁶Al in the Galaxy has become the topic of many investigations (see, e.g. reviews by [4–6]). At the core of all such investigations are the nuclear reactions that produce and destroy ²⁶Al inside stellar objects, from giant stars to novae and supernovae. Large uncertainties, for example, in the processes of mixing in stars and supernovae, and transport of radionuclides in the interstellar medium hamper the interpretation of the observational constraints. Nevertheless, we need to produce stellar yields that do not include significant nuclear physics uncertainties. This requirement is timely because models of supernovae, the Galaxy, and molecular clouds are improving rapidly and the description of various physics processes is becoming more detailed than ever. If the stellar yields are systematically incorrect, due to inaccurate reaction rates, then even the most sophisticated stellar and galactic models will provide us with the incorrect answers. Furthermore, in the case of stardust grains (presented in section 1.4), an almost direct signature of nuclear reactions is recorded in the grains and therefore reaction rates are essential to make any meaningful comparison between models and observations (see, e.g. [7]).

The aim of this review is to provide an updated, broad overview of the production and destruction of ²⁶Al in different stellar objects and of the status of the reactions involved, in order to support stellar modellers with stronger and clearer information about the nuclear physics inputs to include in their calculations. Using stellar yields from these models we can then interpret observational data, either directly (as in the case of stardust grains, section 1.4) or by feeding the yields into models of the Galaxy, of the interstellar medium, and of Giant

²⁹ All throughout the paper the notation ²⁶Al indicates the ground state of ²⁶Al; when relevant the notations ²⁶Al_a and ²⁶Al_m are used, respectively, to refer to the ground and isomeric states, while ²⁶Al_t refers to the total ²⁶Al. The focus of this paper is the stellar production and ejection of the ground state of ²⁶Al only because the half-life of the isomer of 6 s is too short to allow this nucleus to survive and be ejected by any stellar source.



Figure 1. Section of the nuclide chart illustrating the main nuclear reactions favouring (green arrow) or inhibiting (red arrows) the production of 26 Al in stellar objects. For clarity, we do not show the decay of the ground state of 26 Al into 26 Mg.

Molecular clouds. These allow us to use the abundance of ²⁶Al as a tracer to address currently debated topics, from the physics of the interstellar medium to the circumstances of birth of the Sun.

Figure 1 shows the main nuclear reactions that directly affect the production and destruction of ²⁶Al, which include both proton and neutron captures. These are relevant for most of the astrophysical sites responsible for the production of ²⁶Al in the Galaxy and will be covered in detail here. There are many more reactions that affect the production and destruction of ²⁶Al indirectly. For example, neutron source reactions such as the ²²Ne(α , n)²⁵Mg reaction [8] can affect the destruction of ²⁶Al via neutron reactions in low-mass (section 2.1) and massive stars (section 2.2.2), while the bypass reaction ²⁵Al(p, γ)²⁶Si affects the production of ²⁶Al in novae (see section 2.3). Iliadis *et al* [9] also listed the ²⁵Mg(α , n)²⁸Si, ²⁴Mg(n, γ)²⁵Mg, and ²³Na(α , p)²⁶Mg reactions as relevant, some of these will be discussed in section 3.5. In particular, the specific case of nucleosynthesis in core-collapse supernovae (CCSNe) (section 2.2.2) involves several different types of burning episodes and

related reactions. A fully comprehensive analysis needs to be performed within the context of stellar physics uncertainties and is beyond the scope of this work.

In the sections below, we present an overview of the observational opportunities and implications related to ²⁶Al, from γ -ray observations and Earth samples, to meteoritic stardust, and the early Solar System, and we finish the Introduction with some general considerations about the evolution of ²⁶Al in the Galaxy. Section 2 describes more specifically the production of ²⁶Al in different astrophysical sites, from asymptotic giant branch (AGB) stars (i.e. stars with initial masses roughly less than 10 M_☉), to massive stars (i.e. with initial masses roughly above 10 M_☉ and and their CCSNe, and novae (i.e. accreting white dwarfs). For further reading on the topic of observations and models we refer to the review from an ISSI workshop series by Diehl *et al* [10]. Section 3 covers the reaction rates responsible for the production and destruction of ²⁶Al in stars, from those directly involved with ²⁶Al, to a selection of the most important indirectly related. Section 5 summarises the information presented here and proposes the future work needed to overcome the current major problems and uncertainties in the investigation of the production of ²⁶Al in stars.

1.1. Live ²⁶Al from γ -ray observations

The observation of cosmic radioisotopes relies on radioactive decay occurring outside the radioisotope stellar production sites, therefore, they are not distorted from absorption of photons by gas, which occur within the high density stellar matter. Hence, such astronomical data from radioactive decay convey direct information about nuclear reactions within cosmic sites that is otherwise hidden from direct observation (with the exception of neutrinos, which are, however, not observable from distant sites). Commonly available astronomical abundance data from atomic-line spectroscopy are also interpreted in terms of cosmic nucleosynthesis; this is, however, quite indirect information, in particular because the density and ionization state of atoms at the surface of stars is controlled not only by nuclear reactions but also by atomic processes that strongly affect the abundances. Therefore, the characteristic γ ray lines measured from radioactive decay provide more direct astronomical data. The detection of the characteristic γ rays from ²⁶Al decay is the first direct, convincing proof that nucleosynthesis is going on within the current Galaxy³⁰, because ²⁶Al has a characteristic decay time of a million years, much shorter than the age of the Galaxy of more than 10 billion years. Therefore, ²⁶Al γ rays can be used to study recent nucleosynthesis sources and the transport of ejected material into the interstellar medium.

Direct observations of ²⁶Al decay in interstellar space through its characteristic γ -rays with energy 1808.65 keV had been motivated by theorists [12], and was first achieved by the HEAO-C satellite in 1978/1979 observing the central regions of our Milky Way Galaxy [13]. The NASA Compton Gamma-Ray Observatory (1991–2000) with the COMPTEL instrument provided a sky image of the ²⁶Al γ -ray line, which showed a structured ²⁶Al emission, extended along the plane of the Galaxy [14–16] (figure 2). This image was obtained from measurements taken over years 1991–2000 throughout the sky. It uses a maximum-entropy regularization together with the likelihood of the image's projected data fitting the measurement, and varies the image iteratively until a best image is found to fit the measured events. Such *forward convolution* analysis is required, as the direct inversion of measured data is not possible; the signal of the ²⁶Al sky is translated into the data space of measured events by the instrument response function, which includes Compton scattering (as a

³⁰ The detection of the atomic lines of the radioactive elements technetium (Tc) in S-type stars by Merrill [11] represents clear evidence for currently active nucleosynthesis.



Figure 2. The ²⁶Al sky as imaged with data from the COMPTEL telescope on NASA's Compton Gamma-Ray Observatory [14]. Reproduced with permission from [12].

probabilistic process), and is singular (hence cannot be inverted). The high instrumental background needs careful modelling, and Poissonian statistics must be properly included, hence the maximum-likelihood method is used (see [17, 18] for details on COMPTEL data analysis). The reliability of such γ -ray imaging has been consolidated in many studies (see, e.g. [19]). The ²⁶Al γ -ray image and the structures it showed was found to be in broad agreement with earlier expectations of ²⁶Al being produced throughout the Galaxy mostly from massive stars and their CCSNe since young stars are typically located on the plane of the Galaxy, and these young stars are preferentially massive.

In 2002, the continuing INTEGRAL mission of the European Space Agency (ESA) started, with its high-resolution γ -ray spectrometer SPI, deepening the astronomical harvests of ²⁶Al emission (figure 3). Note that the COMPTEL scintillation detectors had an instrumental resolution of ~200 keV, compared to ~3 keV for the SPI Ge detectors. This led to deeper, Galaxy-wide investigations of ²⁶Al [20], as recently reviewed [21]. Furthermore, INTEGRAL allowed to spatially resolve specific and well-constrained massive star groups (OB associations), and therefore to test our understanding of massive star groups and how they shape the star-forming interstellar medium (see [22] for a review of astrophysical issues and lessons). Important herein are the Cygnus, the Orion [23] and the Scorpius–Centaurus [24] stellar groups. Altogether, astronomical ²⁶Al observations have led to both the tracing of the path of nucleosynthesis ejecta after they leave their sources and eventually end up in next generation stars, and the investigation of the cosmic production sites, i.e. stars and supernovae. For the latter objective, it is essential to have the best-possible knowledge of the physics of the stellar sites and of the nuclear reactions involving ²⁶Al, as discussed here.

1.2. Live ²⁶Al in terrestrial archives

Ice cores, deep-sea sediments, and deep-sea FeMn crust material are favourable locations to search for live radionuclides on Earth produced by nearby (in time and space) stellar nucleosynthetic events. These materials have very low growth rates, of the order of mm to cm per thousands to millions of years, and therefore they can provide time-resolved information over time scales of million years. However, because the number of radioactive atoms to be



Figure 3. The ²⁶Al line as seen with INTEGRAL high-resolution spectrometer SPI integrated on 13 years of measurements [25]. Reproduced with permission from [20].

counted is tiny (e.g. ²⁶Al is typically 12 to 16 orders-of-magnitude lower in abundance than the stable terrestrial ²⁷Al), only accelerator mass spectrometry (AMS) [3] has so far reached the sensitivity required for such studies. AMS directly counts the radionuclide of interest one by one by means of a particle detector after the sample material is dissolved and the radionuclide of interest is chemically separated from the bulk material. Thanks to this methodology it has been possible to detect on Earth ⁶⁰Fe from one or several nearby CCSNe that occurred roughly 2–8 Myr ago [26–28], where ⁶⁰Fe is another radioisotope with a half-life $T_{1/2} = 2.62$ Myr produced by massive stars and their supernovae, also observable via γ -ray satellites [29].

Detection of ⁶⁰Fe of stellar origin is possible because its terrestrial production is negligible. In contrast, ²⁶Al is produced not only in stars but also in the terrestrial atmosphere through cosmic-ray induced nuclear spallation reactions on abundant stable isotopes, such as ²⁷Al(p, p–n), ²⁶Mg(p, n), ²⁸Si(p, ³He), and ²⁴Mg(³He, p). Furthermore, production inside the terrestrial archives themselves and influx of interplanetary dust grains may add spurious amounts of cosmic-ray produced ²⁶Al. Stellar ²⁶Al may be of the order of only a few percent, up to roughly 10%, relative to its terrestrial component [3]. Therefore, to identify a stellar ²⁶Al signal above the terrestrial background requires an extremely sensitive and efficient detection technique. Feige *et al* [3] searched for presence of stellar ²⁶Al in an extensive set of deep-sea sediment samples that covered a time-period between 1.7 and 3.2 Myr ago and found an exponential decline of ²⁶Al. This indicates no significant ²⁶Al above the terrestrial signal. Nevertheless, owing to the large number of samples analyzed, these data allowed the deduction of an upper limit for the stellar ²⁶Al.

This upper limit is crucial when taken together with the previously derived stellar ⁶⁰Fe, as the live ²⁶Al and ⁶⁰Fe radioisotopes found on Earth originated from nucleosynthesis in massive stars and, in particular, constrain models of the nearby CCSN that occurred 2 Myr ago. These are the same sources that dominate both the current abundances of live ²⁶Al and ⁶⁰Fe in the Galaxy and their extinct abundances in the early Solar System—since massive stars are present in star-forming regions (sections 1.1 and 1.3). Therefore, comparison between three different types of constraints can provide us with significant information on



Figure 4. Isochrone (solid line) obtained from the pioneering analytical work of [33], and later confirmed by [34]. The slope of this line allowed to obtain for the first time the canonical early Solar System ${}^{26}\text{Al}/{}^{27}\text{Al}$ ratio of $\simeq 5 \times 10^{-5}$ from specific CAI inclusions from different meteorites (Allende, Efremovka, and Murchison, different symbols). The ${}^{26}\text{Mg}/{}^{24}\text{Mg}$ ratio measured in the different minerals that make up the inclusions clearly correlates with the ${}^{27}\text{Al}/{}^{24}\text{Mg}$ ratio of each mineral. This proves that the excess ${}^{26}\text{Mg}$ was built inside each mineral from the ${}^{26}\text{Al}$ decay after, rather than before, the mineral formed. In the same words of the title of [33]: ${}^{26}\text{Al}$ is a 'fuel' and not a 'fossil' in the early Solar System, i.e. it was present 'live', not already decayed. Note that there are also some samples that show no evidence of ${}^{26}\text{Al}$ instead (open symbols). Data from [35], and references therein.

both massive star nucleosynthesis and the environment of the formation of the the Sun. The Earth samples produced a lower limit ${}^{60}\text{Fe}/{}^{26}\text{Al}$ between 0.1 and 0.33, which is close to the value obtained from Galaxy-wide gamma-ray spectrometry with INTEGRAL of 0.2–0.4 [29]. However, it is well above the ${}^{60}\text{Fe}/{}^{26}\text{Al}$ ratio derived for the early Solar System of 0.002. This calls for a different origin of ${}^{26}\text{Al}$ in the early Solar System, relative to the current live ${}^{26}\text{Al}$ in the Galaxy and in Earth archives. The problem is further compounded by theoretical CCSN yields, which currently overproduce ${}^{60}\text{Fe}$ relative to ${}^{26}\text{Al}$, even compared to the spectroscopic γ -ray observations [30–32].

1.3. Extinct ²⁶AI in the early Solar System

Analysis of the isotopic composition of Mg in Ca–Al-rich inclusions (CAIs) from primitive meteorites, the oldest solid objects to have formed within the Solar System, demonstrates that ²⁶Al was present in the early Solar System with ²⁶Al/²⁷Al $\simeq 5 \times 10^{-5}$. The isochrone method with which this is achieved is explained using figure 4, which presents the first observational evidence of the presence of ²⁶Al. Several different minerals were analysed within the same sample (of same color in the plot), and for each of these minerals the ratios ²⁷Al/²⁴Mg and ²⁶Mg/²⁴Mg were measured and plotted against each other as in the figure. ²⁷Al is the only stable isotope of Al, and ²⁴Mg the most abundant stable isotope of Mg. Therefore, the

 27 Al/ 24 Mg ratio is a good measure of how much total Al and Mg are present inside each mineral³¹. Because 26 Mg is the daughter nucleus of 26 Al, the 26 Mg/ 24 Mg ratio can trace the potential initial presence of 26 Al: i.e. 26 Mg/ 24 Mg = 26 Mg^{*}/ 24 Mg + 26 Mg^{initial}/ 24 Mg, where 26 Mg^{*} is the radiogenic abundance from the decay of 26 Al, and 26 Mg^{initial} its initial abundance in the material from which the mineral comes from, which is a constant. The discovery of the presence of 26 Al is based on the fact that the 26 Mg/ 24 Mg ratios measured in different types of Mg-rich (i.e. low Al/Mg) and Al-rich (i.e. high Al.Mg) show a linear correlation with Al/Mg. The only way to explain such linear correlation is that the excess of 26 Mg was initially due to an excess of 26 Al. The slope of the line provide us with the initial 26 Al/ 27 Al ratio, given that the first term in the equation above can be written as 26 Al/ 27 Al × 27 Al/ 24 Mg (figure 4).

The presence of ²⁶Al in the early Solar System was actually predicted in the 1950s before its discovery, because an early heating source was needed to melt the interiors of the first planetesimals that formed within the first Myr [36]. This heat was driven by the γ -ray photons generated when ²⁶Al decays to ²⁶Mg inside a rocky body, the same photons that are observed via the INTEGRAL satellite when ²⁶Al decays in the interstellar medium (figure 3). One of the consequences of such heat is that the ice inside those planetesimals that formed beyond the ice line (initially made of roughly 50% ice) melted and the water was lost. The timescale of this water loss was shorter than the accretion timescale of planetesimals into terrestrial planets. As sketched in figure 5 from [37], if ²⁶Al is present in planetesimals, water-poor planets, such as the Earth, which is only a few percent water, result and are known to be habitable world. If ²⁶Al is not present in significant quantity, instead, water-rich, ocean planets are predicted, which are potentially more difficult to harbour life. Therefore, the presence of ²⁶Al in star-forming regions can strongly affect the habitability of the planetary systems formed in such regions. Understanding the production of ²⁶Al in stars is therefore crucial to understand the water context of extrasolar terrestrial planets. However, the origin of ²⁶Al in the early Solar System is still unclear and strongly debated with several separate stellar origin scenarios proposed³², each of which have different probabilities to occur in starforming regions [6].

For example, Cameron and Truran [39] were the first to propose a simultaneous enrichment plus triggered collapse scenario, in which a nearby CCSN ejects freshly synthesised material into a dense molecular cloud core thereby triggering its collapse to form the solar nebula (see e.g. [40–42]). Alternate mechanisms for the injection of ²⁶Al-rich material from a CCSN have been proposed, including, for example, pollution of the already formed disk [43–45]. Other scenarios postulate that the gas that later collapsed to form the protosolar molecular cloud was pre-enriched in ²⁶Al by an earlier generation of massive stars either within the star-forming region or the galactic interstellar medium itself [46–51]. The winds of stars of mass > 30 M_{\odot} could also produce enough ²⁶Al to be a candidate source [52, 53]. Brinkman *et al* [54] showed that lower mass stars could also achieve high yields if they are part of a binary system (section 2.2.1). Another possible origin is an AGB star [55], however, this source seems unlikely because these stars cannot produce the required ²⁶Al abundance without also overproducing several radionuclides heavier than iron [35]. Furthermore, low-mass stars formed in the same molecular cloud as the Sun take a long time to reach the AGB phase (~1 Gyr), by which time the molecular cloud is since long dispersed. Finally, that a

³¹ Isotopic ratios of the same elements are not expected to vary significantly even in different types of minerals since both isotopes have similar chemical properties that will keep their ratio constant. This is of course not true for ratios between different elements, such as the ²⁷Al/²⁴Mg ratio.
³² In addition, there is a scenario that hypothesised that ²⁶Al was produced locally by spallation reactions induced by

 $^{^{32}}$ In addition, there is a scenario that hypothesised that 26 Al was produced locally by spallation reactions induced by solar accelerated particles from the young Sun [38].



Figure 5. Qualitative sketch of the effect of the ²⁶Al radioactive fuel in the early Solar System, within the framework where water is carried to terrestrial planets from planetesimals that formed beyond the snow line. The left and right sides show the build up of terrestrial planets in potential ²⁶Al-poor and ²⁶Al-rich (like the Solar System) planetary systems, respectively. The middle grey arrow indicate the process of the accretion of planetesimal (the first sizable rocks with radius of the order of 50 km) that lead to the formation of rocky planets like the Earth. The blue and red arrows on the bottom right indicate the evolution of the planetesimal water content and of the abundance of live ²⁶Al, respectively, for the case of ²⁶Al-rich systems. The difference in the planets radius (ΔR_P) between the two cases indicated at the top of the figure is a measurable quantity for extrasolar planets. Reprinted by permission from Springer Nature: Springer Nature Astronomy, 'A water budget dichotomy of rocky protoplanets from ²⁶Al-heating', Lichtenberg, T; Golabek, GJ; Burn, R; Meyer, MR; Alibert, Y; Gerya, TV; Mordasini, C, 3, 307–313, 2019. Reproduced from [38], with permission from Springer Nature.

molecular cloud would be visited by an AGB star formed elsewhere has been shown observationally to be very unlikely [56].

In summary, investigation of the production of ²⁶Al by nuclear reactions in massive stars, and its ejection from massive stars, both during the wind phases and the following CCSN explosion, is relevant to understand the evolution and properties of planetesimals and planets both within solar and extrasolar systems.

1.4. Extinct ²⁶Al in stardust grains

Stardust grains are recovered from meteorites and carry the pure signature of the nucleosynthesis that occurred in their parent stars, therefore, they are effectively tiny specks of stars [57, 58]. Evidence that ²⁶Al was incorporated into stardust grains that formed around stars and supernovae is inferred from the Mg composition of the grains, and in particular from the excess in the daughter nucleus ²⁶Mg, relative to the other stable Mg isotopes. Most of the grains originated from AGB stars, with some (a few percent) of grains also showing the signature of an origin from CCSNe and novae. Therefore, even if AGB stars and novae are not the major producers or ²⁶Al in the Galaxy, relative to massive stars, it is necessary to investigate their ²⁶Al production to interpret the presence of ²⁶Al in stardust grains, at the time of their formation.

Many recovered and analysed stardust minerals are rich in Al and poor in Mg, so that the signature of ²⁶Al is evident and measurable. These include silicon carbide (SiC) and graphite, which are carbon (C)-rich grains that form in a gas when C > O, and corundum (Al₂O₃) and hibonite (CaAl₁₂O₁₉), which are oxygen (O)-rich grains that form when C < O. If there are only just traces of Mg originally in the grains, then the full initial abundance of ²⁶Al at the time of the grain formation can be recovered as the whole abundance of ²⁶Mg. In other words, the abundance of ²⁶Al is derived directly from the abundance of ²⁶Mg because Mg is not a main component of the material: the Mg abundance is orders-of-magnitude smaller than that of Al in, e.g. aluminium oxides and silicon carbide grains (see, e.g. figure 2 of [59]), therefore, stable ²⁶Mg is an orders-of-magnitude less significant contributor to the atoms at mass 26.³³ Groopman *et al* [60] significantly improved the derivation of the initial ²⁶Al abundance by using the isochrone method for stardust grains as done for Solar System materials (section 1.3). This method produces more accurate results, generally showing higher ratios than previously estimated due to a better estimate of contamination.

Overall, C-rich stardust grains believed to have originated from CCSNe show very high abundances of ²⁶Al, with inferred ²⁶Al/²⁷Al ratios in the range 0.1–1, higher than standard theoretical predictions in the C > O regions of the ejecta. These ratios can be used to constrain the nucleosynthesis models, and they require an extra production mechanism for ²⁶Al to be at work in the C-rich regions of CCSNe beyond those described in section 2.2.2. This mechanism may be related to ingestion of hydrogen into the He-burning shell and the subsequent explosive nucleosynthesis [62]. The grains that are known to have originated in AGB stars show somewhat lower ²⁶Al abundances than grains from CCSNe, with ²⁶Al/²⁷Al ratios in the range 10^{-3} to 10^{-2} . Also these grains can be used to constrain AGB nucleosynthesis models [7, 63, 64]. For example, oxide grains belonging to a specific group (Group 2) show strong depletion in ¹⁸O/¹⁶O and have also relatively high ²⁶Al/²⁷Al ratios. Both features are a product of efficient hydrogen burning, possibly connected to hot bottom burning (HBB) in

³³ Note that in the case of stardust spinel (MgAl₂O₄), instead, the initial abundance of ²⁶Al needs to be disentangled from the initial abundance of ²⁶Mg. This is complicated by the fact that in single stardust spinel grains the proportion of Mg to Al may vary from the stoichiometric value of 1:2, and such variation needs to be taken into account when attempting to derive the initial ²⁶Al/²⁷Al ratio [61].

massive AGB stars [7] or extra-mixing in low-mass AGB stars [65] (see section 2.1). Finally, some grains have been potentially interpreted as nova condensates and their relatively high ${}^{26}\text{Al}/{}^{27}\text{Al}$ ratios, up to 0.3–0.5, have been used as one of the main indications of such signature origin [66, 67] (see section 2.3 for more details).

1.5. Evolution of ²⁶Al in the Galaxy

The evolution of the average abundance of a radioactive nucleus such as ²⁶Al in the galactic interstellar medium is generally controlled by the establishment of a steady-state equilibrium between its ejection by stellar sources and its radioactive decay. When such equilibrium is established, the number of ²⁶Al nuclei N_{26} no longer changes with time t: $dN_{26}/dt = 0$. The $dN_{26}/dt = 0$ rate is made of two terms: one is a positive production term given by the stellar production rate per unit time, defined as dP_{26}/dt ; the other is a negative destruction term, wrought by the decay and equal to $N_{26} \times \lambda_{26} = N_{26}/\tau_{26}$, where λ_{26} is the decay rate of ²⁶Al, and τ_{26} its mean lifetime. If the total abundance change is zero, then the two terms are equal and the equilibrium abundance N_{26} is equal to $(dP_{26}/dt)\tau_{26}$. This formula, together with the stellar production rates predicted for the main stellar producers of ²⁶Al in the Galaxy (see section 2), enables us to quickly compare the predicted ²⁶Al abundance in the Galaxy to that inferred from γ -ray observations, which represents the sum of the contribution of all nearby young stellar populations currently ejecting this radioisotope.

However, this simple steady-state formula is not enough to interpret the data accurately. Theoretical models must also account for the star formation rate of the Milky Way today; the initial mass function, in order to model stellar populations; and the fact that stellar yields may vary with stellar mass and metallicity, as well as potentially their binary status. Furthermore, stellar enrichment within the interstellar medium is not continuous but represented by events discrete in time and space, therefore, it cannot be accurately described by a continuous dP_{26}/dt production rate. Local enhancements or reductions in the ²⁶Al abundance due to spatial and temporal inhomogeneities must also be considered in numerical simulations [68, 69]. This is a challenging task because the evolution of 26 Al depends both on the time interval between the formation of the progenitor star that led to the enrichment event, a parameter that is currently poorly constrained, as well as their spatial distribution. Comparing 3D hydrodynamic simulated distributions of ²⁶Al to the observed 1.8 MeV emission line flux maps of figure 2 [70, 71] has provided constraints on the Galaxy-wide distribution of ²⁶Al, and showed that our observer position may be highly biased by the local environment and the stars that populated it. Furthermore, dedicated models [72, 73] are needed when considering specific star-forming regions and the 'super-bubbles' generated by the energy from massive stars within them.

Interpreting the abundances of ²⁶Al derived from meteoritic data also requires the use of chemical evolution models, in this case specifically because the initial ²⁶Al abundance in the mineral can be measured only relative to that of the stable ²⁷Al. For the early Solar System, while the abundance of ²⁶Al reflects the local star formation rate at the time of the formation of the Sun, the abundance of the stable isotope ²⁷Al encodes the complete past enrichment history of the Galaxy and can only be predicted using galaxy models that properly integrate the galactic star formation history with stellar yields [74–77]. These predictions are, however, affected by many uncertainties such as the total stellar mass formed prior to the formation of the Solar System, the amount of stable ²⁷Al locked in stellar remnants (white dwarfs, black holes, neutron stars), and large-scale outflows that remove some of the ²⁷Al content from the Galaxy [76, 77].

All the uncertainties described above can be significantly reduced by considering the 60 Fe/ 26 Al ratio, since 60 Fe is a radioisotope with a similar half-life (2.62 Myr) and, like 26 Al, can be measured via γ -rays and meteoritic analysis, and is also produced mostly by massive stars. Therefore, its ratio relative to ²⁶Al solves some of the problems listed above, i.e. a chemical evolution simulation that follows the complete history of the Galaxy is not necessary to give us a direct insight into the stellar sources of these radioisotope. The steady-state equilibrium number ratio of the two radioisotope is $N_{60}/N_{26} = (dP_{60}/dP_{26})(\tau_{60}/\tau_{26})$, and the number ratio of the two radioisotope derived from the flux (F) ratio observed via γ -rays is $N_{60}/N_{26} = (F_{60}/F_{26})(\tau_{60}/\tau_{26})^{34}$. Therefore, the ⁶⁰Fe/²⁶Al production ratio in massive stars (by number) can be directly compared to the observed flux ratio [29]. The result is that current models overproduce ⁶⁰Fe relative to ²⁶Al compared to the spectroscopic γ -ray observations by a factor of 3-10 [30-32], and there are inconsistencies not only between models and observations, but also between observations of different types (see end of section 1.2). Moreover, in reality, local inhomogeneities can also affect the ⁶⁰Fe/²⁶Al ratio, even if these two radioisotope came from exactly the same sources, since they decay with different halflives. Considering temporal heterogeneities within a statistical framework results in an increase of roughly 10% in the ⁶⁰Fe/²⁶Al ratio relative to that calculated using the basic steady-state formula [78], but even larger fluctuations are found in more sophisticated models of the interstellar medium [51] and of giant molecular clouds [79].

Finally, we stress that the fundamental input for any numerical predictions of the evolution of ²⁶Al in the Galaxy—whether associated with chemical evolution models, interstellar medium simulations, or single-source enrichment models are the adopted stellar yields discussed below and e.g. in [9, 80–83]. In fact, the quantitative predictive capabilities of even the most sophisticated simulations are still limited by the large uncertainties affecting nucleo-synthesis and stellar evolution calculations. In the following section, we describe in more detail the production of ²⁶Al in different types of astronomical objects, from low to high mass stars and binary interaction objects, and the associated uncertainties. Lower mass stars during their AGB phase (section 2.1) are specifically relevant to understand the origin of ²⁶Al in the majority of meteoritic stardust grains. Massive stars and their CCSNe (section 2.2) are the dominant producers of ²⁶Al in the Galaxy and in star-forming regions, which are relevant for the early Solar System. Novae are also relevant as potential contributors to galactic ²⁶Al, as well as sources of rare stardust grains; they will be discussed in section 2.3.

2. Stellar production sites

2.1. Asymptotic giant branch (AGB) stars: extra-mixing and HBB

Stars with initial mass in the range $1-8 \text{ M}_{\odot}$ end their lives as AGB stars. Their structure consists of a degenerate carbon–oxygen core, above which sit a helium-burning shell and a hydrogen-burning shell separated by an He-rich region called the 'intershell'. Surrounding this central region of the star is an extended, hydrogen-rich, convective envelope. The configuration of thin helium and hydrogen burning shells is unstable, leading to periodic runaway helium-burning episodes, known as thermal pulses. During these thermal pulses, convection mixes the ashes of helium-burning in the intershell region. As a thermal pulse subsides, the star undergoes a structural readjustment that allows the convective envelope to deepen, penetrating the intershell and dragging freshly synthesised material to the surface. This is known as the third dredge-up and it may happen after each thermal pulse. Depending on the

³⁴ Since the flux corresponds to dN/dt and the decay equation is $dN/dt = -N/\tau$.



Figure 6. Main proton-capture reactions and β^+ decays (with half-lives indicated) involved in the MgAl cycles. The solid- and dashed-line boxes represent stable and unstable nuclei, respectively. The red arrows show the reactions and β^+ decays that result in the by-passing of the production of the ground state of ²⁶Al, due to the production of the isomeric state instead. In particular the by-pass via ²⁶Si can be activated at high temperatures (200–400 MK) during the nova nucleosynthesis described in section 2.3, while the by-pass via ²⁶Mg is also activated at the relatively low temperatures of AGB stars (from roughly 60 to 100 MK).

strength of the stellar winds (which strip mass from the surface) and the mass of the envelope, an AGB star may undergo a few to many tens of such thermal pulses before the entire envelope is removed and the star transitions to the post-AGB phase. For detailed reviews of AGB stars and their evolution, we refer the reader to Herwig [84] and Karakas and Lattanzio [85].

The production of ²⁶Al in AGB stars has been studied by many authors [35, 63, 86, 87]. Both the hydrogen-burning and the helium-burning shells are relevant to synthesis of ²⁶Al. In the latter, the initial abundances of the two heavy magnesium isotopes, ²⁵Mg and ²⁶Mg, are enhanced via α -captures onto ²²Ne, and then dredged-up into the stellar envelope. Directly at the base of the envelope, or in the radiative region just below it, depending on the initial stellar mass, shell hydrogen burning converts ²⁵Mg into ²⁶Al via proton captures as part of the Mg–Al chain shown in figure 6.

Above initial masses around 4 M_{\odot} , the exact value depending on the metallicity and the choice of the convective model, the base of the stellar convective envelope is deep enough that it lies within the upper regions of the hydrogen-burning shell. Convection therefore cycles material from the entire envelope of the star through the hydrogen burning shell, in a process referred to as HBB. The combined action of the third dredge-up adding freshly synthesised ²⁵Mg to the envelope, and the HBB processing this material via the Mg–Al chain

makes massive AGB stars substantial producers of ²⁶Al [87, 88]. This is in agreement with the high ²⁶Al/²⁷Al ratios in Group 2 oxide grains, and make massive AGB stars that experience HBB a candidate source of these grains [7], together with the Cool Bottom Process in low-mass stars are discussed below. The effect of reaction rate uncertainties on HBB in massive AGB stars has been carefully examined by Izzard *et al* (2007) [89], who concluded that uncertainties in the ²⁵Mg(p, γ)²⁶Al and ²⁶Al(p, γ)²⁷Si rates lead to an uncertainty in the ²⁶Al yields from a factor of few at solar metallicity to up to two orders-ofmagnitude at lower metallicities. The so-called super-AGB stars also evolve to the AGB but experience carbon burning in the core after the helium-burning has taken place. This results in ONe- rather than CO-rich cores³⁵. The initial masses of these stars are in the range 8–10 M_☉, depending on metallicity. In these super-AGB stars the base of the convective envelopes is very hot (up to 100 MK) and therefore HBB is very efficient leading to significant production of ²⁶Al. Nevertheless, the overall super-AGB contribution to the estimated galactic content of roughly 2.8 M_☉ does not exceed 0.3 M_☉, i.e. 10% of the total [90].

In canonical low-mass AGB models, where only convective mixing is taken into account, the hydrogen-burning shell is separated from the convective envelope by a radiative 'buffer' region where no mixing occurs. Therefore, the ²⁶Al produced by H burning in the top layers of the H-burning ashes³⁶ is ingested inside the thermal pulse, where it can be destroyed by neutron-captures with neutrons generated by the ²²Ne(α , n)²⁵Mg reaction. What is left is then carried to the stellar surface via the third dredge-up. By this mechanism, the surfaces of low-mass AGB stars are predicted to have ²⁶Al/²⁷Al of the order of a few 10⁻³, in qualitative agreement with those observed in the SiC grains that originated in these stars [63].

The main stellar model uncertainties associated with AGB stars that impact the production of ²⁶Al are the efficiency of the third dredge-up, the choice of mass-loss rate, and the convective mixing model. The efficiency of the third dredge-up is affected by the method employed to find the convective boundary, e.g. [91]. More efficient third dredge-up in massive AGB stars, for example, carries more ²⁵Mg from the intershell into the envelope, which is then processed into ²⁶Al via HBB. The mass-loss rate influences the duration of the AGB phase, with stronger mass loss leading to fewer thermal pulses and less nucleosynthesis [92]. The choice of the convective model affects the temperature structure of the stellar envelope and therefore the temperature at which HBB can take place. More efficient convection leads to higher HBB temperatures, favouring ²⁶Al production [93, 94]. It can also lead to higher stellar luminosities, which may accelerate mass loss [93].

Another main uncertainty is related to the possible occurrence of non-convective mixing in AGB stars with initial mass below 2–3 M_{\odot} . This mixing may allow the crossing of the radiative buffer region and carry ashes from the hydrogen-burning shell into the convective envelope during the periods in-between thermal pulses (refereed to as interpulse periods) and boost the production of ²⁶Al. Wasserburg *et al* [95] first suggested a non-convective mixing process, which they called Cool Bottom Process (CBP, in contrast to HBB in the most massive stars) as an explanation for some CNO isotope anomalies observed in low-mass AGB stars and stardust grains of AGB origin. In the CBP model, it is assumed that material is carried from the lower edge of the convective envelope down to the innermost layers of the hydrogen shell where it experiences proton-capture reactions and then returns it to the convective zone.

³⁵ These cores are the progenitor of the ONe white dwarfs onto which accretion results in novae producing 26 Al, see section 2.3.

 $^{^{36}}$ In the bottom layers of the H-ashes ^{26}Al is destroyed by neutron-captures, with neutrons generated by the $^{13}C(\alpha,n)^{16}O$ reaction.

The work of [96] showed that the surface of AGB stars with mass $\leq 2 M_{\odot}$ and close to solar metallicity can be enriched in ${}^{26}Al$ up to ${}^{26}Al/{}^{27}Al = 0.1$. However, they did not provide any hypothesis on the physical mechanism driving the mixing, and treated the depth and the mixing rates as free parameters.

Furthermore, to reach ${}^{26}\text{Al}/{}^{27}\text{Al} = 0.1$ in the stellar envelope the CBP model of the quoted authors must push the carried materials down to the deepest layers of the H-shell, where the temperature is greater than 5.5×10^7 K, before returning to the stellar envelope. The so-induced circulation of hot (still burning) matter can strongly affect the stellar energy balance, with relevant luminosity feedback.

In the last two decades many studies have been carried out on non-convective mixing phenomena of low-mass red giants and numerous hypotheses have been formulated on their cause: from stellar rotation [97], to thermohaline mixing [98], and gravity waves [99], stellar magnetic fields [100], and their combined effect [101, 102]. In the case of ²⁶Al the problem remains that to synthesize this radioisotope in significant amounts via extra-mixing, material must experience relatively high temperatures, and most of the proposed mixing models listed above do not predict ²⁶Al production. For example, the average molecular weight inversion due to the ³He(³He, pp)⁴He reaction, which triggers the thermohaline mixing, occurs in the H shell where the temperature is $\sim 3.5 \times 10^7$ K, too low to efficiently activate the ²⁵Mg(p, γ)²⁶Al reaction [64, 103]. Only the extra-mixing induced by the effects of the stellar magnetic field proposed in [104] is currently able to produce the ²⁶Al/²⁷Al ratios of up to a few 10⁻¹ measured in oxide stardust grains of Group 2, also showing strong deficits in ¹⁸O, an isotope efficiently destroyed by H burning [105].

Magnetic-induced mixing in very low-mass (≤1.5 M_☉) AGB stars can predict high ²⁶Al/²⁷Al because it operates via small bubbles of magnetized material, which rise from the H-burning shell to the base of the convective envelope [65], instead of moving material from top to bottom as in the classic CBP model. With state-of-the-art methods, the magnetic extramixing predictions of the Al isotopic ratios in low-mass AGB stars do not appear to be significantly affected by reaction rate uncertainties. For example, when using the rates by [106] and [107] for the (p, γ) captures on ²⁵Mg and ²⁶Al^g, respectively, instead of those reported by [108] the changes in the resulting ${}^{26}Al/{}^{27}Al$ isotopic ratio is smaller than the variations due to the stellar model parameters (such as the stellar mass, the mass loss, and the mixing depth). However, the magnetically induced extra-mixing is relatively fast and the transported material has no time to be affected by proton captures along the path from above the H-burning shell to the envelope (as instead it might happen in the classic CBP). Therefore, any change induced by the mixing in the stellar surface composition reflects the abundances in the H-burning shell. As a consequence any uncertainty or change in the nuclear physics input that affects the ²⁶Al/²⁷Al distribution in the shell will also affect the one in the stellar envelope (see the brief analysis by [109]).

2.2. Massive star as the main source of ²⁶Al in the Galaxy

From the map of the γ -ray observations from the ²⁶Al decay (see, e.g. figure 2), it is clear that most ²⁶Al is confined to the galactic plane and to some specific clumps (see, e.g. figure 16 of [110] and [111–113]). These clumps coincide with known groups of massive stars (i.e, with initial mass > 10 M_{\odot}^{37}), usually referred to as 'OB associations', due to the fact that these massive stars are blue/blue-white stars with surface temperatures roughly above 20 000 K

³⁷ These stars typically end their lives in a CCSN explosion, as opposed to the low- and intermediate-mass stars discussed in the previous section that become AGB stars at the end of their evolution and shed material via stellar winds.

belonging to the spectroscopic O and B classes [114, 115]. The ²⁶Al γ -ray map therefore indicates that most of the ²⁶Al in our Galaxy is produced by massive stars [19, 116, 117]. Theoretical models in fact predict that massive stars eject large abundances of ²⁶Al, both through stellar winds and CCSN explosions. Like in most of other stellar sources, ²⁶Al is mainly made via the ²⁵Mg(p, γ)²⁶Al reaction, while there are two main destruction channels: proton and neutron capture reactions, depending on the burning phase. Here, we focus first in section 2.2.1 on the winds from both single massive stars and massive stars that have a companion in a close binary system. We also discuss very massive stars (VMS), i.e. with masses above 100 M_{\odot} [118]. Second, in section 2.2.2 we discuss in detail the contribution to ²⁶Al coming from the CCSN explosive ejecta.

Overall, for stars of masses below roughly 40 M_{\odot} , the contribution of the explosive ejecta is typically dominant relative to that of the winds. For example, when looking at table 3 of Limongi and Chieffi [119], both contributions to ²⁶Al, from the hydrostatic and explosive phases (see section 2.2.2), are ejected during the explosion. In stars of higher masses, instead the winds are stronger (see section 2.2.1) and therefore their contribution to the total amount ejected increases to become similar to that ejected during the explosion. Neutrino processes are not usually included in the CCSN models, but can contribute a relatively minor component of ²⁶Al, as we present at the end of section 2.2.2. It should be kept in mind that, as discussed in detail below, these different contributions are strongly model-dependent. Stellar rotation and binarity, mixing in the hydrostatic and explosive phases of the stellar evolution, CCSN properties, such as the mass of the remnant and the energy of the explosion, as well as the choice of the reaction rates can all affect the different contributions to the total ²⁶Al yield from massive stars of different masses.

2.2.1. Massive star winds in single and binary systems. The ²⁶Al that is expelled from a massive star by winds is produced by hydrogen burning both in the core and, later, in a shell via proton-captures on ²⁵Mg. This ²⁶Al can be ejected by stellar winds when layers that once belonged to the H-burning core are exposed at the surface (in the case of Wolf-Rayet (WR) stars) or in the non-WR regime if some mixing mechanism allows the ²⁶Al produced in H-burning regions to diffuse into the stellar envelope up to the surface. Convection, rotational mixing in the radiative zones of the star and mass losses are key processes that may enrich the surface in ²⁶Al. For all massive stars, after the main sequence, the convective envelope penetrates into the layers where ²⁶Al has been produced and transports this radioisotope to the stellar surface. The strong winds following the main sequence expel these layers from the stars, carrying the ²⁶Al into the surrounding interstellar medium (ISM). For WR stars, the stellar winds already start during hydrogen burning and are so strong that the entire hydrogenrich envelope is removed, all the way down to the top of the layer processed by the CNOcycle (also known as the helium core), and this eventually includes the hydrogen-burning shell. The deeper layers exposed this way contain more ²⁶Al, leading to increased wind yields for these stars. After core hydrogen burning, ²⁶Al is quickly destroyed in the core during helium-burning by neutron capture reactions, specifically the (n, p) and (n, α) channels. However, because the convective helium-burning core is smaller than the original convective hydrogen-burning core, enough ²⁶Al survives to be expelled from the star into the ISM.

At solar metallicity, Z = 0.014, all single massive stars above 30 M_{\odot} experience phases of strong mass loss during their lifetimes. The amount of ²⁶Al ejected by the winds of massive stars, considering the currently recommended mass loss rate prescriptions (see [120] for the hot phase, [121, 122] for the cool phase, and [123] or [124] for the WR phase), depends in a sensitive way on the initial metallicity. At very low metallicity the amount of ²⁶Al ejected is much smaller than at solar metallicity because the winds are expected to be much weaker, and



Figure 7. The ²⁶Al yields (in the form of total mass of ²⁶Al ejected by the winds in units of solar masses) as function of the initial stellar mass from various studies reported in the literature for non-rotating single stars at solar metallicity [81, 125–128]. The red line gives the effective binary yields, i.e. the average increase of the yields of the primary star when considering a flat distribution for the binary periods and non-conservative mass-transfer, which assumes that all the mass transferred to the secondary star is subsequently ejected by the system and therefore results in an upper limit for the yields. The dotted pink line gives the VMS yields deduced from the models by [129] (figure based on figure 3 from [130]).

therefore the mass loss is smaller. Figure 7 shows the ²⁶Al yields ejected by the stellar winds as a function of initial stellar mass for models of solar metallicity predicted by various studies reported in the literature for non-rotating, solar metallicity stars. The highest yields are for stars with initial masses $>30-40 \text{ M}_{\odot}$. These stars become the so-called WR stars mentioned before, as they lose their entire hydrogen-rich envelope, exposing their helium cores. During the phase where layers that belonged to the core H-burning phase (which are enriched in helium and nitrogen) are exposed at the surface, large amounts of ²⁶Al are expelled into the ISM by these stars. Massive stars with masses between 10 and 30 M_{\odot} instead do not lose enough mass to expose the layers that have been processed by CNO burning.

Interestingly, most massive stars are found in binary systems (see e.g. [131]) and are close enough to each other to interact. Sana *et al* (2012) [132] found that more than 50% of all O-type stars (stars with initial masses from 15 M_{\odot} and higher) will interact with their companion during their lifetimes. More than 25% of these stars will interact with their companion even before the end of the main sequence [133]. These interactions influence both the evolution of the stars, and the ²⁶Al yields [125, 134]. The process resulting from binary interaction that mostly influences the yields is the mass-transfer between the two stars due to Roche lobe overflow. The evolution of the primary (i.e. the initially heavier star of the binary) can be strongly affected by this, as compared to their single-star counterparts. For example, the time at which mass loss starts and the amount of mass lost by the star can be influenced by binary interaction. The main effect of the mass-transfer is that more mass is lost from the primary stars, uncovering the layers rich in ²⁶Al that otherwise would not be uncovered if the star was evolving in isolation (for more details see [125]). The ²⁶Al injected into the ISM by binary systems is a combination of the ²⁶Al present in the layers stripped by mass-transfer and

expelled, and the ²⁶Al present in the deeper layers of the star that are driven off by the stellar winds (see figures 10 and 11 of [125]). The effect of binary interactions can be seen in figure 7 by comparing the red and the blue lines. The yields of the primary stars increase strongly below 30–40 M_{\odot}, up to a factor of 100 for the least massive stars (10–15 $_{\odot}$). Above 30–40 M_{\odot}, the binary interactions do not increase the yields of the stars anymore, as the winds are already very efficient in ejecting ²⁶Al.

Aside from massive star binaries and Wolf-Rayet stars, VMSs can also contribute significantly to the ²⁶Al enrichment of the ISM. The opinion widely held until 2010 was that the most massive stars in the Universe are of an order of 100–150 M_☉. More recent studies, however, have found evidence for the existence of VMSs of higher masses [135-137]). These stars are thought to dominate the mechanical energy input and ionising radiation [138, 139] of star-forming regions such as the Tarantula nebula. Moreover, the mass-loss rates of VMSs have been shown theoretically [140] and observationally [136] to be larger than previously assumed via mass-loss rates of Vink et al 2001 [122]. The discovered upturn in mass loss for the most massive stars occurs at a transition point where optically thin O-star winds transform to becoming optically thick [140, 141]. Recent population synthesis models [142] including stellar evolution models for VMSs [129, 143] with the new higher mass-loss rates [140] need to be constructed to predict the likely dominant contribution of VMSs to the galactic ²⁶Al emission budget. We expect such contributions to be high because VMSs are nearly homogeneous stars: their convective core during the main sequence phase extends over more than 90% of the total mass of the star. This means that almost all ²⁵Mg initially present in the star can be converted into ²⁶Al via proton captures and the reservoir of matter enriched in newly produced ²⁶Al may correspond to almost the whole star. Furthermore, VMSs are very luminous and are expected to have strong radiation-driven winds. These two factors lead us to predict large amounts of ²⁶Al to be ejected from these stars. For example, the non-rotating 500 M_{\odot} model by [129] shown in figure 7 loses about 450 M_{\odot} during the main sequence, leading to an ²⁶Al yield of 7.6×10^{-3} M_{\odot}. This is a factor 100 more ²⁶Al than for a 60 M_{\odot} star computed with the same code. Of course, these stars are very rare, however, their yields are so large that even a few events can have a strong impact on the galactic ²⁶Al budget.

The main uncertainties that affect the production of ²⁶Al in massive stars are of two types: those involving the nuclear reaction rates, in particular the ²⁵Mg(p, γ)²⁶Al rate and its branching ratio to the ground state of ²⁶Al, and the ²⁶Al(p, γ)²⁷Si rate; and those involving the physics input of the stellar models, including: the size of the convective core, the mass-loss rates, either induced by radiative line driven winds or by mass loss due to mass-transfer episodes in close binaries, and the mixing processes in the radiative zones of the stars, such as turbulence induced mixing due to rotation. An increase either in either the size of the convective core, the mass-loss rates, or the mixing in radiative zones, would lead to an increase of the ²⁶Al yields. See e.g. the discussion in Palacios *et al* [80].

2.2.2. CCSN from massive stars, hydrostatic and explosive nucleosynthesis. Several studies have been dedicated to the production of ²⁶Al in massive stars including their following CCSN explosions [9, 75, 81, 144]. On the one hand, it is expected and shown by theoretical stellar simulations that the H-burning and C-burning ashes are ²⁶Al-rich, as compared to the rest of the ejecta because these regions are rich in the protons needed to produce ²⁶Al (protons are produced during C-burning via the ¹²C(¹²C, p)²³Na reaction). On the other hand, during He-burning there are no protons available to efficiently produce ²⁶Al, and if there is any ²⁶Al already present here, it is typically destroyed by neutron captures, with neutrons produced by the ¹³C(α , n)¹⁶O and ²²Ne(α , n)²⁵Mg reactions. In more advanced stages like explosive O-burning and Si-burning, neither ²⁵Mg or ²⁶Al are efficiently produce [75].



Figure 8. Final mass fraction distributions of the isotopes H, ⁴He, ¹²C, ¹⁶O and ²⁸Si, indicative of the stellar structure, and of ²⁶Al and its main seed isotope ²⁵Mg as function of mass coordinate for the ejecta of CCSN models with initial mass M = 15 M_{\odot} (top panel) and M = 20 M_{\odot} (bottom panel) and initial metallicity Z = 0.02 [145].

While these general guidelines are derived from the nuclear astrophysics properties leading to the nucleosynthesis of ²⁶Al, stellar models show significant variations due to intrinsic properties and simulation parameters. In figure 8 we show the ²⁶Al mass fraction profile as function of mass coordinate for a $M = 15 \text{ M}_{\odot}$ star and a $M = 20 \text{ M}_{\odot}$ star model after the explosion [145], together with the profile of other major isotopes indicative of the stellar structure, and of ²⁵Mg, the seed nucleus for the production of ²⁶Al. Moving from the outer mass coordinate towards the center of the star, the first ²⁶Al peak is observed in the H-burning layers for both models, this derives from destruction of most of the initial ²⁵Mg via proton capture. Just below the H-burning layers, in the upper part of the H-poor, He-rich shell there is a significant amount of ²⁶Al left from the burning that happened before the CCSN. For the 15 M_☉ model, for example, the peak is around a mass fraction of 2×10^{-5} . This peak is due

to either direct mixing of ²⁶Al from the H-burning region just above, or to mixing of ¹⁴N, which provides protons via the ¹⁴N(n, p) ¹⁴C reaction, using the neutrons produced by ¹³C(α , n)¹⁶O. In the 20 M_{\odot} model this peak abundance is much more restricted in mass than in the 15 M_{\odot} model. At the bottom of the He shell, instead, ²⁶Al is completely destroyed by the neutron captures triggered during the CCSN explosion in this region of the stars (the so-called 'neutron burst', or n-process, [146–148]). Further differences between the 15 and the 20 M_{\odot} models are seen in the C-burning ashes. While the ²⁶Al abundances before the explosion are comparable in the two cases (with a mass fraction of the order of few 10⁻⁶), the 20 M_{\odot} model shows a much stronger explosive production than the 15 M_{\odot} model, visible at a mass coordinate roughly 3.6 M_{\odot}, and comparable to the abundance made by H-burning.

Alternative nucleosynthesis conditions from those described above may also be present and provide a significant contribution to the amount of ²⁶Al ejected by a CCSN, for instance, these can be related to convective-reactive events during the hydrostatic evolution of the progenitor star. The work of [62] showed that a significant amount of ²⁶Al can be also produced in the explosive He-burning ejecta, following the ingestion of H in the convective He-shell [149, 150].

Finally, neutrinos from the collapsing stellar core leading to the ν -process [151, 152] also affect the production of ²⁶Al in two ways: directly via the ²⁶Mg (ν_e , e^-) reaction, and indirectly by providing additional protons for the ²⁵Mg (p, γ) reaction, mostly from ²⁰Ne (ν_x , $\nu_x'p$) and spallation from other abundant nuclei. The cross sections for the neutrinoinduced reactions are very well constrained [153], in particular, the Gamow–Teller strength for ²⁶Mg (ν_e , e^-) has been determined by charge-exchange reactions [154]. The contribution of this process to ²⁶Al, however, is very sensitive to the rather uncertain neutrino-energy spectrum. Depending on the neutrino energies, the ν process may lead to an increase of the ²⁶Al yields by 10%–40% [75, 153].

2.3. Nova outbursts

Classical novae are the stellar explosions that take place in stellar binary systems, consisting of a compact, white dwarf star and a low-mass companion, typically a K or M main sequence star, although observations increasingly reveal more evolved companions. Novae exhibit a sudden rise in optical brightness, with peak luminosity reaching 10^4-10^5 solar luminosity. During the explosion, roughly $10^{-5}-10^{-3}$ M_{\odot} of material is ejected into the interstellar medium, at a speed of several 10^3 km s⁻¹. Novae are expected to recur with typical periodicity between 1 and 100 year (recurrent novae) and 10^4-10^5 year (classical novae).

The main nuclear reactions involved in the production and destruction of ²⁶Al in novae, and their associated uncertainties, have been discussed in several papers (e.g. [155, 156]) and are illustrated in figure 6). The synthesis of ²⁶Al in novae requires the presence of some seed nuclei, such as ^{24,25}Mg, or to some extent, ²³Na, and ^{20,22}Ne. Since novae do not achieve high enough temperatures to power CNO-breakout, ²⁶Al production requires an underlying ONe white dwarf (rather than a CO white dwarf) and some mixing to occur at the interface between the outer layer of the core and the envelope. The main nuclear reaction path leading to ²⁶Al is ²⁴Mg(p, γ)²⁵Al(β^+)²⁵Mg(p, γ)^{26g}Al, whereas destruction is dominated by the ^{26g}Al(p, γ)²⁷Si reaction. The current main source of nuclear uncertainty comes from the rate of the ²⁵Al(p, γ)²⁶Si reaction: because ²⁶Si only decays to the isomeric state of ²⁶Al this reaction determines the fraction of the nuclear path that proceeds through the isomeric ²⁶ⁱAl state, via the decay of ²⁶Si thus by-passing ^{26g}Al synthesis. Already before the discovery of ²⁶Al in the interstellar medium by the HEAO-3 satellite

Already before the discovery of ²⁶Al in the interstellar medium by the HEAO-3 satellite through the detection of the 1809 keV γ -ray line [157, 158], Ward [159] suggested that ²⁶Al

could be produced efficiently in astrophysical environments such as classical nova outbursts, characterized by a rapid rise to maximum temperatures around $T_{\text{peak}} \sim (2-3) \times 10^8$ K, followed by a relatively fast decline. One-zone, explosive H-burning nucleosynthesis studies corroborated this idea (see, e.g. [160, 161]), and concluded that while classical novae might produce sufficient amounts of ²⁶Al to reproduce some of the observed isotopic anomalies found in meteorites, they would not represent major galactic factories of ²⁶Al. These calculations, however, assumed solar composition (or CNO-only enhanced) envelopes. With the advent of models of nova explosions on ONeMg white dwarf stars [162], one-zone nova nucleosynthesis models predicted large amounts of radioisotope (such as ²²Na and ²⁶Al) in their ejecta [163, 164], suggesting that these novae might represent significant, though still not dominant, sources of the Galactic ²⁶Al.

The following 1D hydrodynamic simulations [165, 166] stressed the crucial role played by convection in carrying a fraction of the fresh ²⁶Al synthesized at the base of envelope to the outer, cooler layers where destruction through proton captures could be prevented. Still, the composition adopted for the underlying ONeMg white dwarfs adopted in these models was too crude as it was based on calculations of hydrostatic C-burning nucleosynthesis by Arnett and Truran [167] with mass fraction ratios X(¹⁶O):X(²⁰Ne):X(²⁴Mg) of 1.5:2.5:1. Stellar evolution models of intermediate-mass stars [168, 169] revealed that ONe white dwarfs are instead made basically of ¹⁶O and ²⁰Ne, with above ratios of 10:6:1. The dramatic reduction in the ²⁴Mg seeds resulted in a significant decrease in the contribution of novae to the galactic ²⁶Al predicted by the first 1D hydrodynamic simulations from accretion to ejection for a realistic composition of the underlying white dwarf, and with updated nuclear reaction rates [170, 171].

Since the late 1990s, all hydrodynamic 1D nova simulations systematically resulted in some ²⁶Al production. This includes the most recent *12321* nova models [172], which include the effect of the inverse energy cascade that characterizes turbulent convection in nova outbursts on the time-dependent amount of mass dredged-up from the outer white dwarf layers, and a time-dependent convective velocity profile throughout the envelope, as computed by 3D simulations [173–175]. While these state-of-the-art models yield more massive envelopes than those previously reported, and result in more violent outbursts characterized by higher peak temperatures and greater ejected masses, their ²⁶Al yields are similar to previous estimates for ONe novae (see [172] for details).

A crude estimate of the contribution of novae to the amount of 26 Al present in our Galaxy can be obtained from [163, 170]:

$$M(^{26}\text{Al}) \sim \tau(^{26}\text{Al}) f(\text{ONe}) M_{\text{ejec}} X(^{26}\text{Al}) R_{\text{nova}},$$
(1)

where $M_{\rm ejec}$ is the mean ejected mass during a nova outburst, $X(^{26}\text{Al})$ is the mean mass fraction of ^{26}Al in the ejecta, f(ONe) is the fraction of ONe novae (typically, 1/3; see Livio and Truran 1994), $R_{\rm nova}$ is the nova rate $(\sim 50^{+31}_{-23} \text{ year}^{-1} [176])$, and $\tau(^{26}\text{Al})$ is the mean lifetime of ^{26}gAl (1 Myr). From these estimates, and adopting a relatively favorable ONe nova model (e.g. $M_{\rm ejec}(^{26}\text{Al}) \sim 2 \times 10^{-8} \text{ M}_{\odot} [171]$), we obtain an upper limit to the contribution of novae to the Galactic ^{26}Al content of $\leq 0.34 \text{ M}_{\odot}$. This corresponds to about 12% of the Galactic ^{26}Al ($\sim 2.8 \pm 0.8 \text{ M}_{\odot} [177]$) and is in qualitative agreement with the analysis of COMPTEL/CGRO 1.809 MeV ^{26}Al emission map [177, 178], which favors younger progenitors (i.e. WR stars and CCSN, as discussed in section 2.2). However, it is worth noting that this estimate is affected by large uncertainties, since the mean ejected mass per nova outburst and the variation of the nova rate since the formation of our Galaxy are not well constrained.

3. Relevant nuclear reactions

²⁶Al has two long-living states: the ground state with spin and parity $J^{\pi} = 5^+$ and half-life $T_{1/2} = 0.717(24)$ My, and an isomeric state ²⁶Al^m at 228 keV with $J^{\pi} = 0^+$ and $T_{1/2} = 6.3460(8)$ s [1]. It is the abundance of the ²⁶Al ground state that is relevant for the cosmic 1809 keV γ -ray flux. Namely, the β^+ -decays from the ground state of ²⁶Al feed the first excited state in ²⁶Mg, which de-excites by emitting 1809 keV γ -rays. The isomeric state ²⁶Al^m, instead, decays via a fast superallowed β decay directly to the 0⁺ ground state of ²⁶Mg and hence does not contribute to the cosmic γ -ray flux from ²⁶Al.

In astrophysical environments (see section 2), 26 Al is mainly produced via radiative proton captures on 25 Mg (see section 3.1). There, de-excitations from the populated states feeding ultimately either the ground or the isomeric state in 26 Al are relevant in order to determine the population ratio between the two states of 26 Al. At lower temperatures, these two states act like separate nuclear species, but at temperatures above 0.4 GK, thermal excitation populating the isomeric state starts to play a role and reduce the effective lifetime of 26 Al, as discussed in section 4. Moreover, at high stellar temperatures and densities, capture of free electrons from the continuum will also affect the lifetime of 26 Al (see section 4). In addition to the production reaction 26 Mg(p, $\gamma){}^{26}$ Al, key reactions to determine the abundance of 26 Al are the destruction p-capture reaction 26 Al(p, $\gamma){}^{27}$ Si (section 3.2), the neutron-induced reactions on 26 Al (see section 3.3) and the bypass route via 26 Si (see section 3.4). Other reactions relevant for the production and destruction of 26 Al are briefly discussed in section 3.5. The reaction network around 26 Al summarizing the relevant nuclear reactions are shown in figures 1 and 6. In summary, in table 7 all the reactions considered here are listed, together with their relevant stellar sites, and corresponding temperatures.

We have recalculated some of the reaction rates presented in the following subsections using the RATESMC code [179] based on the information presented in the tables in each subsection. The resonance energies have been recalculated from the excitation energies, the separation energies and including the corrections for atomic binding as in [180]. Details as to resonance strengths and/or proton widths are provided in each subsection, as needed, together with figures of the new rates. The tabulated data for the rates can be found in tables 8–12.

3.1. The production reaction ${}^{25}Mg(p, \gamma){}^{26}AI$

The rate of the ²⁶Al production reaction is dominated by resonant proton captures to levels above the proton threshold at 6306.33(6) keV [181] in ²⁶Al. Direct proton captures to bound states in ²⁶Al and the contribution from the subthreshold (3⁺) resonance at $E_{\rm res} = -24.86(10)$ keV are negligible compared to the resonant captures at temperatures above ≈ 0.006 GK [182]. Therefore, we focus here on the resonant proton captures. Table 1 summarises the available data on the excitation energies, spins and parities as well as the resonance energies and strengths for the relevant states in ²⁶Al. The ground state spin and parity of ²⁵Mg is 5/2⁺, and therefore $\ell = 0$ proton captures populate states with $J^{\pi} = 2^+$ or 3^+ in ²⁶Al, $\ell = 1$ proton captures states with $J^{\pi} = 1^-, ..., 4^-$, and $\ell = 2$ states with $J^{\pi} = 0^+, ..., 5^+$. All states, except the $J^{\pi} = (7)$ state at 6695 keV, can be populated via $\ell = 0 - 2$ proton captures, however, many of the spin-parity assignments are still tentative (see table 1) and further studies are needed.

The first studies on excited states above the proton threshold in ²⁶Al were carried out via $^{25}Mg(^{3}He,d)$ reactions with the Tandem Van de Graaff accelerator at the University of Pennsylvania in late 1970s [196]. Several states were discovered and angular momenta assigned for the proton transfers based on the angular distribution of the cross sections and distorted-wave Born approximation analysis. Champagne *et al* did a thorough investigation of the ²⁵Mg(³He,d) reaction at the Wright Nuclear Structure Laboratory MP Tandem Van de Graaff accelerator in

Table 1. Excitation energies (E_x) together with the spins and parities (J^{π}) for the excited states above the proton separation energy $(S_p = 6306.33(6) \text{ keV } [181])$ in ²⁶Al. The excitation energies, spins and parities are from from [1] unless stated otherwise. The resonance energies have been recomputed from the excitation energies include a correction for atomic binding of $\Delta B_e = -1.14$ keV. The resonance energies ($E_{\rm res}$), and experimentally determined resonance strengths $\omega\gamma$ for the relevant states are given. The resonance strengths are the total resonance strengths—the f_0 factors are the branching of the resonance to the ground state of 26 Al. The f_0 has been recomputed [183] from the listed values in the ENSDF repository including the full cascade to the ground state and the isomer. Only states up to $E_x = 6800$ keV are listed.

E_x (keV)	J^{π}	E_{res} (keV)	$\omega\gamma~(\mathrm{eV})$	f ^a
6280.33(9)	(3 ⁺)	-24.85(11)	$\theta_p^2 = 0.0127(26)^0$	0.770(3)
6343.46(8)	4 ⁺ [184]	38.29(10)	$4.9(21) \times 10^{-22b}$ [184]	0.79(5)
6363.99(8)	3^{+}	58.81(10)	$2.9(5) \times 10^{-13}$ [185]	0.81(5)
6398.64(21)	2 ⁻ [186]	93.46(22)	$3.5(4) \times 10^{-10}$ [187, 188]	0.67(4)
				[188, 189]
6414.46(10)	(0 to 2 ⁺)	109.28(12)	$2.3(1) \times 10^{-11}$ c [190]	$0.0042(6)^{d}$
6436.44(11)	(3 to 5 ⁺)	131.26(13)	\leqslant 2.5 × 10 ⁻¹⁰ [187]	0.727(3)
6495.94(7)	(3 to 5 ⁺)	190.76(9)	$5.2(36) \times 10^{-7}$ e	0.75(2) [187]
6550.68(7)	$(4^+, 5^-)$	245.50(9)	$55.0(63) \times 10^{-7}$ [179]	0.80(1)
6598.32(16)	(5 ⁺)	293.14(17)	$45.0(52) \times 10^{-6}$ [179]	0.71(1)
6610.40(6)	(3 ⁻)	305.22(8)	$2.8(3) \times 10^{-2f}$	$0.878(10)^{g}$
6680.45(7)	(2^{+})	375.27(9)	$6.0(6) \times 10^{-2}$ [191]	0.67(1)
6724.25(7)	(4 ⁻)	419.07(9)	$7.4(2) \times 10^{-2}$ [191]	0.96(1)
6783.79(5)	(2^{-})	478.61(8)	$7.3(11) \times 10^{-2}$ [179]	0.56(1)
6789.30(4)	(3 ⁻)	484.12(7)	$60.0(77) \times 10^{-3}$ [179]	0.90(1)

^a Spectroscopic factor $C^2S = 0.022$ from Endt and Rolfs [192], single-particle proton width calculated from the parameters given by Iliadis [193]. An uncertainty on the spectroscopic factor of 20% has been assumed.

^b Expectation and variance of the resonance strength using $\omega \gamma = 4.5 \times 10^{-22}$ and a factor 1.5 uncertainty in [184].

^c Expectation and variance of the resonance strength using $\omega \gamma = 2.1 \times 10^{-11}$ and a factor 1.5 uncertainty in [184].

^d This resonance is given as $f_0 = 0.71$ in [182] citing then yet-to-be-published paper by Endt, de Wit and Alderliesten which is presumably [194]. The decay branches listed in [194] give $f_0 = 0.0041(7)$. The listed γ -ray branches in the ENSDF database give $f_0 = 0.0042(6)$. We adopt $f_0 = 0.0042(6)$. This resonance is rather weak for both radiative capture to the ground state and isomeric state and the astrophysical impact of this reassignment is negligible.

^e Weighted average with additional estimate of systematic uncertainty of $\omega \gamma = 9.0(6) \times 10^{-7}$ [187] and $\omega \gamma_g = 1.1(2) \times 10^{-7}$ and $f_0 = 0.74(1)$ [191]. ^f Weighted average 3.07(13) × 10⁻² [195] and $\omega \gamma = 2.1(2) \times 10^{-2}$ and $f_0 = 0.87(1)$ [191].

^g $f_0 = 0.91(1)$ using ENSDF values.

early 1980s [197, 198]. States at 6343 and 6400 keV were assigned as 3⁺, the latter only tentatively. Proton widths and resonance strengths were deduced for many of the states by scaling from the determined proton width for the 374 keV resonance. The ²⁵Mg(³He,d) reaction was revisited at the Princeton AVF cyclotron, and it was found that the 6343 keV state is actually the 6364 keV (3⁺) state and the 6400 keV is a J = 2 state at 6398 keV [199]. The state reported at 6343 keV in [197] was observed using the 27 Al(3 He, α) 26 Al but had been misassigned as a 25 Mg+p resonance. It was not populated in the 25 Mg(3 He,d) reaction in [199], suggesting that the 6343 keV state is not a strong single-proton state and therefore does not play a crucial role in the overall reaction rate. The proton width for the 374 keV resonance was re-determined, using the γ - ray branching ratio together with previous data, in [199], and found to be significantly lower, $\Gamma_p = 0.82(20) \text{ eV}$ [199], than the previously determined value $\Gamma_p = 460(129) \text{ eV}$ [198]. The calculated resonance strength for the 92 keV resonance ($\omega \gamma \leq 2.7 \times 10^{-13} \text{ eV}$ [199]) is significantly lower than the recently measured value, suggesting that the proton width might have been underestimated for the 374 keV resonance in [199]. Indeed, the resonance strength for the 92 keV resonance was revised to $8.5 \times 10^{-11} \text{ eV}$ in [200]. This is already much closer to the recently measured value $\omega \gamma = 2.9(6) \times 10^{-10}$ [187].

The doublet of states at 6343 and 6364 keV was confirmed in [201], where $J^{\pi} = 2^{-}$ was proposed for the 6399 keV state. A spin of (1⁺, 2) for the 6399 keV state has been adopted in the latest Nuclear Data Sheet [1] instead of the previous suggestions of 3⁺ [197, 198] and 2⁻ [199, 201]. More recently, angular distribution data, measured with the Gammasphere detector array for the two most intense γ -ray transitions from the 6399 keV state, support a $J^{\pi} = 2^{-}$ assignment for this state [186].

The resonance widths and strengths for the ²⁵Mg(p, γ)²⁶Al reaction have been studied directly using a low-energy proton beam and ²⁵Mg target, for example in [202–205]. In addition, spectroscopic factors for proton-unbound levels in ²⁶Al and their influence on stellar reaction rates have been investigated, e.g. in [206]. For low-energy resonances, the strength is almost entirely determined by the proton width $\Gamma_p : \omega\gamma = \omega \frac{\Gamma_p \Gamma_{\gamma}}{\Gamma} \approx \omega \Gamma_p$, when $\Gamma_p \ll \Gamma_{\gamma}$. The proton width depends on the spectroscopic factor, C^2S , and the single-particle width $\Gamma_{s.p.}$ as $\Gamma_p = C^2S\Gamma_{s.p.}$. For a *nlj* proton-transfer, single-particle widths scale with the center-of-mass-energy as shown in figure 2 of [184]. Spectroscopic factors can be obtained from measurements [196, 200, 206], or from shell model calculations. For example, the strength for the 58 keV resonance has been recently extracted based on spectroscopic factors determined in the ²⁵Mg(⁷Li, ⁶He)²⁶Al reaction at the Q3D magnetic spectrometer of the HI-13 tandem accelerator [185].

Direct underground measurements of several resonances have been reported by the LUNA collaboration. The rate has also been recently measured underground at JUNA [207] and these data are being analysed. Limata *et al* [195] measured the strength for the 304 keV resonance from the emitted γ -rays and found it to be 30.7 ± 1.7 meV, in good agreement with earlier work, with the exception of the AMS work of Arazi *et al* [191]. Limata *et al* also performed an AMS study and could not reproduce the result of Arazi *et al* [191] but instead agreed with their own γ -ray based value. They, therefore, neglected the Arazi *et al* [191] value in their recommended strength of 30.8 ± 1.3 meV, which averaged their result with that of the NACRE compilation [208]. This result was then used as a reference strength for a study of the resonances at 92, 130 and 189.6 keV by Strieder *et al* [187]. Only an upper limit could be determined for the 130 keV resonance and it is not expected to contribute to the astrophysical rate.

Endt *et al* [182] studied the astrophysical aspects of the ²⁵Mg(p, γ)²⁶Al reaction and made thorough compilations of the excited states in ²⁶Al [209]. Iliadis *et al* [184] then reinvestigated the previous literature data in 1996, and reported a new suggested rate for the reaction. In particular resonances at $E_r = 58$ and 92 keV were found to dominate the reaction rate in the temperature region 0.02–0.15 GK [184] relevant for hydrogen burning in stars. At 0.1–1.5 GK, the resonances at 190, 304, 374, and 418 keV, start to dominate the reaction rate as shown in [191].

We have recalculated the reaction rates using the RATESMC code. The resonance energy correction results in an effective increase in the resonance energies of 1.14 keV compared to the existing literature values based on $E_{res} = E_x - S_p$. For resonances with only upper limits for the resonance strengths, the reduced widths are estimated by randomly sampling from a Porter–Thomas distribution using the experimental upper limit as an hard cutoff value. This is not entirely statistically accurate since the experimental upper limits should be quoted to some confidence level with an associated probability density function used to derive the upper limit



Figure 9. (Left) The fractional contribution of each resonance to the ²⁵Mg(p, γ)²⁶Al^g based on the resonance parameters given in table 1. (Right) Contour heatmap of the current reaction rate uncertainties. The thick (thin) black curves are the 68% (95%) coverage limits. The green curves are median (solid) and 68% coverages (broken) for the ²⁵Mg(p, γ)²⁶Al^g reaction rate from the compilation of Iliadis *et al* [213]. The decrease in the reaction rate at low temperatures is due to the shifted resonance energy computed, taking the atomic binding into account. The decrease in the reaction rate at $T \approx 0.1$ GK is due to the updated resonance strength of the 93 keV resonance from LUNA and JUNA [187, 188]. The resonance strength and ground state branching fraction for the $E_r = 93$ keV resonance are weighted averages of [187, 188] and [188, 189], respectively.

at that confidence level [210] (though these data are frequently lacking in the published studies). However, the effect of this is small (see [210–212] for more details). The corresponding contribution plots for the resonances are shown in figures 9 and 10. The 93- and 305 keV resonances dominate over the astrophysically relevant temperature range and both resonances have been measured directly by LUNA. The 59 keV resonance strength has thus far remained inaccessible for direct measurements. The corresponding re-evaluated reaction rates to the ground state and isomeric state of ²⁶Al are given in tables 8 and 9. In addition to the proton-capture rate, the de-excitations from the populated states in ²⁶Al to the ground and isomeric states of ²⁶Al need to be taken into account. The rates are typically multiplied by the corresponding ground state branching fraction f_0 , see, e.g. [184]. Thermal excitation between the states, discussed in section 4, complicates the situation.

As recently evident in the study of Lotay *et al*, there remains some uncertainty and occassional inconsistencies in the ground state branching fractions (f_0) for each resonance. For example, the f_0 value of the $E_r = 95$ keV resonance was revised from $f_0 = 0.52 \pm 0.02(\text{stat.}) \pm 0.06$ (syst.) [186] to $f_0 = 0.76(10)$ [189]. Similarly, on the basis of the γ -ray branching information stored in the ENSDF database, the f_0 value for the astrophysically unimportant $E_r = 109$ keV resonance has values ranging from $f_0 = 0.0041(7)$ to $f_0 = 0.71$ depending on the source. New, independent measurements of these ground state branching fractions are advisable in order to validate the existing results.



Figure 10. Same as figure 9 but for ${}^{25}Mg(p, \gamma){}^{26}Al^m$. The decrease in the reaction rate at low temperatures is due to the shifted resonance energy computed, taking the atomic binding into account. The difference at $T \approx 0.1$ GK is due to the updated information on the $E_r = 93$ keV resonance from [187–189].

3.2. The destruction reaction ${}^{26}Al(p, \gamma)^{27}Si$

Proton capture on ²⁶Al provides the main destruction mechanism for ²⁶Al in several stellar sites such as classical novae, convective core hydrogen burning in massive stars, and hydrogen burning in intermediate-mass AGB stars. The uncertainties in the ²⁶Al(p, γ)²⁷Si reaction rate at the temperatures present in these environments can result in large variations in the ²⁶Al abundance. For example, sensitivity studies show that this uncertainty leads to variations of up to two orders-of-magnitude in AGB calculations [89]. The situation is further complicated by the existence of the 228 keV isomeric state in ²⁶Al, which must be treated separately from the ground state at temperatures below 0.4 GK, as discussed above [216]. Thus, the ²⁶Al^g</sup>(p, γ)²⁷Si and ²⁶Al^m(p, γ)²⁷Si reaction rates must be determined independently to understand the destruction of ²⁶Al in the stellar sites described above. Due to the impact of these reaction rates on the abundance of galactic ²⁶Al, there have been a wide variety of direct and indirect measurements aimed at determining these rates.

For ²⁶Al^g(p, γ)²⁷Si resonances at $E_r > 190$ keV, which have less of an influence on the destruction of ²⁶Al, the strengths are well constrained by previous direct measurements [217, 218]. The resonance around $E_r = 184-190$ keV is an important resonance but there is some disagreement in its resonance energy. The most recent direct measurement of ²⁶Al^g(p, γ)²⁷Si was completed in inverse kinematics at TRIUMF using the DRAGON recoil separator with an intense ²⁶Al ion beam (~2.5 × 10⁹ ²⁶Al s⁻¹). This study determined the energy and strength of the resonance that dominates the rate in classical novae to be $E_r = 184 \pm 1$ keV and $\omega\gamma = 35 \pm 7 \mu$ eV, respectively [219], resulting in an increase of 20% in ²⁶Al^g production in nova models when compared with the previous unpublished values [217]. The properties of this resonance are consistent with a *p*-wave assignment for this resonance $J^{\pi} = (7 - 13)/2^{-1}$ based on the spectroscopic factor from a ²⁶Al(³He, *d*)²⁷Si measurement by Vogelaar *et al* [220]. A subsequent γ -ray spectroscopy study of ²⁷Si gave a $J^{\pi} = 11/2^{+}$ assignment to a state at $E_x = 7651.9(6)$ keV [221, 222] based on comparison with the $E_x = 7948$ keV state in the mirror nucleus, ²⁷Al, corresponding to an $\ell_p = 0$ resonance at $E_r = 188.6(4)$ keV. A later ²⁶Al(*d*, *p*)²⁷Al study clarified the spin and parity of the mirror state in ²⁷Al as $J^{\pi} = 11/2^{-1}$

[214]. There is now a consensus that the resonance between $E_r = 184 - 190 \text{ keV}$ has a $J^{\pi} = 11/2^{-}$, $\ell_p = 1$ assignment. The energy of this resonance remains a matter of some disagreement and there is not, at present, any way of resolving this discrepancy. To account for this we have computed the resonance energy with an inflated uncertainty following the procedure set out in [223].

While the measurement of Ruiz et al [219] significantly reduced the uncertainty in ${}^{26}Al^{g}(p,$ γ)²⁷Si for nova nucleosynthesis, lower energy resonances dominate this reaction rate at the lower temperatures found in AGB and massive stars. At these lower energies, direct measurements become unfeasible with currently available ²⁶Al beam intensities and indirect measurements are required. Specifically, the 127 keV resonance in ²⁷Si is thought to dominate the reaction rate in these environments as it is the only known $\ell_p = 0$ proton-capture resonance in this energy regime [224]. This and other resonances have been studied indirectly in a variety of measurements including transfer and γ -ray transition studies (e.g. [220, 221, 225, 226]). More recently, there have been multiple studies in inverse kinematics with unstable ²⁶Al beams including two measurements of resonances in the mirror ²⁷Al nucleus in inverse kinematics via the ${}^{26}Al(d, p){}^{27}Al$ reaction [107, 214] and a measurement of states in ²⁷Si via ²⁶Al(d, n)²⁷Si [227]. In these studies, spectroscopic factors of states in ²⁷Al and ²⁷Si were measured to determine the resonance strengths of those states. The values of the strength of the 127 keV resonance obtained via the mirror studies [107, 214] are in agreement with each other, but a factor of four higher than the previously accepted value [220]. However, there are worrying discrepancies for this resonance between the resonance information reported in [107] ($C^2S = 0.0102(21)$ and $\omega\gamma = 2.6^{+0.7}_{-0.9} \times 10^{-8}$ eV) and [228] ($C^2S = 0.0093(7)$ and $\omega\gamma = 5.7(4) \times 10^{-8}$ eV), i.e. a lower spectroscopic factor is calculated to result in a larger partial width and resonance strength. Based on this, some of the discrepancies between these experimental results are likely due to the theoretical treatment of the experimental data. Revisiting the original experimental studies and treating them with consistent experimental methods may help to resolve these discrepancies and will provide better constraints on ²⁶Al destruction by proton capture. As an example, the later study of [228] notes that the results of [214] has a technical fault in the number of nodes for the computation of the transfer amplitudes. Notwithstanding these concerns, the 127 keV resonance dominates the reaction rate at relevant temperatures for ²⁶Al nucleosynthesis in massive and AGB stars. While the ²⁶Al(d, n)²⁷Si measurement only yielded an upper limit on the spectroscopic factor of this state, the results were consistent with these mirror studies [227]. Clearly, a direct measurement of this resonance strength -one which obviates some of the theoretical inconsistencies of the transfer data is a high priority for future studies once more intense ²⁶Al beams become available.

As discussed above, at temperatures below around 0.4 GK, the isomer and ground state must be treated as separate nuclei and thus the ²⁶Al^m(p, γ)²⁷Si reaction rate should be determined independently from proton capture on the ground state. However, previous determinations of this reaction rate were typically scaled from the ²⁶Al^g(p, γ)²⁷Si rate, despite the large spin difference between the ground (5⁺) and isomeric (0⁺) states, as little experimental data for proton capture on the isomer was available [229]. A direct measurement of the strength of the $E_r = 447$ keV resonance in ²⁶Al^m(p, γ)²⁷Si is currently the only direct resonance information for this reaction [230]. A measurement of the ²⁷Al(³He, t)²⁷Si^{*}(p)²⁶Al^{g,m} and ²⁸Si(³He, α)²⁷Si^{*}(p)²⁶Al^{g,m} reactions was performed at the Wright Nuclear Structure Laboratory to indirectly determine the ²⁶Al^m(p, γ)²⁷Si reaction rate based on experimental information [231]. While this study was only able to put a lower limit on the reaction rate, as proton decays from states in ²⁷Si at energies of $E_r \ge 445$ keV could be measured, this study confirmed that different resonances in ²⁷Si dominate the two rates. A similar study of the ²⁷Al(³He, t)²⁷Si^{*}(p)²⁶Al reaction using the same Enge Split-Pole spectrograph, now installed at the John D Fox Accelerator laboratory at Florida State University, was recently performed detecting proton decays down to $E_r \simeq 300 \text{ keV}$ in order to further improve the reaction rate determination [232].

Alongside these charge-exchange reaction studies, a complementary investigation of the γ -decaying properties of ²⁶Al^m + p resonant states was performed at Argonne National Laboratory [222, 233, 234]. In that work [222, 233, 234], a ¹²C(¹⁶O, n) fusion-evaporation reaction was used to populate excited states in ²⁷Si, located above the ²⁶Al^m + p emission energy of 7691.3(1) keV [235], and the resulting γ decays were recorded with the Gammasphere detector array [236, 237]. γ decays were observed from all resonant states with energies $E_r \leq 500$ keV and spin assignments were obtained from angular distribution measurements. Furthermore, by examining the mirror nucleus ²⁷Al over a suitable energy range, it was possible to propose parity assignments for key resonances. In [222, 233, 234], it was concluded that a $J^{\pi} = 5/2^+$ state at $E_r = 146.3(3)$ keV is likely to dominate the astrophysical ²⁶Al^m(p, γ) reaction for low stellar temperatures, while a proposed $J^{\pi} = 3/2^-$ state at $E_r = 378.3(30)$ keV governs the rate for temperature, T > 0.15 GK. However, it should be noted that due to the very high excitation energies of ²⁶Al^m + p resonant states, the accurate matching of mirror states is extremely challenging. In particular, it is very difficult to know how mirror shifts are affected when both the ²⁷Si and ²⁷Al systems become particular unbound, which is the case for a number of the proposed analog pairs.

More recently, a measurement of the ²⁶Al^{*m*}(*d*, *p*)²⁷Al reaction in inverse kinematics was performed using an isomeric ²⁶Al beam produced at the ATLAS facility at Argonne National Laboratory [215]. Similar to the studies of Pain *et al* [107] and Margerin *et al* [214], this measurement aimed to determine spectroscopic factors of states in ²⁶Al(*d*, *p*)²⁷Al reactions that are mirrors of the ²⁶Al^{*m*} + *p* resonances in ²⁷Si. Using this mirror symmetry, an upper limit of the reaction rate was determined, which is dominated by resonances at $E_r = 146$ and 378 keV over astrophysically relevant temperatures. The ²⁶Al^{*m*}(*p*, γ)²⁷Si reaction rate determined here is smaller than that for the ground state by an order of magnitude or more at $T_9 \leq 0.3$ GK, implying that destruction via the isomer is not significant in most stellar sites. However, further study of resonances in ²⁷Si both directly and indirectly is still warranted.

We have recomputed the ${}^{26}Al(p, \gamma)^{27}Si$ reaction rates (i.e. for the ground and metastable states) using the RATESMC code [211] and the information in tables 2 and 3. The corresponding contribution plots for the resonances are shown in figures 11 and 12. Resonances for which there is no measured proton width or resonance strength have been treated by assuming that the reduced proton widths are drawn from a Porter–Thomas distribution with mean $\theta^2 = 0.0045$ with a factor of 3 variation on that mean value. This factor variation is based on the observed scatter in the mean of the Porter-Thomas distribution determined from experimental results of proton capture and scattering reactions. For more details about this assumption including the data upon which this assumption is based, see the discussion in section 5.2.1 of [210] and the experimentally determined spread in the reduced widths reported in figure 4 and section IV.B of [212]. Experimental upper limits are used to truncate the distribution where appropriate. There are a number of different sources for the resonance information for the two reactions which have been discussed in the text above. The sources for different spectroscopic information used in the calculations of the rates are given in tables 2 and 3. Of particular note in the present evaluation is the increased uncertainty in the resonance energy of the $E_r = 188$ keV resonance due to the disagreement between the resonances energies determined with DRAGON and γ -ray spectroscopy, and the probable need for a reconsideration of the various ${}^{26}Al(d, p){}^{27}Al$ mirror studies to try to account for systematic differences between experiments before a full re-evaluation of the

²⁶Al^{*m*}(*p*, γ)²⁷Si reaction with realistic uncertainties. For the ²⁶Al^{*m*}(*p*, γ)²⁷Si reaction rate, the rate has been recalculated only using known level information. While this information is somewhat lacking in the region of interest, the recent

Table 2. Recommended excitation energies (E_x) together with the spins and parities (J^{π}) for the excited states above the proton separation energy $(S_p = 7463.34(13))$ keV [181]) in ²⁷Si for the ²⁶Al^g $(p, \gamma)^{27}$ Si reaction. The resonance energies (E_{res}) and experimentally determined resonance strengths ($\omega\gamma$) for the relevant states are given where available. The atomic shift for this reaction is $\Delta B_e = -1.27$ keV. The states listed in brackets are tentative resonance states which were included in the evaluation of the reaction rate. As demonstrated in figure 11, the impact of these resonances on the reaction rate is negligible.

E_x (keV)	J^{π}	$E_{\rm res}({\rm keV})$	$\omega\gamma({ m eV})$
7469.2(6)	$(1/2, 5/2)^+$	6.8(9)	$< 1.8 \times 10^{-63}$ [226]
(7493.1(40))	$(3/2^+)$	(31(4))	< 1.5 $ imes$ 10 ^{-28a}
7531.5(5)	$5/2^{+}$	69.3(7)	$< 3.6 \times 10^{-16}$ [228]
(7557(3)) [226]	$(3/2^{+})$	(95(3))	$< 3.4 \times 10^{-15}$ [107]
7589.89(12)	$9/2^{+}$	128.1(9)	$4.2(16) \times 10^{-8b}$
7651.68(11)	$11/2^{+}$	187.7(23)	$35(7) \times 10^{-6}$ [219]
7693.8(9)	$5/2^+$	231.8(9)	$< 1.0 \times 10^{-5}$ [217]
7704.3(2)	$7/2^{+}$	242.3(2)	$1.0(5) \times 10^{-5}$ [217]
7739.06(11)	$9/2^+$	277.01(17)	$3.8(10) \times 10^{-3}$ [238]
7831.5(5)	$9/2^{-}$	369.5(5)	$65(18) \times 10^{-3}$ [238]
8156(2)		694(2)	$51(27) \times 10^{-3}$ [238]
8167.3(12)	$(11/2^{+})$	705.3(12)	$16(6) \times 10^{-3}$ [238]
8224(2)	$(7/2^{+})$	762(2)	$35(13) \times 10^{-3}$ [238]
8287(3)	$(7/2^+ \text{ to } 13/2^+)$	825(3)	$41(16) \times 10^{-3}$ [238]
8356(2)	$(3/2^+ \text{ to } 9/2^+)$	894(2)	$67(28) \times 10^{-3}$ [238]

^a Resonance strength upper limit obtained using the Wigner limit for the proton width. ^b Weighted average of [107, 228].

Table 3. Recommended excitation energies (E_x) together with the spins and parities (J^{π}) (taken from [234]) for the excited states above the proton separation energy $(S_p = 7691.65(13))$ keV [181]) in ²⁷Si for the ²⁶Al^m $(p, \gamma)^{27}$ Si reaction. The resonance energies ($E_{\rm res}$) and experimentally determined resonance strengths ($\omega\gamma$) for the relevant states are given where available. The atomic shift for this reaction is $\Delta B_e = -1.27$ keV.

E_x (keV)	J^{π}	$E_{\rm res}({\rm keV})$	$\omega\gamma(eV)$
7693.8(9)	$5/2^{+}$	3.5(9)	$< 2.90 \times 10^{-86}$ [239]
7704.3(2)	$7/2^+$	14.0(2)	$< 4.61 \times 10^{-44}$ [239]
7739.3(4)	$9/2^{+}$	49.0(4)	$< 2.69 \times 10^{-22}$ [239]
7794.8(19)	$7/2^{+}$	104.5(19)	$< 1.92 \times 10^{-14}$ [239]
7831.5(5)	$9/2^{-}$	141.2(5)	$< 2.39 \times 10^{-14}$ [239]
7837.6(2)	$5/2^{+}$	147.2(2)	$< 1.5 \times 10^{-8}$ [240]
7899.0(8)	$5/2^{+}$	208.7(8)	$< 1.61 \times 10^{-5}$ [239]
7909.1(7)	$3/2^{+}$	218.8(7)	$< 1.4 \times 10^{-6}$ [240]
7966.3(8)	$5/2^{+}$	276.0(8)	$< 2.08 imes 10^{-4}$ [239]
8031.5(11)	$5/2^{+}$	341.2(11)	$< 3 \times 10^{-8}$ [215]
8069.6(30)	$3/2^{-}$	379.3(30)	$< 3.3 \times 10^{-4}$ [240]
8139.3(6)	$1/2^{-}$	449.3(6)	$434(214) \times 10^{-3}$ [230]
8318(3)	$1/2^{+}$	626(3)	0.35(7) [231]
8375(3)	$1/2^{-}/3/2^{-}$	683(3)	0.24(6)/0.48(12) [231]
8446(3)	Assumed $1/2^+$	754(3)	0.32(5) [231]



Figure 11. Same as figure 9 but for ${}^{26}\text{Al}^g(p, \gamma){}^{27}\text{Si}$. The variations in the rates are due to the updated Γ_p proton partial widths derived from the ${}^{26}\text{Al}(d, p){}^{27}\text{Al}$ experiments of [107, 214, 215].



Figure 12. Same as figure 9 but for ${}^{26}\text{Al}^m(p, \gamma){}^{27}\text{Si}$, except the green lines are for ${}^{26}\text{Al}^g(p, \gamma){}^{27}\text{Si}$ since [213] suggests using this rate as a proxy for the ${}^{26}\text{Al}^m(p, \gamma){}^{27}\text{Si}$ reaction rate due to the paucity of spectroscopic information in ${}^{27}\text{Si}$.

direct measurement of the 447 keV resonance strength, which dominates the reaction rate from 0.3 to 2.5 GK [230], now allows for a more accurate reaction rate determination. Nevertheless, some caution is required in the interpretation of the ${}^{26}\text{Al}^m(p, \gamma){}^{27}\text{Si}$ reaction rate since many of the known states in ${}^{27}\text{Si}$ have spins and parities identified from fusion-evaporation reactions [221]; these reactions introduce a large amount of angular momentum and low-spin states may readily be missed in these experiments. Studies of low-spin states are therefore encouraged, especially indirect measurements of the 218 keV resonance, which is likely to dominate the reaction rate at temperatures below 0.3 GK. Comparison with the mirror nucleus, ${}^{27}\text{Al}$, which has been rather well studied may help to rule out the existence of additional states.

3.3. Neutron-induced destruction reactions

The sensitivity study by Iliadis *et al* [241] has shown that the ²⁶Al(n, p)²⁶Mg and ²⁶Al(n, α)²³Na reactions are of importance for the determination of ²⁶Al abundances produced during hydrostatic C-shell and explosive Ne/C-shell burning phases in massive stars. These reactions involve excited states in ²⁷Al within about 500 keV above the ²⁶Al + *n* threshold ($S_n = 13057.91$ (12) keV) where the level density ρ is extremely high ($\rho \equiv dN(E_x)/dE_x > 80 \text{ MeV}^{-1}$ [242]). These states decay by proton or α -particle emission because of the lower ²⁶Mg + *p* and ²³Na + α thresholds ($S_p = 8271 \text{ keV}$, $S_\alpha = 10092 \text{ keV}$).

At present, only few experimental data on both reactions are available. The first measurement of the 26 Al(n, p_1)³⁸ reaction was performed by Trautvetter and Käppeler using a quasi-Maxwellian neutron spectrum at around kT = 31 keV [243]. This was followed by a more comprehensive study in 1984 [244] using neutron spectra around various energies (40 meV, 31 keV, 71 keV, and 310 keV), including also the ${}^{26}Al(n, p_0)$ channel, which is 3-100 times weaker than (n, p_1) , and providing an upper limit on the ²⁶Al (n, p_2) channel at 40 meV. Roughly 10 years later, Koehler et al [245] determined ²⁶Al(n, p_1) and ²⁶Al(n, α_0) cross sections using the neutron time-of-flight technique at the Los Alamos Neutron Science Center (LANSCE). The 26 Al(n, p_1) cross section was found to be in disagreement with the earlier data [244] in the limited neutron energy range of overlap (at around 30 keV), leading to a higher stellar reaction rate by a factor of about two. Roughly 15 years ago, De Smet et al reported a measurement of ${}^{26}Al(n, \alpha_{0+1})$ reaction cross sections using the GELINA neutron time-offlight facility at the Geel Joint Research Centre of the European Commission [246]. The GELINA measurements overlapped in the lower neutron regime with the the LANSCE experimental study (the maximum neutron energy for the (n, α_0) study was 10 keV [245]) and also data at higher neutron energies were obtained. De Smet et al identified several new resonances for the ²⁶Al(n, α) reaction. Both, Koehler *et al* and De Smet *et al*, provided resonance strengths for a resonance at around 6 keV neutron energy, however, their results disagree by a factor of 1.8. This leads to a large discrepancy of the astrophysical reaction rates deduced from these data.

Additional data on states above the neutron separation threshold and resonance strengths were obtained by Skelton *et al* [247], who performed an experiment using the time-reverse ${}^{26}Mg(p, n){}^{26}Al$ and ${}^{23}Na(\alpha, n){}^{26}Al$ reactions, thereby accessing information on the (n, p_0) and (n, α_0) channels. The (n, p_1) channel is thought to be astrophysically dominant, but it is not accessible in time-reversed experiments.

Recently, there have been new direct measurements of ²⁶Al(n, p) ²⁶Mg and ²⁶Al(n, α) ²³Na reactions at the new high neutron flux beamline EAR-2 at n_TOF CERN, and at the GELINA facility [248, 249]. Both reaction cross sections were measured up to about 150 keV neutron energy, extending the previously available experimental range for energy dependent data. Resonance strengths of several resonances were provided for the first time. Astrophysical reaction rates, including all relevant branches could be deduced from the data up to about 0.6 GK stellar temperature. Resonance strengths obtained for the ²⁶Al(n, α) ²³Na reaction in [249] agree well with previous data by De Smet *et al* [246], leading to a good agreement of astrophysical reaction rates at low stellar temperatures. For the ²⁶Al(n, p) ²⁶Mg channel astrophysical reaction rates are higher in the energy region of overlap compared to Trautvetter *et al* [244], however compatible within 2 standard deviations. Resonance strengths for both reactions are lower than results by Koehler *et al* [245].

³⁸ The subscript 1 refers to particle emission to the first excited state of ²⁶Mg.

Author	E_R (keV)	$\omega \gamma_{\alpha} \ ({\rm eV})$	$\omega \gamma_{\alpha 0} \ ({\rm eV})$	$\omega \gamma_{p1} \ ({\rm eV})$
Lederer-Woods <i>et al</i> [248, 249]	5.9 ± 0.1	4.25 ± 0.41	4.04 ± 0.39	1.28 ± 0.20
	21.9 ± 0.2	1.62 ± 0.41	1.56 ± 0.40	< 0.6
	31.4 ± 0.4	1.62 ± 0.63		5.8 ± 1.5
	35.7 ± 0.4	3.7 ± 1.0	< 0.55	43.4 ± 10.7
	41.3 ± 0.4	19.1 ± 3.6	9.0 ± 2.0	22.9 ± 5.3
	57 ± 2	1.8 ± 1.2		2.7 ± 1.8
	75 ± 2			8.1 ± 3.7
	86 ± 4	8.9 ± 7.7		85 ± 23
	≈ 105	38 ± 11		53 ± 14
	≈ 120	34 ± 10		46 ± 13
	≈ 140	151 ± 30		71 ± 23
De Smet et al [246]	5.87 ± 0.02	4.23 ± 0.36	3.68 ± 0.34	
	21.98 ± 0.1	1.83 ± 0.27	1.83 ± 0.27	
	34.95 ± 0.2	5.98 ± 0.86	only α_1	
	41.3 ± 0.2	20.19 ± 2.02	11.1 ± 1.5	
	85.2 ± 0.8			
	108.5 ± 1.1			
Koehler et al [245]	5.578		6.6 ± 1.7	2.03 ± 0.51
	33.7			128 ± 22
Skelton <i>et al</i> [247]	5.8 ± 2		≤6.4	
	22.4 ± 2		≤2.5	
	42 ± 2		14 ± 1.4	

Table 4. Resonance energies E_R and resonance strengths $\omega\gamma$ determined in previous direct and time-reversed experiments for ${}^{26}\text{Al}(n, \alpha)$ and ${}^{26}\text{Al}(n, p_1)$ resonances.

A summary of experimental resonance strengths for ${}^{26}Al + n$ resonances is listed in table 4 (note that these data refer to reactions on the experimentally accessible ground state of ${}^{26}Al$).

Indirect studies have also been undertaken to determine the properties of ²⁷Al states above the ²⁶Al^g + n and the ²⁶Al^m + n thresholds, e.g. excitation energy, spin/parity, branching ratio. ²⁷Al states have been populated using proton inelastic scattering at the Tandem-ALTO (Orsay, France) and MLL (Munich, Germany) facilities. Protons were detected using the Enge Split-Pole [250] and Q3D [251] high-resolution magnetic spectrometers as the main detection system, respectively. Energies of more than 30 new ²⁷Al states have been determined above the neutron threshold up to an excitation energy of 13.8 MeV [250]. Proton inelastic scattering has a very unselective reaction mechanism that is well adapted to populate all excited states [252–254], however, on its own, it does not easily allow to identify low orbital momentum neutron capture resonances. Based on the energy of populated ²⁷Al states, the first four lowest energy resonances observed by De Smet *et al* [246] were populated [250]. Proton and α -particle branching ratios have also been determined for these states by coupling a DSSSD (Double-sided Silicon Stripped Detector) array to the Enge Split-Pole spectrometer [251].

At present, the main remaining challenge is to extend our present knowledge of the properties (energy and strength) of the dominating resonances up to about 500 keV above the 26 Al + *n* threshold. In the alternative approach of indirect measurements it may be interesting

to complete the branching ratio measurement by the study of the ${}^{26}\text{Al}(d, p){}^{27}\text{Al}$ reaction. This could be used to determine the neutron width, hence providing an indirect determination of the resonance strength. The interest of such transfer reaction is to have the same selectivity as the neutron capture reactions. Such measurements have been reported [107, 214], however, they only cover excitation energies lower than 12 MeV in ${}^{27}\text{Al}$. Extending these studies to higher energies would be interesting, though challenging due to the increasing background, the low proton energies, and the limited ${}^{26}\text{Al}$ beam intensity.

3.4. The bypass reaction ${}^{25}Al(p, \gamma){}^{26}Si$

Understanding the ²⁵Al(p, γ)²⁶Si astrophysical reaction rate is especially important in highertemperature environments such as novae, where this reaction becomes faster than the ²⁵Al β decay (7.2 s). If the proton-capture rate on ²⁵Al is faster than β decay, ²⁶Si will be produced, which in turn decays to the ²⁶Al isomer. The isomer subsequently decays ($t_{1/2} = 6.3$ s) to the ground state of ²⁶Mg, and production of the long-lived ²⁶Al ground state is bypassed (figure 6).

As radioactive beams of ²⁵Al are not currently available at sufficient intensities to directly measure the reaction cross section, estimates of the astrophysical reaction rate have generally been based upon knowledge of the nuclear structure of ²⁶Si. Of relevance to the rate are nuclear levels near the proton threshold at $S_p = 5513.8(5)$ keV in ²⁶Si [255]. Especially important is identifying 2⁺ or 3⁺ levels near the threshold that could provide *s*-wave resonances for the ²⁵Al(p, γ)²⁶Si reaction. Shell model calculations and comparisons with the ²⁶Mg mirror nucleus indicate that levels of interest may include two 4⁺ states, a 1⁺ state, a 3⁺ state, and a 0⁺ state in the rough excitation energy range $E_x = 5400-6200$ keV [184, 256, 257].

Some of the first studies searching for relevant ²⁶Si states utilized measurements of the ²⁸Si(p, t)²⁶Si [258] and ²⁹Si(³He,⁶He)²⁶Si reactions [259]. Energies for astrophysicallyimportant levels were extracted from extrapolations of lower-lying level energies previously measured with high precision using γ rays [260]. The energies of several levels near threshold were determined with greater precision, and triton angular distributions from the ²⁸Si(p, t)²⁶Si reaction provided sensitivity to the angular momentum transfers. In 2004, Parpottas *et al* [261] studied the ²⁴Mg(³He, n)²⁶Si reaction and largely confirmed the excitation energies extracted previously [258, 259]. More interestingly, however, Parpottas *et al* [261] deduced, from comparisons with statistical model calculations, that the previously-observed level at ~5916 keV was actually the important 3⁺ level providing an *s*-wave resonance in the ²⁵Al(p, γ)²⁶Si reaction. This hypothesis was later deemed to be consistent with the angular distribution measured in the ²⁸Si(p, t)²⁶Si reaction [262].

As this 3⁺ resonance dominates the ²⁵Al(p, γ)²⁶Si astrophysical reaction rate, the next most important factor, after its energy, to be determined is its resonance strength. Since the proton width is expected to be much larger than the γ width [184], the resonance strength can be determined once the γ width is known. Early estimates simply assumed the width was the same as the mirror ²⁶Mg level (i.e. $\Gamma_{\gamma} = 33 \pm 14$ meV) where the uncertainty comes from the uncertain ²⁶Mg lifetime and does not account for uncertainties in isospin symmetry [184, 262]. This lifetime was recently remeasured by [263] resulting in $\Gamma_{\gamma} = 33 \pm 5$ meV for the mirror level. Other estimates have come from combining the proton width estimated from a ²⁵Al(d, n)²⁶Si proton-transfer measurement [264] with subsequent determinations of the γ to proton branching ratios, $\Gamma_{\gamma}/\Gamma_{p}$, to extract $\Gamma_{\gamma} = 39 \pm 21$ meV [265], $\Gamma_{\gamma} = 59 \pm 29$ meV [257], and $\Gamma_{\gamma} = 71 \pm 32$ meV [266].

The second most important resonance contribution arises from the 1⁺ state at ~5675 keV [255]. The resonance is expected to dominate at lower nova temperatures (T < 0.2 GK). The existence of this state was first identified by Caggiano *et al* [259], and was later verified in

Table 5. Recommended excitation energies (E_x) together with the spins and parities (J^{π}) for the excited states above the proton separation energy $(S_p = 5513.98(13))$ keV [181]) in ²⁶Si. The resonance energies (E_{res}) , proton widths (Γ_p) , and experimentally determined resonance strengths $(\omega\gamma)$ for the relevant states are given. The atomic shift for this reaction is $\Delta B_e = -1.27$ keV. Only states producing resonances below $E_{res} = 500$ keV are listed.

E_x (keV)	J^{π}	$E_{\rm res}({\rm keV})$	$\Gamma_p (\mathrm{eV})$	$\omega\gamma({ m eV})$
5675.2(14) [255] 5890.0(8) [255] 5928(1) [255] 5950(5) [255]	1^{+} [269] 0^{+} [269] 3^{+} [261] (4^{+}) [257]	162.5(14) 377.3(8) 415(1) 437(5)	$ \begin{array}{c} <1\times10^{-8} \ [270] \\ 4.2(13)\times10^{-3} \ [270]^{a} \\ 2.9(10) \ [264] \\ 7.8(39)\times10^{-3} \ [257]^{b} \end{array} $	$\begin{array}{c} <2.6\times 10^{-9} \ [270]\\ 2.4(7)\times 10^{-4} \ [270]^a\\ 2.3(13)\times 10^{-2} \ [265]\\ 4.5(23)\times 10^{-3} \ [257]^b\end{array}$

^a A 30% uncertainty was assumed for properties extrapolated from the mirror [272].

^b A 50% uncertainty was assumed for properties calculated with the shell model [256].



Figure 13. Same as figure 9 but for ${}^{25}\text{Al}(p, \gamma){}^{26}\text{Si}$. The main difference here is that the $E_r = 162$ keV resonance is treated as an upper limit rather than as having a measured resonance strength.

²⁴Mg(³He, n)²⁶Si studies detecting neutrons [261] and γ rays [267–269]. The strength of this resonance is determined by its proton width and estimates currently rely on shell model calculations [256] as only upper limits have been obtained for the strength of the mirror level in ²⁵Mg(*d*, *p*)²⁶Mg studies [270].

An additional open question has been recently highlighted by studies of the ²⁴Mg(³He, $n\gamma$)²⁶Si reaction [268, 269, 271]. Population of a new level at 5890 keV has been observed and conclusively identified as a 0⁺ state [269]. This seemingly presents an open issue since the 5949 keV level had previously been assigned as 0⁺ by Parpottas *et al* [261], and shell model calculations indicate that there should only be one 0⁺ state in this energy range [241, 256, 257]. Various authors have speculated that the 5949 keV may in fact be the expected 4⁺ level [255, 257], but this would be at odds with the cross section comparison made by Parpottas *et al* [261].

Recommended resonance values are displayed in table 5 and our newly calculated rate in figure 13. Considering the current state of our knowledge, it appears that the astrophysical

Table 6. Maxwellian-averaged capture cross sections of ${}^{24}Mg(n, \gamma)$ at temperatures higher than those reported in [286]. The contributions from the unresolved resonance region and the direct radiative capture are given separately. The uncertainty on the DRC contribution is mainly related to the uncertainty on the spectroscopic factors of the low-lying states populated by the direct transitions and is estimated to be approximately 20%.

Temper	rature		MA	ACS		Reaction
<i>kT</i> (keV)	<i>T</i> ₉ (K)	RRR (mb)	URR (mb)	DRC (mb)	Total (mb)	$\begin{array}{c} \text{Rate} \\ \text{cm}^3 \text{ mol}^{-1} \text{ s}^{-1} \end{array}$
120	1.4	2.3 ± 0.2	0.0	0.3	2.6 ± 0.3	$7.48 imes 10^{+05}$
140	1.6	2.0 ± 0.2	0.0	0.3	2.3 ± 0.3	$7.40 imes10^{+05}$
160	1.9	1.8 ± 0.2	0.0	0.3	2.1 ± 0.2	$7.29\times10^{+05}$
180	2.1	1.6 ± 0.2	0.0	0.3	2.0 ± 0.2	$7.18 imes10^{+05}$
200	2.3	1.4 ± 0.1	0.0	0.4	1.8 ± 0.2	$7.06 imes10^{+05}$
220	2.6	1.3 ± 0.1	0.1	0.4	1.7 ± 0.2	$6.94 imes10^{+05}$
240	2.8	1.2 ± 0.1	0.1	0.4	1.6 ± 0.2	$6.82 imes10^{+05}$
260	3.0	1.1 ± 0.1	0.1	0.4	1.5 ± 0.2	$6.71\times10^{+05}$
280	3.2	1.0 ± 0.1	0.1	0.4	1.5 ± 0.2	$6.60 imes10^{+05}$
300	3.5	0.9 ± 0.1	0.1	0.4	1.4 ± 0.2	$6.51\times10^{+05}$

²⁵Al(p, γ)²⁶Si reaction rate is uncertain by roughly a factor of 3 at nova temperatures, primarily due to the uncertain Γ_{γ} of the $J^{\pi} = 3^+$ resonance. Perhaps this could be improved by directly measuring the lifetime of the ²⁶Si 3⁺ level. Measurements of the neutron spectroscopic factor of the ²⁶Mg $J^{\pi} = 1^+$ mirror state would also be useful to constrain the contribution of this state to the reaction rate. A repetition of the ²⁵Mg(d, p)²⁶Mg reaction study [270] at higher energies may be useful to improve the direct to compound nuclear component of the cross section.

This discussion of the reaction rate uncertainties assumes that we have a good understanding of the ²⁶Si level structure. There are a number of open questions, however, that stretch our ability to make this claim. For instance if the 5928/5890 keV states are indeed a $3^+/0^+$ doublet, why was the 5928 keV state populated so strongly in the ²⁸Si(*p*, *t*)²⁶Si reaction [258], while the 0⁺ state was populated so weakly? One would expect natural parity states to be populated much more strongly. Note that in [258], the 5928 keV state was labeled as 5916 keV as a result of the uncertain calibration of lower-lying levels [273], and it would be worthwhile to revisit the data from that measurement in light of the more precise energy measurements currently available. Another question is why is the 5890 keV 0⁺ state so readily observable in the ²⁴Mg(³He, $n\gamma$)²⁶Si studies [266, 268, 269, 271], but no neutrons were observed populating the state in the ²⁴Mg(³He, n)²⁶Si measurement [261], which seemingly had the resolution to observe it? Finally, the question as to whether we are seeing too many 0⁺ levels and the assertion in [263] of a missing 1⁻ level clearly strains our ability to claim complete knowledge of the relevant ²⁶Si level structure.

3.5. Other reactions affecting the ²⁶Al abundance

The sensitivity study by Iliadis *et al* [241] identified a number of other reactions that, while not direct producing or destroying ²⁶Al, do affect its final abundance in massive stars. The most influential are the ²⁵Mg(α , n)²⁸Si, the ²³Na(α , p)²⁶Mg, and the neutron capture reactions



Figure 14. The large number of transitions to and from short-lived, intermediate states that become available in stellar environments (left side) are being simplified by only explicitly calculating the coupling rates between all long-lived states, but including the effect the short-lived states have on them (right side). The dashed lines indicate the additionally calculated rates if the 3^+ state is considered as long-lived as well, which might be relevant in certain scenarios.

 $^{24}Mg(n, \gamma)^{25}Mg$ and $^{25}Mg(n, \gamma)^{26}Mg$. We discuss these reactions separately in the sections below.

3.5.1. ²⁵Mg(α , n)²⁸Si. The ²⁵Mg(α , n)²⁸Si reaction is most influential during explosive Ne/C-shell burning, at a temperature around 2.3 GK ($E_{\rm cm} = 1.8-3.5$ MeV). It acts as a neutron source for the neutron-induced reactions described above, as well as reducing the ²⁵Mg available for proton capture to ²⁶Al.

The reaction rate currently reported in REACLIB [274] comes from the NACRE compilation [229]. Above 2 GK, the rate comes from Hauser–Feshbach calculations and below this temperature it is based on the direct measurements of Van der Zwan and Geiger [275], Anderson *et al* [276] and Wieland [277]. Between 0.86 and 3 MeV, only the Wieland data are used, even though this work is unpublished. However, Iliadis *et al* [241] questioned both the decision to use HF rates above 2 GK, as experimental data are available, and the exclusion of the Anderson *et al* [276] data. They further recommended a reanalysis of the available data as well as a new measurement. Several new measurements have been made at both Notre Dame and Argonne, and these data are currently under analysis.

3.5.2. ²³Na(α , p)²⁶Mg. The ²³Na(α , p)²⁶Mg reaction is thought to be influential during convective shell carbon/neon burning at temperatures around 1.4 GK [278]. It is the second most important reaction after ¹²C(¹²C, p)²³Na for production of protons, which are subsequently captured by ²⁵Mg.



Figure 15. Effective coupling rates between the two long-lived states of ²⁶Al under stellar conditions. Increasing the number of states above the isomer to be considered in the calculation as possible bypass paths from one (green) to two (blue) shows good agreement for the transition rates from ground state to isomer (top panel) and isomer to ground state (bottom panel) at lower energies. At ~50 keV, the calculated rates start to diverge.

Four direct measurements of this reaction cross section have recently been performed, three in inverse kinematics [239, 279, 280] and one in forward kinematics [281]. The work of Almaraz-Calderon *et al* [239] used a ²³Na beam on a cryogenic ⁴He target, and detected protons between 6.8 and 13.5 deg in the laboratory. Angle-integrated cross sections were reported for the p_0 and p_1 channels. Tomlinson *et al* [279] also utilised a ²³Na beam on a ⁴He target, this time at room temperature. Angle-integrated cross sections were given for the p_0-p_2 channels. Avila *et al* [280] used the active target detector, MUSIC, to determine total cross sections. Finally, the forward kinematics measurement of Howard *et al* [281] extracted angular distributions for the p_0 and p_1 proton channels. All measurements were consistent with the Non-Smoker [282] cross sections above 1.75 MeV in the centre of mass. Finally, Hubbard *et al* [283] corrected the cross sections from Almaraz-Calderon *et al* [239] and



Figure 16. Effective coupling rates between the two long-lived states and the short-lived isomer (third level in figure 14) for upward (top panel) and downward (bottom panel) transitions between the long-lived states. The differences in calculated rates are much smaller and occur at higher temperatures.

Tomlinson *et al* [279] to account for the proton angular distributions measured by Howard *et al* [281] and calculated a new combined rate with a total uncertainty of 30% for temperatures relevant to 26 Al production. This reaction rate is now considered to be sufficiently well constrained for this purpose.

3.5.3. ²⁴Mg(n, γ)²⁵Mg and ²⁵Mg(n, γ)²⁶Mg. Iliadis *et al* [278] identified the ²⁴Mg(n, γ) reaction as the most important radiative neutron capture reaction impacting ²⁶Al abundances. For example, during explosive C/Ne burning a 2 times higher ²⁴Mg(n, γ) rate is predicted to yield a change in ^{26t}Al abundance by a factor 1.6. Moreover, a correct interpretation of isotopic ratios in stardust spinel grains, which contain both Mg and Al (section 1.4), requires an accurate ²⁵Mg(n, γ)²⁶Mg reaction cross section as both this reaction and the ²⁶Al decay lead to the production of ²⁶Mg.

The Maxwellian-averaged cross sections (MACS) for these reactions were recommended by the Karlsruhe Astrophysical Database of Nucleosynthesis in Stars



Figure 17. Effective half-lifes of ²⁶Al for different numbers of isomeric states and total states. Setting the cutoff time for which to explicitly treat a state as an isomer to 1ns adds a short-lived isomeric state (third level in figure 14) to the network.

(KADoNiS) [284], quoting Maxwellian-averaged neutron capture cross sections with large uncertainties. These MACS values are based on one measurement from the 1970s [285]. Recently, high precision measurements of neutron capture on Mg isotopes have been performed at the n_TOF facility at CERN [286, 287]. In [286], resonance energies, spins and partial widths are presented for resonances in the ²⁴Mg(n, γ) reaction up to neutron energies of about 660 keV. By using the cross section reconstructed from these resonance parameters obtained in the resolved resonance region (RRR) and the small contribution to the cross section data from evaluations at higher energy, i.e. in the unresolved resonance region (URR) [288], it was possible to determine a reliable MACS up to about kT = 300 keV, which corresponds to stellar temperatures of 3.6 GK, covering the neutron energy range of interest for ²⁶Al synthesis. The results for different temperatures not given in [286] are listed in table 6, including the contribution of p-wave direct radiative capture [289].

4. Decay rate of ²⁶Al in stellar environments

While the reaction rates for the production and destruction of both 26g Al and 26m Al can be experimentally determined in terrestrial settings (section 3), they do not adequately reflect the interplay of the two states in a stellar environment. The Maxwellian temperature distribution in these scenarios leads to possible shifts in the isomeric and ground state abundance distribution via thermally excited, short-lived states (figure 14). Such a change in the final abundances would, among other effects, have direct implications for γ -ray observations as described in section 1.1. As alluded to in section 3, stellar nucleosynthesis codes can reproduce this behavior by treating the ground and isomeric states as two independent species, and modifying their respective transition, reaction and decay rates. The exact calculation of the rates shown in this work is explained in further detail in [290].

The distribution into the excited states, and thus the calculated transition and decay rates, are highly temperature dependent. This applies to both the rates themselves, and to the

number of short-lived states that need to be considered depending on the maximum temperature of the specific astrophysical scenario. Figure 15 compares the cases of calculating the transition rates between the ground state and isomeric state by considering either just the short-lived state at 417 keV (system of 3 states), or both states at 417 and 1058 keV (see figure 14). While the transition rates agree for lower energies, a noticeable difference can be seen above temperatures of \sim 50 keV. This illustrates the importance of considering the specific case for which such a rate will be used, and the upper temperature limits of achieving accurate rates with less complex systems of considered states. *However, as a rule of thumb, the more complex system will never be less accurate in itself, given accurate input parameters.*

Additionally, and probably less obviously, the categorization into long- and short-lived states is not static, either, but depends on the stellar scenario and average time-stepping of the nucleosynthesis code describing it. In the case of ²⁶Al, there is the established isomeric 0⁺ state at 228 keV; but for extreme cases, the 3⁺ state at 417 keV with $t_{1/2} = 1.2$ ns could be considered as an isomeric state as well and be treated explicitly, changing the resulting reaction and transition rates, as illustrated in figure 16. Note that the two systems being compared contain four and eleven states here, since the case of three states in figure 15 would now not contain any short-lived states as bypass paths, but rather be just a static system. While there are branchings in the calculated rates here as well, those occur at much higher temperatures, are smaller in magnitude, and are based on an extreme case to begin with. One can therefore assume that the system with just one isomeric state and four states in total already leads to accurate rates for most scenarios.

Both ground and isomeric states of ²⁶Al decay almost exclusively to ²⁶Mg via positron emission. Their individual decay rates are not affected by temperature, however, the average lifetime of the nucleus is influenced by the changes in distribution between energetic states with different decay rates. Coc *et al* [291] compared the *effective half-life*, derived from the same general approach as the one described above, with the half-life calculated from analytical off-equilibrium and equilibrium decay rates, see figure 17.

Note that these *effective half-lives* are only a theoretical concept and do not correlate with actual transition rates that might be usable in a stellar model. In order to generate those, one would have to first set the correct parameters for the specific stellar model, mainly the cutoff energy as determined by the maximum temperature of the star, and the time cutoff leading to the number of states to be considered long-lived, which is based on the shortest time-step of the model in question.

The difference in *effective half-life* in the temperature region between 10 and 30 keV, depending on the exact set of input parameters chosen, underlines the importance of considering both the temperature regime and time-stepping of the stellar scenario to produce and use the appropriate rates.

5. Summary and conclusions

We have reviewed the astrophysical importance of ²⁶Al, as demonstrated by the many different types of astrophysical problems that sprang from the variety of ²⁶Al observations. We have described how ²⁶Al is produced by proton captures on the stable ²⁵Mg in a variety of different astrophysical environments, where destruction paths via proton and neutron captures as well as by-passes can also be activated hindering its production. Finally, we have detailed the nuclear properties of ²⁶Al and the nuclear reactions that affect its production in the

Reaction	Relevant sites	T (GK)
$^{25}Mg(p, \gamma)^{26}Al$	Low- and intermediate-mass AGB stars	0.06-0.1
	Hydrostatic H-core burning in massive stars	0.03-0.08
	Hydrostatic C-shell burning in massive stars	0.8-1.2
	Explosive Ne/C-shell burning in massive stars	1.9-2.8
	Novae	0.2-0.4
26 Al(<i>p</i> , γ) ²⁷ Si	Intermediate-mass AGB stars	0.06-0.1
	Hydrostatic H-core burning in massive stars	0.03-0.08
	Novae	0.2-0.4
${}^{26}Al + n$	Low- and intermediate-mass AGB stars	0.2-0.4
	Hydrostatic C-shell burning in massive stars	0.8 - 1.2
	Explosive Ne/C-shell burning in massive stars	1.9-2.8
$^{25}Al(p, \gamma)^{26}Si$	Novae	0.2-0.4
$^{25}Mg(\alpha, n)^{28}Si$	Explosive Ne/C-shell burning in massive stars	1.9-2.8
23 Na(α , p) 26 Mg	Hydrostatic C-shell burning in massive stars	0.8-1.2
$^{24}Mg(n, \gamma)^{25}Mg$	Hydrostatic C-shell burning in massive stars	0.8-1.2
$^{25}Mg(n, \gamma)^{26}Mg$	Explosive Ne/C-shell burning in massive stars	1.9–2.8

Table 7. Summary of reactions and relevant sites. Temperatures refer to the site listed and do not necessarily represent the optimum temperature for ²⁶Al production.

different stellar sites. In table 7 we collect the relevant reactions, their sites and the temperatures.

In summary, astrophysical observations of live ²⁶Al include its presence in the Milky Way Galaxy, observed by satellite telescopes using γ -ray spectrometers that can detect the 1.8 MeV photons produced by its decay, and potentially in terrestrial archives. The latter is, however, difficult to disentangle from the ²⁶Al produced locally via spallation reactions. It is expected that future MeV γ -ray missions based on more advanced detector technology with unprecedented line sensitivity [2] will provide us further unique constraints from ²⁶Al on the physics of CCSNe and how material is distributed in star-forming regions and transported in the Galaxy. Astrophysical observations of extinct ²⁶Al come from meteoritic inclusions via measuring in the laboratory excesses in its daughter nucleus ²⁶Mg. These samples include both stardust grains, which formed in stars and supernovae, and the first solids that formed in the first few Myr of the Solar System's life made an impact on the evolution of the planetesimals from which the terrestrial planets formed. However, we still do not know the origin of such ²⁶Al, nor if it is a common radioactive nucleus in planet-forming discs in the Galaxy.

Astrophysical observations and their wide implications can only be addressed by understanding how stars and supernovae produce ²⁶Al. Specifically, massive stars are the most relevant sites to be investigated to interpret the live galactic abundance of ²⁶Al and its extinct abundance in the early Solar System, given that they are present in star-forming regions. These massive stars eject ²⁶Al both via winds and by their final CCSN explosions. Stellar rotation and binarity add complexity to the modelling of ²⁶Al production in these stars and we are still in the process of exploring using 3D modelling nucleosynthetic patterns that move beyond standard current 1D modelling. These range from proton-ingestion episodes to the merger of regions of different composition. AGB stars and novae, instead, produce roughly <10% each of the total amount of ²⁶Al in the Galaxy, and they are of relevance

Table 8. The ${}^{25}Mg(p, \gamma){}^{26}Alg$ reaction rate in units of cm³ mol⁻¹ s⁻¹ calculated with the resonance information from table 1. The lower, median and upper rates correspond to the 32%, 50%, and 68% percentiles.

T [GK]	Lower limit	Median rate	Upper limit
0.010	2.10×10^{-33}	$3.10 imes 10^{-33}$	4.67×10^{-33}
0.011	1.29×10^{-31}	1.79×10^{-31}	2.55×10^{-31}
0.012	$7.04 imes 10^{-30}$	8.77×10^{-30}	1.10×10^{-29}
0.013	$3.31 imes 10^{-28}$	4.06×10^{-28}	4.98×10^{-28}
0.014	$1.11 imes 10^{-26}$	1.37×10^{-26}	1.70×10^{-26}
0.015	2.49×10^{-25}	3.09×10^{-25}	3.85×10^{-25}
0.016	$3.85 imes 10^{-24}$	4.77×10^{-24}	5.94×10^{-24}
0.018	$3.68 imes 10^{-22}$	4.55×10^{-22}	5.66×10^{-22}
0.020	1.39×10^{-20}	1.72×10^{-20}	2.14×10^{-20}
0.025	$9.18 imes10^{-18}$	1.13×10^{-17}	1.40×10^{-17}
0.030	$6.63 imes 10^{-16}$	8.17×10^{-16}	1.01×10^{-15}
0.040	$1.35 imes 10^{-13}$	1.65×10^{-13}	2.02×10^{-13}
0.050	4.05×10^{-12}	$4.72 imes 10^{-12}$	5.54×10^{-12}
0.060	$5.58 imes10^{-11}$	6.26×10^{-11}	7.03×10^{-11}
0.070	4.42×10^{-10}	4.93×10^{-10}	$5.52 imes 10^{-10}$
0.080	$2.24 imes10^{-09}$	2.51×10^{-09}	2.82×10^{-09}
0.090	8.09×10^{-09}	$9.08 imes10^{-09}$	$1.02 imes 10^{-08}$
0.100	$2.29 imes10^{-08}$	2.57×10^{-08}	$2.90 imes 10^{-08}$
0.110	$5.55 imes10^{-08}$	$6.22 imes 10^{-08}$	$7.00 imes 10^{-08}$
0.120	$1.29 imes10^{-07}$	$1.45 imes 10^{-07}$	$1.63 imes 10^{-07}$
0.130	$3.47 imes10^{-07}$	$3.84 imes10^{-07}$	$4.30 imes 10^{-07}$
0.140	$1.17 imes10^{-06}$	$1.29 imes 10^{-06}$	1.43×10^{-06}
0.150	4.34×10^{-06}	4.80×10^{-06}	5.31×10^{-06}
0.160	1.54×10^{-05}	1.71×10^{-05}	1.89×10^{-05}
0.180	$1.41 imes10^{-04}$	$1.57 imes10^{-04}$	$1.73 imes 10^{-04}$
0.200	8.55×10^{-04}	$9.48 imes10^{-04}$	1.05×10^{-03}
0.250	2.19×10^{-02}	2.41×10^{-02}	2.66×10^{-02}
0.300	1.88×10^{-01}	$2.07 imes10^{-01}$	$2.27 imes 10^{-01}$
0.350	$8.75 imes10^{-01}$	$9.54 imes10^{-01}$	$1.04 imes10^{+00}$
0.400	$2.77 imes10^{+00}$	$3.00 imes10^{+00}$	$3.26 imes 10^{+00}$
0.450	$6.80\times10^{+00}$	$7.33\times10^{+00}$	$7.90 imes10^{+00}$
0.500	$1.40\times10^{+01}$	$1.50\times10^{+01}$	$1.60 imes 10^{+01}$
0.600	$4.09\times10^{+01}$	$4.35\times10^{+01}$	$4.63 imes 10^{+01}$
0.700	$8.75\times10^{+01}$	$9.25\times10^{+01}$	$9.78 imes 10^{+01}$

predominantly for the study of the origin of extinct ²⁶Al in stardust grains. Mixing and mass loss are the major uncertainties related to their modelling. In all the sites we discussed here, nuclear reaction uncertainties play a major role in the final estimate of the ²⁶Al yields.

Significant progress has been made experimentally in constraining the nuclear reaction rates that determine the abundance of ²⁶Al in the astrophysical sites discussed in this review. The ²⁵Mg(p, γ)²⁶Al reaction is the main production reaction in all the sites discussed. The key resonances at 93, 191, and 305 keV have been measured directly, but confirmation of the 93 keV strength would be useful. The 59 keV resonance dominates at temperatures below 0.05 GK (core H-burning in massive stars), but has remained inaccessible to direct measurements. The destruction route of the ²⁶Al ground state via proton capture has also been studied

Table 9. The ${}^{25}\text{Mg}(p, \gamma){}^{26}\text{Alm}$ reaction rate in units of cm³ mol⁻¹ s⁻¹ calculated with the resonance information from table 1. The lower, median and upper rates correspond to the 32%, 50%, and 68% percentiles.

T [GK]	Lower limit	Median rate	Upper limit
0.010	$5.35 imes 10^{-34}$	$8.21 imes 10^{-34}$	1.28×10^{-33}
0.011	3.17×10^{-32}	4.60×10^{-32}	6.86×10^{-32}
0.012	1.62×10^{-30}	2.14×10^{-30}	2.86×10^{-30}
0.013	$7.11 imes 10^{-29}$	$9.42 imes 10^{-29}$	1.26×10^{-28}
0.014	$2.30 imes10^{-27}$	3.13×10^{-27}	4.27×10^{-27}
0.015	5.08×10^{-26}	$7.01 imes 10^{-26}$	9.65×10^{-26}
0.016	$7.82 imes 10^{-25}$	1.08×10^{-24}	1.49×10^{-24}
0.018	$7.46 imes 10^{-23}$	$1.03 imes 10^{-22}$	1.42×10^{-22}
0.020	2.82×10^{-21}	$3.89 imes 10^{-21}$	5.37×10^{-21}
0.025	1.86×10^{-18}	2.56×10^{-18}	3.53×10^{-18}
0.030	$1.35 imes 10^{-16}$	1.85×10^{-16}	2.55×10^{-16}
0.040	$2.98 imes10^{-14}$	$3.94 imes 10^{-14}$	5.27×10^{-14}
0.050	$1.20 imes 10^{-12}$	1.43×10^{-12}	1.74×10^{-12}
0.060	$2.10 imes10^{-11}$	2.43×10^{-11}	2.83×10^{-11}
0.070	$1.87 imes10^{-10}$	2.17×10^{-10}	2.54×10^{-10}
0.080	$9.97 imes10^{-10}$	1.17×10^{-09}	1.37×10^{-09}
0.090	$3.69 imes 10^{-09}$	$4.33 imes 10^{-09}$	$5.08 imes 10^{-09}$
0.100	$1.05 imes 10^{-08}$	$1.23 imes 10^{-08}$	1.45×10^{-08}
0.110	2.52×10^{-08}	2.94×10^{-08}	3.44×10^{-08}
0.120	$5.45 imes 10^{-08}$	$6.34 imes 10^{-08}$	$7.39 imes 10^{-08}$
0.130	$1.18 imes10^{-07}$	$1.36 imes 10^{-07}$	$1.58 imes 10^{-07}$
0.140	$2.91 imes 10^{-07}$	$3.30 imes 10^{-07}$	3.80×10^{-07}
0.150	8.37×10^{-07}	$9.40 imes 10^{-07}$	1.07×10^{-06}
0.160	2.57×10^{-06}	$2.89 imes 10^{-06}$	3.28×10^{-06}
0.180	2.14×10^{-05}	2.41×10^{-05}	2.72×10^{-05}
0.200	$1.28 imes 10^{-04}$	1.44×10^{-04}	1.63×10^{-04}
0.250	3.47×10^{-03}	3.86×10^{-03}	4.31×10^{-03}
0.300	3.22×10^{-02}	3.54×10^{-02}	3.91×10^{-02}
0.350	$1.60 imes 10^{-01}$	$1.74 imes 10^{-01}$	$1.91 imes 10^{-01}$
0.400	$5.34 imes 10^{-01}$	$5.79 imes 10^{-01}$	6.31×10^{-01}
0.450	$1.37\times10^{+00}$	$1.48 imes10^{+00}$	$1.60 imes10^{+00}$
0.500	$2.90\times10^{+00}$	$3.13\times10^{+00}$	$3.38 imes 10^{+00}$
0.600	$8.94\times10^{+00}$	$9.59\times10^{+00}$	$1.03 imes 10^{+01}$
0.700	$1.98 imes10^{+01}$	$2.12\times10^{+01}$	$2.27 \times 10^{+01}$

directly at temperatures above around 0.1 GK. However, the strength of the 128 keV resonance, which dominates at lower temperatures, is still not well known and represents a high priority for future direct measurements. Proton capture on the ²⁶Al isomeric state is much weaker than on the ground state and not considered significant in most stellar sites. For the destruction reactions through neutron capture, discrepancies between existing data at low neutron energy have been largely resolved. Additional data at higher neutron energies up to about 500 keV, relevant for ²⁶Al destruction in massive stars are still needed. The ²⁵Al(p, γ) by-pass reaction has been constrained through transfer studies of the relevant level

Table 10. The ²⁶Al^g $(p, \gamma)^{27}$ Si reaction rate in units of cm³ mol⁻¹ s⁻¹ calculated with the resonance information from table 2. The lower, median and upper rates correspond to the 32%, 50%, and 68% percentiles.

T [GK]	Lower limit	Median rate	Upper limit
0.010	$2.96 imes 10^{-37}$	$4.35 imes 10^{-37}$	6.38×10^{-37}
0.011	$8.04 imes 10^{-36}$	1.18×10^{-35}	1.74×10^{-35}
0.012	1.51×10^{-34}	2.20×10^{-34}	3.22×10^{-34}
0.013	2.11×10^{-33}	$3.08 imes 10^{-33}$	4.49×10^{-33}
0.014	2.42×10^{-32}	$3.58 imes 10^{-32}$	5.44×10^{-32}
0.015	$2.35 imes 10^{-31}$	3.75×10^{-31}	7.13×10^{-31}
0.016	$1.97 imes 10^{-30}$	3.74×10^{-30}	1.19×10^{-29}
0.018	$9.41 imes 10^{-29}$	$3.97 imes 10^{-28}$	2.25×10^{-27}
0.020	$3.22 imes 10^{-27}$	2.61×10^{-26}	1.63×10^{-25}
0.025	$4.74 imes 10^{-24}$	5.55×10^{-23}	3.58×10^{-22}
0.030	$1.18 imes 10^{-21}$	9.34×10^{-21}	5.80×10^{-20}
0.040	$4.37 imes 10^{-17}$	$7.03 imes 10^{-17}$	$1.17 imes 10^{-16}$
0.050	$4.62 imes 10^{-14}$	$7.04 imes10^{-14}$	1.07×10^{-13}
0.060	$5.08 imes 10^{-12}$	$7.58 imes 10^{-12}$	1.13×10^{-11}
0.070	$1.48 imes 10^{-10}$	$2.15 imes 10^{-10}$	3.14×10^{-10}
0.080	$2.00 imes10^{-09}$	2.78×10^{-09}	3.92×10^{-09}
0.090	$1.69 imes 10^{-08}$	$2.26 imes10^{-08}$	3.03×10^{-08}
0.100	$1.04 imes10^{-07}$	$1.35 imes 10^{-07}$	$1.75 imes 10^{-07}$
0.110	4.98×10^{-07}	$6.35 imes 10^{-07}$	8.11×10^{-07}
0.120	1.94×10^{-06}	2.45×10^{-06}	3.12×10^{-06}
0.130	6.34×10^{-06}	$8.00 imes 10^{-06}$	1.02×10^{-05}
0.140	$1.80 imes10^{-05}$	2.27×10^{-05}	2.86×10^{-05}
0.150	4.58×10^{-05}	5.70×10^{-05}	7.15×10^{-05}
0.160	$1.06 imes 10^{-04}$	1.30×10^{-04}	1.61×10^{-04}
0.180	4.53×10^{-04}	5.43×10^{-04}	6.55×10^{-04}
0.200	1.57×10^{-03}	1.82×10^{-03}	2.13×10^{-03}
0.250	1.87×10^{-02}	2.05×10^{-02}	2.27×10^{-02}
0.300	1.21×10^{-01}	1.30×10^{-01}	1.40×10^{-01}
0.350	$5.07 imes 10^{-01}$	5.44×10^{-01}	5.82×10^{-01}
0.400	$1.55 imes 10^{+00}$	$1.67 \times 10^{+00}$	$1.79 \times 10^{+00}$
0.450	$3.76 imes 10^{+00}$	$4.05 \times 10^{+00}$	$4.36 \times 10^{+00}$
0.500	$7.65 imes 10^{+00}$	$8.26 \times 10^{+00}$	$8.93 \times 10^{+00}$
0.600	$2.20 imes 10^{+01}$	$2.39 \times 10^{+01}$	$2.60 \times 10^{+01}$
0.700	$4.64 \times 10^{+01}$	$5.05\times10^{+01}$	$5.50 imes 10^{+01}$

information, and the remaining uncertainty is dominated by that of the radiative width of the 415 keV resonance. In relation to the main reactions that indirectly affect the abundance of ²⁶Al, for the ²⁵Mg(α , n)²⁸Si reaction, new measurements have been performed and it is not yet clear whether further data will be needed. Finally, both the ²³Na(α , p)²⁶Mg and ²⁴Mg(n, γ)²⁵Mg reactions are now considered sufficiently well constrained across temperatures relevant in massive stars.

26	27		. 1 1		
Table 11. The ${}^{20}\text{Al}^m(p,$	γ) ² Si reaction rate in	units of cm ³	$mol^{-1} s^{-1}$	calculated	with
the resonance informati	on from table 3.				

T [GK]	Lower limit	Median rate	Upper limit
0.010	2.81×10^{-37}	$4.09 imes 10^{-37}$	6.02×10^{-37}
0.011	7.71×10^{-36}	1.13×10^{-35}	1.64×10^{-35}
0.012	1.45×10^{-34}	$2.12 imes 10^{-34}$	3.09×10^{-34}
0.013	2.01×10^{-33}	2.93×10^{-33}	4.25×10^{-33}
0.014	2.16×10^{-32}	3.16×10^{-32}	4.55×10^{-32}
0.015	1.89×10^{-31}	$2.74 imes 10^{-31}$	3.95×10^{-31}
0.016	$1.37 imes 10^{-30}$	$1.98 imes 10^{-30}$	2.87×10^{-30}
0.018	4.51×10^{-29}	$6.51 imes 10^{-29}$	9.37×10^{-29}
0.020	8.95×10^{-28}	$1.30 imes 10^{-27}$	1.87×10^{-27}
0.025	3.42×10^{-25}	4.99×10^{-25}	7.20×10^{-25}
0.030	$3.22 imes 10^{-23}$	4.71×10^{-23}	6.82×10^{-23}
0.040	$2.69 imes 10^{-20}$	$3.84 imes 10^{-20}$	$5.50 imes 10^{-20}$
0.050	4.82×10^{-18}	$9.89 imes10^{-18}$	2.16×10^{-17}
0.060	3.00×10^{-16}	1.35×10^{-15}	4.04×10^{-15}
0.070	$1.18 imes10^{-14}$	$6.09 imes10^{-14}$	1.86×10^{-13}
0.080	$3.16 imes 10^{-13}$	$1.20 imes 10^{-12}$	3.36×10^{-12}
0.090	$4.56 imes 10^{-12}$	$1.52 imes 10^{-11}$	3.41×10^{-11}
0.100	$3.97 imes 10^{-11}$	$1.30 imes10^{-10}$	2.52×10^{-10}
0.110	$2.41 imes10^{-10}$	$7.58 imes10^{-10}$	$1.60 imes 10^{-09}$
0.120	$1.11 imes10^{-09}$	$3.36 imes 10^{-09}$	8.34×10^{-09}
0.130	$4.23 imes 10^{-09}$	$1.25 imes 10^{-08}$	$3.50 imes 10^{-08}$
0.140	$1.37 imes10^{-08}$	$4.08 imes10^{-08}$	$1.21 imes 10^{-07}$
0.150	3.91×10^{-08}	$1.19 imes10^{-07}$	$3.58 imes 10^{-07}$
0.160	$1.04 imes10^{-07}$	$3.16 imes 10^{-07}$	$9.29 imes 10^{-07}$
0.180	$7.30 imes10^{-07}$	1.84×10^{-06}	4.79×10^{-06}
0.200	$5.50 imes10^{-06}$	1.03×10^{-05}	2.09×10^{-05}
0.250	$3.74 imes10^{-04}$	$5.71 imes 10^{-04}$	8.63×10^{-04}
0.300	$7.70 imes 10^{-03}$	$1.20 imes 10^{-02}$	$1.88 imes 10^{-02}$
0.350	$6.99 imes 10^{-02}$	$1.10 imes10^{-01}$	$1.74 imes 10^{-01}$
0.400	$3.63 imes 10^{-01}$	$5.71 imes 10^{-01}$	9.06×10^{-01}
0.450	$1.28 imes10^{+00}$	$2.02 imes 10^{+00}$	$3.21 \times 10^{+00}$
0.500	$3.47 imes 10^{+00}$	$5.48 imes10^{+00}$	$8.70 imes10^{+00}$
0.600	$1.49\times10^{+01}$	$2.36\times10^{+01}$	$3.74 imes 10^{+01}$
0.700	$4.10\times10^{+01}$	$6.47 imes 10^{+01}$	$1.03 \times 10^{+02}$

In conclusion, the radioisotope ²⁶Al provides us with a wealth of information about the Galaxy, its stars and supernovae as well as the early Solar System. Many of the influential reactions are, or will shortly be, sufficiently constrained and we have summarised above the remaining experimental priorities. Further sensitivity studies, based on the latest rates, such as those newly calculated rates here and using up-to-date stellar models, are required to evaluate the impact of these remaining uncertainties. Future work will also need to investigate if more reactions than those considered here may have an impact on the production of ²⁶Al in CCSN explosions.

T [GK]	Lower limit	Median rate	Upper limit
0.010	9.91×10^{-38}	1.46×10^{-37}	2.13×10^{-37}
0.011	2.72×10^{-36}	$3.99 imes 10^{-36}$	$5.87 imes 10^{-36}$
0.012	5.11×10^{-35}	$7.48 imes 10^{-35}$	$1.10 imes 10^{-34}$
0.013	$7.04 imes 10^{-34}$	1.03×10^{-33}	1.51×10^{-33}
0.014	7.42×10^{-33}	1.09×10^{-32}	1.60×10^{-32}
0.015	$6.38 imes 10^{-32}$	$9.32 imes 10^{-32}$	$1.37 imes 10^{-31}$
0.016	4.57×10^{-31}	$6.68 imes 10^{-31}$	$9.79 imes 10^{-31}$
0.018	1.46×10^{-29}	2.13×10^{-29}	3.13×10^{-29}
0.020	2.90×10^{-28}	4.24×10^{-28}	6.29×10^{-28}
0.025	1.16×10^{-25}	1.69×10^{-25}	$2.48 imes 10^{-25}$
0.030	$1.12 imes 10^{-23}$	1.62×10^{-23}	$2.37 imes 10^{-23}$
0.040	8.59×10^{-21}	1.25×10^{-20}	$1.84 imes 10^{-20}$
0.050	1.23×10^{-18}	1.85×10^{-18}	2.68×10^{-18}
0.060	$6.79 imes 10^{-17}$	$1.73 imes 10^{-16}$	4.42×10^{-16}
0.070	$1.84 imes 10^{-15}$	9.33×10^{-15}	$2.83 imes 10^{-14}$
0.080	3.01×10^{-14}	2.10×10^{-13}	$6.58 imes 10^{-13}$
0.090	$3.00 imes 10^{-13}$	$2.37 imes 10^{-12}$	$7.53 imes 10^{-12}$
0.100	1.99×10^{-12}	$1.63 imes 10^{-11}$	$5.22 imes 10^{-11}$
0.110	$9.48 imes 10^{-12}$	$7.85 imes10^{-11}$	$2.52 imes 10^{-10}$
0.120	3.50×10^{-11}	$2.87 imes10^{-10}$	$9.23 imes 10^{-10}$
0.130	$1.13 imes10^{-10}$	8.62×10^{-10}	2.75×10^{-09}
0.140	$3.78 imes10^{-10}$	$2.26 imes10^{-09}$	$7.02 imes 10^{-09}$
0.150	$1.55 imes10^{-09}$	$5.68 imes10^{-09}$	$1.62 imes 10^{-08}$
0.160	$6.90 imes10^{-09}$	$1.56 imes10^{-08}$	$3.65 imes 10^{-08}$
0.180	1.07×10^{-07}	1.65×10^{-07}	2.45×10^{-07}
0.200	$1.07 imes10^{-06}$	$1.56 imes 10^{-06}$	2.33×10^{-06}
0.250	$8.26 imes10^{-05}$	$1.25 imes10^{-04}$	$1.93 imes10^{-04}$
0.300	$1.52 imes 10^{-03}$	$2.32 imes 10^{-03}$	$3.60 imes 10^{-03}$
0.350	1.19×10^{-02}	$1.82 imes 10^{-02}$	2.82×10^{-02}
0.400	$5.41 imes 10^{-02}$	8.30×10^{-02}	$1.29 imes 10^{-01}$
0.450	1.73×10^{-01}	2.65×10^{-01}	$4.10 imes10^{-01}$
0.500	4.30×10^{-01}	$6.59 imes10^{-01}$	$1.02 imes 10^{+00}$
0.600	$1.63\times10^{+00}$	$2.49\times10^{+00}$	$3.86\times10^{+00}$
0.700	$4.08\times10^{+00}$	$6.25 imes10^{+00}$	$9.66\times10^{+00}$

Table 12. The ²⁵Al(p, γ)²⁶Si reaction rate in units of cm³ mol⁻¹ s⁻¹ calculated with the resonance information from table 5.

Acknowledgments

This paper is based upon work from the 'ChETEC' COST Action (CA16117), supported by COST (European Cooperation in Science and Technology) and the National Science Foundation under Grant No. OISE-1927130 (IReNA). AML also acknowledges support from STFC (Science and Technology Facilities Council). PA thanks the trustees and staff of the Claude Leon Foundation for support in the form of a postdoctoral fellowship. MP acknowledges the support of NuGrid, JINA-CEE (NSF Grant PHY-1430152) and STFC (through the University of Hulls Consolidated Grant ST/R000840/1), and ongoing access to viper, the University of Hull High Performance Computing Facility. MP acknowledges the support from the 'Lendület-2014' Programme of the Hungarian Academy of Sciences

(Hungary). BC acknowledges the support from the ERC Consolidator Grant (Hungary) funding scheme (Project RADIOSTAR, G.A. n. 724 560), the Hungarian Academy of Sciences via the Lendület project LP2014-17, and the National Science Foundation (NSF, USA) under Grant No. PHY-1430152 (JINA Center for the Evolution of the Elements). RR and DK are thankful for support from BMBF 05P19RFFN1 and the European Research Council under the European Unions's Seventh Framework Programme (FP/2007-2013)/ERC Grant Agreement N. 615126. AK acknowledges the funding from the European Unions Horizon 2020 research and innovation program under grant agreement No. 771036 (ERC CoG MAIDEN). DB acknowledges support from the National Science Foundation under grants PHY-2011890 (University of Notre Dame), PHY-1430152 (JINA Center for the Evolution of the Elements), and OISE-1927130 (International Research Network for Nuclear Astrophysics). CLW acknowledges support from the UK Science and Technologies Facilities Council (STFC), projects ST/P004008/1 and ST/M006085/1, and the European Research Council ERC-2015-STG Nr. 677 497. AS acknowledges support from the U.S. Department of Energy through grant DE-FG02-87ER40328 (UM). JJ acknowledges support by the Spanish MINECO Grant PID2020-117252GB-I00, by the E.U. FEDER funds, and by the AGAUR/ Generalitat de Catalunya grant SGR-661/2017. Finally, we thank the ChETEC-INFRA project funded from the European Unions Horizon 2020 research and innovation programme under Grant agreement No 101008324.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

- A M Laird **b** https://orcid.org/0000-0003-0423-363X
- A Kankainen ^(b) https://orcid.org/0000-0003-1082-7602
- P Adsley **b** https://orcid.org/0000-0003-1373-679X
- R Diehl https://orcid.org/0000-0002-8337-9022
- A Sieverding https://orcid.org/0000-0001-8235-5910
- R J Stancliffe https://orcid.org/0000-0002-6972-9655
- C Massimi https://orcid.org/0000-0003-2499-5586

References

- [1] Basunia M S and Hurst A M 2016 Nuclear data sheets for A = 26 Nucl. Data Sheets 134 1-148
- [2] Timmes F et al 2019 Catching element formation in the act ; the case for a new Mev gamma-ray mission: radionuclide astronomy in the 2020s BAAS 51 2 (https://arxiv.org/pdf/1902.02915.pdf)
- [3] Feige J, Wallner A, Altmeyer R, Fifield L K, Golser R, Merchel S, Rugel G, Steier P, Tims S G and Winkler S R 2018 Limits on supernova-associated ⁶⁰Fe/²⁶Al nucleosynthesis ratios from accelerator mass spectrometry measurements of deep-sea sediments *Phys. Rev. Lett.* 121 221103
- [4] Adams F C 2010 The birth environment of the solar system ARA&A 48 47-85

- [5] Diehl R, Siegert T, Greiner J, Krause M, Kretschmer K, Lang M, Pleintinger M, Strong A W, Weinberger C and Zhang X 2018 INTEGRAL/SPI γ-ray line spectroscopy. Response and background characteristics A&A 611 A12
- [6] Lugaro M, Ott U and Kereszturi Á 2018 Radioactive nuclei from cosmochronology to habitability Progr. Part. Nucl. Phys. 102 1–47
- [7] Lugaro M et al 2017 Origin of meteoritic stardust unveiled by a revised proton-capture rate of ¹⁷O Nat. Astron. 1 0027
- [8] Adsley P et al 2021 Reevaluation of the ²²Ne(alpha, γ)²⁶Mg and ²²Ne(alpha, n)²⁵Mg reaction rates Phys. Rev. C 103 015805
- [9] Iliadis C, Champagne A, Chieffi A and Limongi M 2011 The effects of thermonuclear reaction rate variations on ²⁶Al production in massive stars: a sensitivity study *Astrophys. J. Suppl. Ser.* 193 16
- [10] Diehl R et al 2021 The radioactive nuclei ²⁶Al and ⁶⁰Fe in the Cosmos and in the solar system PASA 38 e062
- [11] Merrill S P W 1952 Spectroscopic observations of stars of class S Astrophys. J. 116 21-6
- [12] Lingenfelter R E and Ramaty R 1978 Gamma-ray lines—a new window to the Universe Phys. Today 31 40–7
- [13] Mahoney W A, Ling J C, Jacobson A S and Lingenfelter R E 1982 Diffuse galactic gamma-ray line emission from nucleosynthetic Fe-60, Al-26, and Na-22—preliminary limits from HEAO 3 *Astrophys. J.* 262 742–48
- [14] Plüschke S et al 2001 The COMPTEL 1.809 MeV survey Exploring the Gamma-Ray Universe ed A Gimenez et al vol 459 (ESA Special Publication) pp 55–8
- [15] Prantzos N and Diehl R 1996 Radioactive ²⁶Al in the galaxy: observations versus theory *Phys. Rep.* 267 1–69
- [16] Diehl R et al 1995 COMPTEL observations of Galactic ²⁶Al emission Astronomy & Astrophysics 298 445–460
- [17] Diehl R, Bennett K, Collmar W, Connors A, Denherder J W, Hermsen W, Lichti G G, Lockwood J A, Macri J and McConnell M 1992 Data analysis of the COMPTEL instrument on the NASA gamma ray observatory NASA Conf. Publ. 3137 95–101
- [18] Strong A W et al 1992 Maximum entropy imaging and spectral deconvolution for COMPTEL Data Analysis in Astronomy ed V di Gesu et al (Boston: Springer) pp 251–60
- [19] Knödlseder J, Dixon D, Bennett K, Bloemen H, Diehl R, Hermsen W, Oberlack U, Ryan J, Schönfelder V and von Ballmoos P 1999 Image reconstruction of COMPTEL 1.8 MeV (26) AL line data Astronomy & Astrophysics 345 813–25
- [20] Diehl R et al 2006 Radioactive ²⁶Al from massive stars in the Galaxy Nature 439 45-7
- [21] Diehl R, Krause M G H, Kretschmer K, Lang M, Pleintinger M M M, Siegert T, Wang W, Bouchet L and Martin P 2021 Steady-state nucleosynthesis throughout the Galaxy *New Astron. Rev.* 92 101608
- [22] Krause M G H et al 2020 The physics of star cluster formation and evolution Space Sci. Rev. 216 64
- [23] Voss R, Diehl R, Vink J S and Hartmann D H 2010 Probing the evolving massive star population in Orion with kinematic and radioactive tracers A&A 520 A51+
- [24] Krause M G H, Burkert A, Diehl R, Fierlinger K, Gaczkowski B, Kroell D, Ngoumou J, Roccatagliata V, Siegert T and Preibisch T 2018 Surround and Squash: the impact of superbubbles on the interstellar medium in Scorpius–Centaurus OB2 A&A 619 A120
- [25] Siegert T 2017 Positron-annihilation spectroscopy throughout the milky way PhD Thesis TU Munich
- [26] Wallner A et al 2016 Recent near-Earth supernovae probed by global deposition of interstellar radioactive ⁶⁰Fe Nature 532 69–72
- [27] Breitschwerdt D, Feige J, Schulreich M M, Avillez M A D, Dettbarn C and Fuchs B 2016 The locations of recent supernovae near the Sun from modelling ⁶⁰Fe transport *Nature* 532 73–6
 [28] Wallner A *et al* 2021 ⁶⁰Fe and ²⁴⁴Pu deposited on Earth constrain the r-process yields of recent
- [28] Wallner A et al 2021 ⁶⁰Fe and ²⁴⁴Pu deposited on Earth constrain the r-process yields of recent nearby supernovae Science 372 742–5
- [29] Wang W, Siegert T, Dai Z G, Diehl R, Greiner J, Heger A, Krause M, Lang M, Pleintinger M M M and Zhang X L 2020 Gamma-ray emission of ⁶⁰Fe and ²⁶Al radioactivity in our Galaxy Astrophys. J. 889 169
- [30] Sukhbold T, Ertl T, Woosley S E, Brown J M and Janka H T 2016 Core-collapse Supernovae from 9 to 120 solar masses based on neutrino-powered explosions Astrophys. J. 821 38

- [31] Austin S M, West C and Heger A 2017 Reducing uncertainties in the production of the gammaemitting nuclei ²⁶Al, ⁴⁴Ti, and ⁶⁰Fe in Core-collapse supernovae by using effective helium burning rates Astrophys. J. 839 L9
- [32] Jones S W, Möller H, Fryer C L, Fontes C J, Trappitsch R, Even W P, Couture A, Mumpower M R and Safi-Harb S 2019 ⁶⁰Fe in core-collapse supernovae and prospects for X-ray and gamma-ray detection in supernova remnants *MNRAS* 485 4287–310
- [33] Lee T, Papanastassiou D A and Wasserburg G J 1977 Aluminum-26 in the early solar system: fossil or fuel? Astrophys. J. 211 L107–10
- [34] Wasserburg G J, Busso M, Gallino R and Nollett K M 2006 Short-lived nuclei in the early Solar System: possible AGB sources *Nucl. Phys. A* 777 5–69
- [35] Vescovi D, Busso M, Palmerini S, Trippella O, Cristallo S, Piersanti L, Chieffi A, Limongi M, Hoppe P and Kratz K L 2018 On the origin of early solar system radioactivities: problems with the asymptotic giant branch and massive star scenarios Astrophys. J. 863 115
- [36] Urey H C 1955 The cosmic abundances of potassium, uranium, and thorium and the heat balances of the earth, the moon, and mars *Proc. Natl Acad. Sci.* 41 127–44
- [37] Lichtenberg T, Golabek G J, Burn R, Meyer M R, Alibert Y, Gerya T V and Mordasini C 2019 A water budget dichotomy of rocky protoplanets from ²⁶Al-heating *Nat. Astron.* 3 307–13
- [38] Duprat J and Tatischeff V 2007 Energetic constraints on in situ production of short-lived radionuclei in the early solar system Astrophys. J. 671 L69–72
- [39] Cameron A G W and Truran J W 1977 The supernova trigger for formation of the solar system *Icarus* 30 447–61
- [40] Boss A P, Ipatov S I, Keiser S A, Myhill E A and Vanhala H A T 2008 Simultaneous triggered collapse of the presolar dense cloud core and injection of short-lived radioisotopes by a supernova shock wave Astrophys. J. 686 L119
- [41] Boss A P, Keiser S A, Ipatov S I, Myhill E A and Vanhala H A T 2010 Triggering collapse of the presolar dense cloud core and injecting short-lived radioisotopes with a shock wave: I. Varied shock speeds Astrophys. J. 708 1268–80
- [42] Gritschneder M, Lin D N C, Murray S D, Yin Q Z and Gong M N 2012 The supernova triggered formation and enrichment of our solar system Astrophys. J. 745 22
- [43] Ouellette N, Desch S J and Hester J J 2010 Injection of supernova dust in nearby protoplanetary disks Astrophys. J. 711 597–612
- [44] Pan L, Desch S J, Scannapieco E and Timmes F X 2012 Mixing of clumpy supernova ejecta into molecular clouds Astrophys. J. 756 102
- [45] Goodson M D, Luebbers I, Heitsch F and Frazer C C 2016 Chemical enrichment of the pre-solar cloud by supernova dust grains MNRAS 462 2777–91
- [46] Gaidos E, Krot A N, Williams J P and Raymond S N 2009 ²⁶Al and the formation of the solar system from a molecular cloud contaminated by Wolf–Rayet winds Astrophys. J. 696 1854–63
- [47] Young E D 2014 Inheritance of solar short- and long-lived radionuclides from molecular clouds and the unexceptional nature of the solar system *Earth Planet. Sci. Lett.* **392** 16–27
- [48] Vasileiadis A, Nordlund Å and Bizzarro M 2013 Abundance of ²⁶Al and ⁶⁰Fe in evolving giant molecular clouds Astrophys. J. 769 L8
- [49] Adams F C, Fatuzzo M and Holden L 2014 Distributions of short-lived radioactive nuclei produced by young embedded star clusters Astrophys. J. 789 86
- [50] Lacki B C 2014 Starbursts and high-redshift galaxies are radioactive: high abundances of ²⁶Al and other short-lived radionuclides MNRAS 440 3738–48
- [51] Fujimoto Y, Krumholz M R and Tachibana S 2018 Short-lived radioisotopes in meteorites from Galactic-scale correlated star formation *MNRAS* 480 4025–39
- [52] Gounelle M and Meynet G 2012 Solar system genealogy revealed by extinct short-lived radionuclides in meteorites A&A 545 A4
- [53] Gounelle M 2015 The abundance of ²⁶Al-rich planetary systems in the Galaxy A&A 582 A26
- [54] Brinkman H E, Doherty C L, Pols O R, Li E T, Côté B and Lugaro M 2019 Aluminium-26 from massive binary stars: I. nonrotating models Astrophys. J. 884 38
- [55] Busso M, Gallino R and Wasserburg G J 1999 Nucleosynthesis in asymptotic giant branch stars: relevance for galactic enrichment and solar system formation ARA&A 37 239–309
- [56] Kastner J H and Myers P C 1994 An observational estimate of the probability of encounters between mass-losing evolved stars and molecular clouds Astrophys. J. 421 605
- [57] Lugaro M 2005 Stardust From Meteorites (World Scientific Series in Astronomy and Astrophysics)

[58] Zinner E 2014 Presolar Grains Meteorites and Cosmochemical Processes 1 181–213

- [59] Groopman E, Zinner E, Amari S, Gyngard F, Hoppe P, Jadhav M, Lin Y, Xu Y, Marhas K and Nittler L R 2015 Inferred initial ²⁶Al/²⁷Al ratios in presolar stardust grains from supernovae are higher than previously estimated *Astrophys. J.* 809 31
- [60] Groopman E, Zinner E, Amari S, Gyngard F, Hoppe P, Jadhav M, Lin Y, Xu Y, Marhas K and Nittler L R 2015 Inferred initial ²⁶Al/²⁷Al ratios in presolar stardust grains from supernovae are higher than previously estimated *Astrophys. J.* 809 31
- [61] Gyngard F, Zinner E, Nittler L R, Morgand A, Stadermann F J and Mairin Hynes K 2010 Automated NanoSIMS measurements of spinel stardust from the Murray meteorite Astrophys. J. 717 107–20
- [62] Pignatari M, Zinner E, Hoppe P, Jordan C J, Gibson B K, Trappitsch R, Herwig F, Fryer C, Hirschi R and Timmes F X 2015 Carbon-rich presolar grains from massive stars: subsolar ¹²C/¹³C and ¹⁴N/¹⁵N ratios and the mystery of ¹⁵N Astrophys. J. 808 L43
- [63] van Raai M A, Lugaro M, Karakas A I and Iliadis C 2008 Reaction rate uncertainties and ²⁶Al in AGB silicon carbide stardust A&A 478 521–6
- [64] Palmerini S, La Cognata M, Cristallo S and Busso M 2011 Deep Mixing in Evolved Stars: I. The effect of reaction rate revisions from C to Al Astrophys. J. 729 3
- [65] Palmerini S, Trippella O and Busso M 2017 A deep mixing solution to the aluminum and oxygen isotope puzzles in pre-solar grains *Monthly Notices of the Royal Astronomical Society* 467 1193–201
- [66] José J, Hernanz M, Amari S, Lodders K and Zinner E 2004 The imprint of nova nucleosynthesis in presolar grains Astrophysical Journal 612 414–28
- [67] Bose M and Starrfield S 2019 Condensation of SiC stardust in co nova outbursts Astrophys. J.
 873 14
- [68] Côté B, Yagüe A, Világos B and Lugaro M 2019 Stochastic chemical evolution of radioactive isotopes with a monte carlo approach Astrophys. J. 887 213
- [69] Kaur T and Sahijpal S 2019 Heterogeneous evolution of the Galaxy and the origin of the shortlived nuclides in the early solar system MNRAS 490 1620–37
- [70] Pleintinger M M M, Siegert T, Diehl R, Fujimoto Y, Greiner J, Krause M G H and Krumholz M R 2019 Comparing simulated ²⁶Al maps to gamma-ray measurements A&A 632 A73
- [71] Fujimoto Y, Krumholz M R, Inutsuka S-I, Boss A P and Nittler L R 2020 Formation and evolution of the local interstellar environment: combined constraints from nucleosynthetic and X-ray data MNRAS 498 5532–40
- [72] Krause M G H, Burkert A, Diehl R, Fierlinger K, Gaczkowski B, Kroell D, Ngoumou J, Roccatagliata V, Siegert T and Preibisch T 2018 Surround and Squash: the impact of superbubbles on the interstellar medium in Scorpius–Centaurus OB2 A&A 619 A120
- [73] Krause M G H, Rodgers-Lee D, Dale J E, Diehl R and Kobayashi C 2021 Galactic ²⁶Al traces metal loss through hot chimneys MNRAS 501 210–8
- [74] Clayton D D 1984 Al-26 in the interstellar medium Astrophys. J. 280 144-9
- [75] Timmes F X, Woosley S E, Hartmann D H, Hoffman R D, Weaver T A and Matteucci F 1995 26al and 60fe from supernova explosions 449 204
- [76] Huss G R, Meyer B S, Srinivasan G, Goswami J N and Sahijpal S 2009 Stellar sources of the short-lived radionuclides in the early solar system *Geochim. Cosmochim. Acta* 73 4922–45
- [77] Côté B, Lugaro M, Reifarth R, Pignatari M, Világos B, Yagüe A and Gibson B K 2019 Galactic chemical evolution of radioactive isotopes Astrophys. J. 878 156
- [78] López A Y, Côté B and Lugaro M 2021 Monte Carlo investigation of the ratios of short-lived radioactive isotopes in the interstellar medium Astrophys. J. 915 128
- [79] Vasileiadis A, Nordlund Å and Bizzarro M 2013 Abundance of ²⁶Al and ⁶⁰Fe in evolving giant molecular clouds Astrophys. J. 769 L8
- [80] Palacios A, Meynet G, Vuissoz C, Knödlseder J, Schaerer D, Cerviño M and Mowlavi N 2005 New estimates of the contribution of Wolf–Rayet stellar winds to the Galactic ²⁶Al A&A 429 613–24
- [81] Limongi M and Chieffi A 2006 The Nucleosynthesis of ²⁶Al and ⁶⁰Fe in solar metallicity stars extending in mass from 11 to 120 M_{solar}: the hydrostatic and explosive contributions Astrophys. J. 647 483–500
- [82] Woosley S E and Heger A 2007 Nucleosynthesis and remnants in massive stars of solar metallicity Phys. Rep. 442 269–83

- [83] Pignatari M et al 2016 NuGrid stellar data set: I. Stellar yields from h to bi for stars with metallicities Z = 0.02 and Z = 0.01 Astrophys. J. Suppl. Ser. 225 24
- [84] Herwig F 2005 Evolution of asymptotic giant branch stars ARA&A 43 435-79
- [85] Karakas A I and Lattanzio J C 2014 The dawes review: II. Nucleosynthesis and stellar yields of low- and intermediate-mass single stars *PASA* 31 e030
 [86] Palmerini S and Busso M 2008 ²⁶Al production from magnetically induced extramixing in AGB
- [86] Palmerini S and Busso M 2008 ²⁰Al production from magnetically induced extramixing in AGE stars New Astron. Rev. 52 412–5
- [87] Wasserburg G J, Karakas A I and Lugaro M 2017 Intermediate-mass asymptotic giant branch stars and sources of ²⁶Al, ⁶⁰Fe, ¹⁰⁷Pd, and ¹⁸²Hf in the solar system Astrophys. J. 836 126
- [88] Mowlavi N and Meynet G 2000 Aluminum 26 production in asymptotic giant branch stars Astron. Astrophysics 361 959–76 (https://adsabs.harvard.edu/pdf/2000A%26A...361..959M)
- [89] Izzard R G, Lugaro M, Karakas A I, Iliadis C and van Raai M 2007 Reaction rate uncertainties and the operation of the NeNa and MgAl chains during HBB in intermediate-mass AGB stars A&A 466 641–8
- [90] Siess L and Arnould M 2008 Production of ²⁶Al by super-AGB stars A&A **489** 395–402
- [91] Mowlavi N 1999 On the third dredge-up phenomenon in asymptotic giant branch stars A&A 344 617–31
- [92] Stancliffe R J and Jeffery C S 2007 Mass loss and yield uncertainty in low-mass asymptotic giant branch stars MNRAS 375 1280–90
- [93] Ventura P and D'Antona F 2005 Full computation of massive AGB evolution: I. The large impact of convection on nucleosynthesis A&A 431 279–88
- [94] Doherty C L, Gil-Pons P, Lau H H B, Lattanzio J C and Siess L 2014 Super and massive AGB stars—II. Nucleosynthesis and yields—Z = 0.02, 0.008 and 0.004 MNRAS 437 195–214
- [95] Wasserburg G J, Boothroyd A I and Sackmann I J 1995 Deep circulation in red giant stars: a solution to the carbon and oxygen isotope puzzles? *Astrophys. J.* 447 L37
- [96] Nollett K M, Busso M and Wasserburg G J 2003 Cool bottom processes on the thermally pulsing asymptotic giant branch and the isotopic composition of circumstellar dust grains Astrophys. J. 582 1036–58
- [97] Charbonnel C and Lagarde N 2010 Thermohaline instability and rotation-induced mixing: I. Low- and intermediate-mass solar metallicity stars up to the end of the AGB Astron. Astrophys. 522 A10
- [98] Eggleton P P, Dearborn D S P and Lattanzio J C 2006 Deep mixing of ³He: reconciling big bang and stellar nucleosynthesis *Science* **314** 1580
- [99] Fuller J, Lecoanet D, Cantiello M and Brown B 2014 Angular momentum transport via internal gravity waves in evolving stars Astrophys. J. 796 17
- [100] Busso M, Wasserburg G J, Nollett K M and Calandra A 2007 Can extra mixing in rgb and agb stars be attributed to magnetic mechanisms? *Astrophys. J.* 671 802–10
- [101] Stancliffe R J 2010 The effects of thermohaline mixing on low-metallicity asymptotic giant branch stars Mon. Not. R Astron. Soc. 403 505–15
- [102] Denissenkov P A, Pinsonneault M and MacGregor K B 2009 Magneto-thermohaline mixing in red giants Astrophys. J. 696 1823–33
- [103] Palmerini S, Cristallo S, Busso M, Abia C, Uttenthaler S, Gialanella L and Maiorca E 2011 Deep mixing in evolved stars: II. Interpreting li abundances in red giant branch and asymptotic giant branch stars Astrophys. J. 741 26
- [104] Nucci M C and Busso M 2014 Magnetohydrodynamics and deep mixing in evolved stars: I. Two- and three-dimensional analytical models for the asymptotic giant branch Astrophys. J. 787 141
- [105] Nittler L R, Alexander O'D, Gao X, Walker R M and Zinner E 1997 Stellar sapphires: the properties and origins of presolar Al₂O₃ in meteorites Astrophys. J. 483 475–95
- [106] Straniero O *et al* 2013 Impact of a Revised ${}^{25}Mg(p, \gamma){}^{26}Al$ reaction rate on the operation of the Mg–Al Cycle Astrophys. J. **763** 100
- [107] Pain S D *et al* 2015 Constraint of the astrophysical ${}^{26g}Al(p, \gamma){}^{27}Si$ destruction rate at stellar temperatures *Phys. Rev. Lett.* **114** 212501
- [108] Iliadis C, Longland R, Champagne A E, Coc A and Fitzgerald R 2010 Charged-particle thermonuclear reaction rates: II. Tables and graphs of reaction rates and probability density functions *Nucl. Phys.* A 841 31–250
- [109] Palmerini S, Cristallo S, Piersanti L, Vescovi D and Busso M 2021 Group II oxide grains: how massive are their agb star progenitors? *Universe* 7 175

- [110] Diehl R 2013 Nuclear astrophysics lessons from INTEGRAL Rep. Prog. Phys. 76 026301
- [111] Martin P, Knödlseder J, Diehl R and Meynet G 2009 New estimates of the gamma-ray line emission of the Cygnus region from INTEGRAL/SPI observations A&A 506 703-10
- [112] Diehl R, Lang M G, Martin P, Ohlendorf H, Preibisch T, Voss R, Jean P, Roques J-P, von Ballmoos P and Wang W 2010 Radioactive ²⁶Al from the Scorpius-Centaurus association A&A 522 A51-
- [113] Voss R, Martin P, Diehl R, Vink J S, Hartmann D H and Preibisch T 2012 Energetic feedback and ²⁶Al from massive stars and their supernovae in the Carina region A&A 539 A66
- [114] Walborn N R 1973 The space distribution of the O stars in the solar neighborhood AJ 78 1067-83
- [115] Martins F, Schaerer D and Hillier D J 2005 A new calibration of stellar parameters of Galactic O stars A&A 436 1049-65
- [116] Diehl R, Prantzos N and von Ballmoos P 2006 Astrophysical constraints from gamma-ray spectroscopy Nucl. Phys. A 777 70-97
- [117] Cerviño M, Knödlseder J, Schaerer D, von Ballmoos P and Meynet G 2000 Gamma-ray line emission from OB associations and young open clusters: I. Evolutionary synthesis models A&A 363 970-83
- [118] Vink J S *et al* 2015 Very massive stars in the local universe *Highlights Astron.* 16 51–79
 [119] Limongi M and Chieffi A 2006 The nucleosynthesis of ²⁶Al and ⁶⁰Fe in solar metallicity stars extending in mass from 11 to 120 M_{\odot} : the hydrostatic and explosive contributions Astrophys. J. 647 483-500
- [120] Nieuwenhuijzen H and de Jager C 1990 Parametrization of stellar rates of mass loss as functions of the fundamental stellar parameters M, L, and R A&A 231 134-6
- [121] Vink J S, de Koter A and Lamers H J G L M 2000 New theoretical mass-loss rates of O and B stars A&A 362 295-309
- [122] Vink J S, de Koter A and Lamers H J G L M 2001 Mass-loss predictions for O and B stars as a function of metallicity A&A 369 574-88
- [123] Hamann F and Ferland G 1999 Elemental abundances in quasistellar objects: star formation and galactic nuclear evolution at high redshifts ARA&A 37 487-531
- [124] Nugis T and Lamers H J G L M 2000 Mass-loss rates of Wolf-Rayet stars as a function of stellar parameters A&A 360 227-44
- [125] Brinkman H E, Doherty C L, Pols O R, Li E T, Côté B and Lugaro M 2019 Aluminium-26 from massive binary stars: II. Nonrotating models Astrophys. J. 884 38
- [126] Ekström S et al 2012 Grids of stellar models with rotation: I. Models from 0.8 to 120 M_{\odot} at solar metallicity (Z = 0.014) A&A 537 A146
- [127] Limongi M and Chieffi A 2018 Presupernova evolution and explosive nucleosynthesis of rotating massive stars in the metallicity range $-3 \leq [Fe/H] \leq 0$ Astrophys. J. Suppl. Ser. 237 13
- [128] Woosley S E, Kasen D, Blinnikov S and Sorokina E 2007 Type ia supernova light curves Astrophys. J. 662 487-503
- [129] Yusof N, Hirschi R, Meynet G, Crowther P A, Ekström S, Frischknecht U, Georgy C, Abu Kassim H and Schnurr O 2013 Evolution and fate of very massive stars MNRAS 433 1114 - 32
- [130] Brinkman H E, Doherty C L, Pols O R, Li E T, Côté B and Lugaro M 2019 Aluminium-26 from massive binary stars: I. Nonrotating Models Astrophys. J. 884 38
- [131] Duchêne G and Kraus A 2013 Stellar multiplicity ARA&A 51 269-310
- [132] Sana H, de Mink S E, de Koter A, Langer N, Evans C J, Gieles M, Gosset E, Izzard R G, Le Bouquin J-B and Schneider F R N 2012 Binary interaction dominates the evolution of massive stars Science 337 444
- [133] de Mink S E, Sana H, Langer N, Izzard R G and Schneider F R N 2014 The incidence of stellar mergers and mass gainers among massive stars Astrophys. J. 782 7
- [134] Braun H and Langer N 1995 New massive close binary models and the 26-Al yield of the WR component of gamma Vel Wolf-Rayet Stars: Binaries; Colliding Winds; Evolution ed K A van der Hucht and P M Williams vol 163 (Dordrecht: Springer) p 305
- [135] Crowther P A, Schnurr O, Hirschi R, Yusof N, Parker R J, Goodwin S P and Kassim H A 2010 The R136 star cluster hosts several stars whose individual masses greatly exceed the accepted 150M_{solar} stellar mass limit MNRAS 408 731-51
- [136] Bestenlehner J M et al 2014 The VLT-FLAMES Tarantula Survey: XVII. Physical and wind properties of massive stars at the top of the main sequence A&A 570 A38

- [137] Martins F 2015 Mass loss of massive stars SF2A-2015: Proc. of the Annual meeting of the French Society of Astronomy and Astrophysics pp 343–8
- [138] Crowther P A *et al* 2016 The R136 star cluster dissected with Hubble Space Telescope/STIS. I. Far-ultraviolet spectroscopic census and the origin of He II λ 1640 in young star clusters *MNRAS* **458** 624–59
- [139] Bestenlehner J M *et al* 2020 The R136 star cluster dissected with Hubble Space Telescope/STIS: II. Physical properties of the most massive stars in R136 MNRAS 499 1918–36
- [140] Vink J S, Muijres L E, Anthonisse B, de Koter A, Gräfener G and Langer N 2011 Wind modelling of very massive stars up to 300 solar masses A&A 531 A132
- [141] Vink J S and Gräfener G 2012 The transition mass-loss rate: calibrating the role of line-driven winds in massive star evolution Astrophys. J. 751 L34
- [142] Voss R, Diehl R, Hartmann D H, Cerviño M, Vink J S, Meynet G, Limongi M and Chieffi A 2009 Using population synthesis of massive stars to study the interstellar medium near OB associations A&A 504 531–42
- [143] Köhler K et al 2015 The evolution of rotating very massive stars with LMC composition A&A 573 A71
- [144] Gasques L R, Brown E F, Chieffi A, Jiang C L, Limongi M, Rolfs C, Wiescher M and Yakovlev D G 2007 Implications of low-energy fusion hindrance on stellar burning and nucleosynthesis *Phys. Rev. C* 76 035802
- [145] Ritter C, Herwig F, Jones S, Pignatari M, Fryer C and Hirschi R 2018 NuGrid stellar data set—II. Stellar yields from H to Bi for stellar models with $M_{ZAMS} = 1-25 M_{\odot}$ and Z = 0.0001-0.02 MNRAS 480 538–71
- [146] Blake J B and Schramm D N 1976 A possible alternative to the r-process Astrophys. J. 209 846–9
- [147] Meyer B S, Clayton D D and The L S 2000 Molybdenum and zirconium isotopes from a supernova neutron burst *Astrophys. J.* **540** L49–52
- [148] Pignatari M, Hoppe P, Trappitsch R, Fryer C, Timmes F X, Herwig F and Hirschi R 2018 The neutron capture process in the He shell in core-collapse supernovae: presolar silicon carbide grains as a diagnostic tool for nuclear astrophysics *Geochim. Cosmochim. Acta* 221 37–46
- [149] Herwig F, Woodward P R, Lin P-H, Knox M and Fryer C 2014 Global Non-spherical oscillations in three-dimensional 4 π simulations of the H-ingestion flash *Astrophys. J.* **792** L3
- [150] Clarkson O and Herwig F 2020 Convective H–He interactions in massive population III stellar evolution models *Monthly Notices of the RAS* 500 2685–2703 arXiv:2005.07748
- [151] Woosley S E, Hartmann D H, Hoffman R D and Haxton W C 1990 The ν-process Astrophysical Journal 356 272–301 (https://adsabs.harvard.edu/pdf/1990ApJ...356..272W)
- [152] Domogatskij G V and Nadezhin D K 1980 Neutrino-induced production of radioactive aluminum-26 Soviet Astron. Lett. 6 127
- [153] Sieverding A, Martínez-Pinedo G, Huther L, Langanke K and Heger A 2018 The ν-process in the light of an improved understanding of supernova neutrino spectra Astrophysical Journal 865 143
- [154] Zegers R G T et al 2006 The (t,He3) and (He3, t) reactions as probes of Gamow–Teller strength Phys. Rev. C 74 024309
- [155] Coc A, Mochkovitch R, Oberto Y, Thibaud J P and Vangioni-Flam E 1995 ONeMg novae: nuclear uncertainties on the 26Âl and 22Na yields A&A 299 479
- [156] José J, Coc A and Hernanz M 1999 Nuclear uncertainties in the NeNa-MgAl cycles and production of ²²Na and ²⁶Al during nova outbursts Astrophys. J. 520 347–60
- [157] Mahoney W A, Ling J C, Jacobson A S and Lingenfelter R E 1982 Diffuse galactic gamma-ray line emission from nucleosynthetic Fe-60, Al-26, and Na-22—Preliminary limits from HEAO 3 *Astrophys. J.* 262 742–8
- [158] Mahoney W A, Ling J C, Wheaton W A and Jacobson A S 1984 HEAO 3 discovery of Al-26 in the interstellar medium Astrophys. J. 286 578–85
- [159] Ward R A and Fowler W A 1980 Thermalization of long-lived nuclear isomeric states under stellar conditions Astrophys. J. 238 266–86
- [160] Hillebrandt W and Thielemann F K 1982 Nucleosynthesis in novae—a source of Ne-E and Al-26 Astrophys. J. 255 617–23
- [161] Wiescher M, Gorres J, Thielemann F K and Ritter H 1986 Explosive hydrogen burning in novae A&A 160 56–72
- [162] Starrfield S, Sparks W M and Truran J W 1986 Hydrodynamic models for novae with ejecta rich in oxygen, neon, and magnesium Astrophys. J. 303 L5

- [163] Weiss A and Truran J W 1990 Na-22 and Al-26 production and nucleosynthesis in novae explosions A&A 238 178-86
- [164] Nofar I, Shaviv G and Starrfield S 1991 The formation of 26Al nova explosions Astrophys. J. 369 440
- [165] Starrfield S, Truran J W, Politano M, Sparks W M, Nofar I and Shaviv G 1993 ²²Na and ²⁶Al production in nova outbursts Phys. Rep. 227 223-34
- [166] Politano M, Starrfield S, Truran J W, Weiss A and Sparks W M 1995 Hydrodynamic studies of accretion onto massive white dwarfs: onemg-enriched nova outbursts: I. Dependence on white dwarf mass Astrophys. J. 448 807
- [167] Arnett W D and Truran J W 1969 Carbon-burning nucleosynthesis at constant temperature Astrophys. J. 157 339
- [168] Dominguez I, Tornambe A and Isern J 1993 On the formation of O-Ne white dwarfs in metal-rich close binary systems Astrophys. J. 419 268
- [169] Ritossa C, Garcia-Berro E and Icko I Jr. 1996 On the evolution of stars that form electrondegenerate cores processed by carbon burning: II. Isotope abundances and thermal pulses in a 10 M_{sun} model with an one core and applications to long-period variables, classical novae, and accretion-induced collapse Astrophys. J. 460 489
- [170] José J, Hernanz M and Coc A 1997 New results on ²⁶Al production in classical novae Astrophys. J. 479 L55-8
- [171] José J and Hernanz M 1998 Nucleosynthesis in classical novae: CO versus ONe white dwarfs Astrophys. J. 494 680–90
- [172] José J, Shore S N and Casanova J 2020 123-321 models of classical novae A&A 634 A5
- [173] Casanova J, José J, García-Berro E, Shore S N and Calder A C 2011 Kelvin-Helmholtz instabilities as the source of inhomogeneous mixing in nova explosions Nature 478 490-2
- [174] Casanova J, José J, García-Berro E and Shore S N 2016 Three-dimensional simulations of turbulent convective mixing in ONe and CO classical nova explosions A&A 595 A28
- [175] Casanova J, José J and Shore S N 2018 Two-dimensional simulations of mixing in classical novae: the effect of white dwarf composition and mass A&A 619 A121
- [176] Shafter A W 2017 The galactic nova rate revisited Astrophys. J. 834 196
- [177] Diehl R et al 2006 Radioactive ²⁶Al from massive stars in the Galaxy Nature 439 45-7
- [178] Diehl R et al 1995 COMPTEL observations of Galactic 26Al emission A&A 298 445
- [179] Iliadis C, Longland R, Champagne A E and Coc A 2010 Charged-particle thermonuclear reaction rates: III. Nuclear physics input Nucl. Phys. A 841 251-322
- [180] Iliadis C 2019 Calculation of resonance energies from Q values Phys. Rev. C 99 065809
- [181] Wang M, Huang W J, Kondev F G, Audi G and Naimi S 2021 The AME 2020 atomic mass evaluation (II). Tables, graphs and references *Chin. Phys.* C **45** 030003 [182] Endt P M and Rolfs C 1987 Astrophysical aspects of the ²⁵Mg(p, γ)²⁶Al reaction *Nucl. Phys.* A
- 467 272
- [183] RadCapFraction. (https://github.com/padsley/RadCapFraction)
- [184] Iliadis C, Buchmann L, Endt P M, Herndl H and Wiescher M 1996 New stellar reaction rates for ²⁵Mg(p, γ)²⁶ Al and ²⁵Al(p, γ)²⁶ Si *Phys. Rev.* C 53 475–96
- [185] Li Y J et al 2020 Indirect measurement of the 57.7 kev resonance strength for the astrophysical γ ray source of the ${}^{25}Mg(p, \gamma){}^{26}Al$ reaction *Phys. Rev.* C 102 025804
- [186] Kankainen A et al 2021 Decay of the key 92 keV resonance in the ${}^{25}Mg(p, \gamma)$ reaction to the [100] Ramanien Rel a 2021 Decay of the Rel 9/2 he (resonance in the Rel 9, γ) reaction to the ground and isomeric states of the cosmic γ-ray emitter ²⁶Al Phys. Lett. B 813 136033
 [187] Strieder F et al 2012 ²⁵Mg(p, γ)²⁶Al reaction at low astrophysical energies Phys. Lett. B 707
- 60-5
- [188] Su J et al 2022 First result from the jinping underground nuclear astrophysics experiment juna: precise measurement of the 92-kev 25 mg(p, γ) 26 al resonance Sci. Bull. 67 125–32
- [189] Lotay G et al 2022 Revised decay properties of the key 93-kev resonance in the ${}^{25}Mg(p, \gamma)$ reaction and its influence on the mgal cycle in astrophysical environments Phys. Rev. C 105 L042801
- [190] Iliadis C, D'Auria J M, Starrfield S, Thompson W J and Wiescher M 2001 Proton-induced thermonuclear reaction rates for A = 20-40 nuclei Astrophys. J. Suppl. Ser. 134 151-71
- [191] Arazi A, Faestermann T, Niello J O F, Knie K, Korschinek G, Poutivtsev M, Richter E, Rugel G and Wallner A 2006 Measurement of ²⁵Mg(p, γ) ²⁶Al^g resonance strengths via accelerator mass spectrometry Phys. Rev. C 74 025802

- [192] Endt P M and Rolfs C 1987 Astrophysical aspects of the ²⁵Mg(p, γ)²⁶Al reaction Nucl. Phys. A 467 261–72
- [193] Iliadis C 1997 Proton single-particle reduced widths for unbound states Nucl. Phys. A 618 166–75
- [194] Endt P M, de Wit P, Alderliesten C and Wildenthal B H 1988 Spins, parities and isospins of ²⁶Al levels: Shell-model aspects *Nucl. Phys.* A 487 221–50
- [195] Limata B *et al* 2010 New experimental study of low-energy (p, γ) resonances in magnesium isotopes *Phys. Rev.* C **82** 015801
- [196] Betts R R, Fortune H T and Pullen D J 1978 A study of ²⁶Al by the ²⁵Mg(³He, d) reaction Nucl. Phys. A 299 412–28
- [197] Champagne A E, Howard A J and Parker P D 1983 Threshold states in ²⁶Al: (I). Experimental investigations Nucl. Phys. A 402 159–78
- [198] Champagne A E, Howard A J and Parker P D 1983 Threshold states in ²⁶ Nucl. Phys. A 402 179–88
- [199] Champagne A E, McDonald A B, Wang T F, Howard A J, Magnus P V and Parker P D 1986 Threshold states in ²⁶Al revisited *Nucl. Phys.* A 451 498–508
- [200] Champagne A E, Howard A J, Smith M S, Magnus P V and Parker P D 1989 The effect of weak resonances on the ²⁵Mg(p, γ)²⁶Al reaction rate *Nucl. Phys.* A 505 384–96
- [201] Wijekumar V, Schmalbrock P, Hausman H J, Donoghue T R, Wiescher M, Suiter H R, Browne C P, Rollefson A A and Tarara R W 1985 Proton threshold states in ²⁶Al Nucl. Phys. A 436 561–72
- [202] Bergmeister F J, Lieb K P, Pampus K and Uhrmacher M 1985 Note on Stellar ²⁶Al Production via the ²⁵Mg(p, γ) Process Z. Phys. A **320** 693
- [203] Endt P M, de Wit P and Alderliesten C 1986 The ²⁵Mg(p, γ)²⁶Al and ²⁵Mg(p, p') resonances for $E_p = 0.31$ -1.84 MeV *Nucl. Phys.* A **459** 61–76 [204] Iliadis C *et al* 1990 Low-energy resonances in ²⁵Mg(p, γ)²⁶Al, ²⁶Mg(p, γ)²⁷Al and ²⁷Al(p,
- [204] Iliadis C *et al* 1990 Low-energy resonances in ²³Mg(p, γ)²⁶Al, ²⁰Mg(p, γ)²⁷Al and ²⁷Al(p, γ)²⁸Si *Nucl. Phys.* A **512** 509–30
- [205] Powell D C, Iliadis C, Champagne A E, Hale S E, Hansper V Y, Surman R A and Veal K D 1998 Low-energy resonance strengths for proton capture on Mg and Al nuclei *Nucl. Phys.* A 644 276
- [206] Rollefson A A, Wijekumar V, Browne C P, Wiescher M, Hausman H J, Kim W Y and Schmalbrock P 1990 Spectroscopic factors for proton unbound levels in ²⁶Al and their influence on stellar reaction rates *Nucl. Phys.* A 507 425
- [207] Liu W P et al 2016 Progress of jinping underground laboratory for nuclear astrophysics (JUNA) Sci. China Phys., Mech., Astron. 59 5785
- [208] Angulo C et al 1999 A compilation of charged-particle induced thermonuclear reaction rates Nucl. Phys. A 656 3–183
- [209] Endt P M 1990 Energy levels of A = 21-44 nuclei (VII) Nucl. Phys. A 521 1-400
- [210] Longland R, Iliadis C, Champagne A E, Newton J R, Ugalde C, Coc A and Fitzgerald R 2010 Charged-particle thermonuclear reaction rates: I. Monte Carlo method and statistical distributions *Nucl. Phys.* A 841 1–30
- [211] Sallaska A L, Iliadis C, Champange A E, Goriely S, Starrfield S and Timmes F X 2013 Starlib: a next-generation reaction-rate library for nuclear astrophysics Astrophys. J. Suppl. Ser. 207 18
- [212] Pogrebnyak I, Howard C, Iliadis C, Longland R and Mitchell G E 2013 Mean proton and αparticle reduced widths of the Porter–Thomas distribution and astrophysical applications *Phys. Rev.* C 88 015808
- [213] Iliadis C, Longland R, Champagne A E, Coc A and Fitzgerald R 2010 Charged-particle thermonuclear reaction rates: Ii. tables and graphs of reaction rates and probability density functions *Nucl. Phys.* A 841 31–250
- [214] Margerin V et al 2015 Inverse kinematic study of the ^{26g}Al(d, p)²⁷Al reaction and implications for destruction of ²⁶Al in Wolf–Rayet and asymptotic giant branch stars Phys. Rev. Lett. 115 062701
- [215] Almaraz-Calderon S *et al* 2017 Study of the ${}^{26}\text{Al}^m(d, p){}^{27}\text{Al}$ Reaction and the Influence of the ${}^{26}\text{Al} 0^+$ Isomer on the Destruction of ${}^{26}\text{Al}$ in the Galaxy *Phys. Rev. Lett.* **119** 072701
- [216] Runkle R C, Champagne A E and Engel J 2001 Thermal equilibration of 26al Astrophys. J. 556 970–8
- [217] Vogelaar R B 1989 The ${}^{26}Al(p, \gamma)^{27}Si$ reaction: stellar origins of galactic ${}^{26}Al$ *PhD Thesis* California Institute of Technology

- [218] Buchmann L, Hilgemeier M, Krauss A, Redder A, Rolfs C, Trautvetter H P and Donoghue T R 1984 The abundance of ²⁶Al in the MgAl cycle *Nucl. Phys.* A **415** 93–113
- [219] Ruiz C *et al* 2006 Measurement of the $E_{c.m.} = 184$ keV resonance strength in the ${}^{26g}Al(p, \gamma){}^{27}Si$ reaction *Phys. Rev. Lett.* **96** 252501
- [220] Vogelaar R B, Mitchell L W, Kavanagh R W, Champagne A E, Magnus P V, Smith M S, Howard A J, Parker P D and O'Brien H A 1996 Constraining ²⁶Al+p resonances using ²⁶Al(³ he,d)²⁷ si *Phys. Rev.* C 53 1945–9
- [221] Lotay G, Woods P J, Seweryniak D, Carpenter M P, Janssens R V F and Zhu S 2009 Identification of key astrophysical resonances relevant for the ^{26g}Al(p, γ)²⁷Si reaction in Wolf– Rayet stars, agb stars, and classical novae *Phys. Rev. Lett.* **102** 162502
- [222] Lotay G, Woods P J, Seweryniak D, Carpenter M P, Janssens R V F and Zhu S 2009 γ -ray spectroscopy study of states in ²⁷Si relevant for the ²⁶Al^m(p, γ)²⁷Si reaction in novae and supernovae *Phys. Rev.* C **80** 055802
- [223] Longland R, Iliadis C and Karakas A I 2012 Reaction rates for the s-process neutron source ²² ne $+ \alpha$ Phys. Rev. C 85 065809
- [224] Parikh A, José J, Karakas A, Ruiz C and Wimmer K 2014 Strength of the $E_R = 127$ kev, ²⁶Al(p, γ)²⁷Si resonance *Phys. Rev.* C **90** 038801
- [225] Schmalbrock P, Donoghue T R, Wiescher M, Wijekumar V, Browne C P, Rollefson A A, Rolfs C and Vlieks A 1986 Proton threshold states in ²⁷Si and their implications on hydrogen burning of ²⁶Al Nucl. Phys. A 457 182–8
- [226] Wang T F, Champagne A E, Hadden J D, Magnus P V, Smith M S, Howard A J and Parker P D 1989 Proton threshold states in ²⁷Si and the destruction of ²⁶Al at low stellar temperatures *Nucl. Phys.* A **499** 546–64
- [227] Kankainen A et al 2016 Angle-integrated measurements of the ²⁶Al(d,n)²⁷Si reaction cross section: a probe of spectroscopic factors and astrophysical resonance strengths Eur. Phys. J. A 52 6
- [228] Lotay G *et al* 2020 High-resolution radioactive beam study of the ²⁶al(*d*, *p*) reaction and measurements of single-particle spectroscopic factors *Eur. Phys. J.* A **56** 1–6
- [229] Angulo C et al 1999 A compilation of charged-particle induced thermonuclear reaction rates Nucl. Phys. A 656 3–183
- [230] Lotay G et al 2022 Radiative capture on nuclear isomers: direct measurement of the 26m Al(p, $\gamma)^{27}$ Si reaction Phys. Rev. Lett. **128** 042701
- [231] Deibel C M, Clark J A, Lewis R, Parikh A, Parker P D and Wrede C 2009 Toward an experimentally determined ²⁶Al^m(p, γ)²⁷Si reaction rate in ONe novae *Phys. Rev.* C 80 035806
 [232] Good E C *et al* in preparation
- [233] Lotay G, Woods P J, Seweryniak D, Carpenter M P, Janssens R V F and Zhu S 2010 γ -ray spectroscopy study of states in ²⁷Si relevant for the ²⁶Al^m(p, γ) ²⁷Si reaction in novae and supernovae *Phys. Rev.* C **81** 029903
 - Lotay G, Woods P J, Seweryniak D, Carpenter M P, Janssens R V F and Zhu S 2009 γ -ray spectroscopy study of states in ²⁷Si relevant for the ²⁶Al^m(p, γ) ²⁷Si reaction in novae and supernovae *Phys. Rev.* C **80** 055802
- [234] Lotay G, Woods P J, Seweryniak D, Carpenter M P, David H M, Janssens R V F and Zhu S 2011 Identification of analog states in the T = 1/2 A = 27 mirror system from low excitation energies to the region of hydrogen burning in the ²⁶ Al ^{g,m}(p, γ) ²⁷ Si reactions *Phys. Rev.* C **84** 035802
- [235] Wang M, Audi G, Kondev F G, Huang W J, Naimi S and Xu X 2017 The AME2016 atomic mass evaluation (II). Tables, graphs and references *Chin. Phys.* C 41 030003
- [236] Lee I-Y 1990 The GAMMASPHERE Nucl. Phys. A 520 c641-55
- [237] Janssens R V F and Stephens F S 1996 Nucl. Phys. News 6 9
- [238] Buchmann L, Hilgemeier M, Krauss A, Redder A, Rolfs C, Trautvetter H P and Donoghue T R 1984 The abundance of ²⁶Al in the MgAl cycle *Nucl. Phys.* A **415** 93–113
- [239] Almaraz-Calderon S, Bertone P F, Alcorta M, Albers M, Deibel C M, Hoffman C R, Jiang C L, Marley S T, Rehm K E and Ugalde C 2015 Direct measurement of the ²³Na(*alpha*, *p*)²⁶Mg reaction cross section at energies relevant for the production of galactic ²⁶Al Phys. Rev. Lett. 115 179901
 - Almaraz-Calderon S *et al* 2017 Study of the 26 Al^m(*d*, *p*) 27 Al Reaction and the Influence of the 26 Al 0+ Isomer on the Destruction of 26 Al in the Galaxy *Phys. Rev. Lett.* **119** 072701
 - Almaraz-Calderon S, Bertone P F, Alcorta M, Albers M, Deibel C M, Hoffman C R, Jiang C L, Marley S T, Rehm K E and Ugalde C 2014 Direct measurement of the ²³Na(*alpha*, *p*)²⁶Mg

reaction cross section at energies relevant for the production of galactic ²⁶Al Phys. Rev. Lett. 112 152701

- [240] Hallam S et al 2021 Exploiting isospin symmetry to study the role of isomers in stellar environments Phys. Rev. Lett. 126 042701
- [241] Iliadis C, Champagne A, Chieffi A and Limongi M 2011 The effects of thermonuclear reaction rate variations on ²⁶al production in massive stars: a sensitivity study *Astrophys. J. Suppl. Ser.* **193** 16
- [242] Shamsuzzoha Basunia M 2011 Nuclear Data Sheets for A = 27 Nucl. Data Sheets 112 1875–948
- [243] Trautvetter H P and Käppeler F 1984 Destruction of ²⁶Al via the ²⁶Al(n,p)²⁶Mg-reaction Z. Phys. A 318 121-2
- [244] Trautvetter H P et al 1986 Destruction of²⁶Al in explosive nucleosynthesis. Z. Phys. A 323 1-11
- [245] Koehler P E, Kavanagh R W, Vogelaar R B, Gledenov Yu M and Popov Y P 1997 ²⁶Al(n, p₁) and (n, α_0) cross sections from thermal energy to 70 keV and the nucleosynthesis of ²⁶ Al Phys. Rev. C 56 1138-43
- [246] De Smet L, Wagemans C, Wagemans J, Heyse J and Van Gils J 2007 Experimental determination of the ${}^{26}Al(n, \alpha)$ ${}^{23}Na$ reaction cross section and calculation of the Maxwellian
- averaged cross section at stellar temperatures *Phys. Rev.* C **76** 045804 [247] Skelton R T, Kavanagh R W and Sargood D G 1987 ²⁶Mg(p,n)²⁶ al and ²³(α , n)²⁶ al reactions Phys. Rev. C 35 45-54
- [248] Lederer-Woods C et al 2021 Destruction of the cosmic γ -ray emitter ²⁶Al in massive stars: study of the key ${}^{26}Al(n, p)$ reaction Phys. Rev. C 104 L022803
- [249] Lederer-Woods C et al 2021 Destruction of the cosmic γ -ray emitter ²⁶Al in massive stars: study
- of the key 26 Al (n, α) reaction *Phys. Rev.* C **104** L032803 Benamara S *et al* 2014 Nucleosynthesis of 26 Al in massive stars: new 27 Al states above α and neutron emission thresholds *Phys. Rev.* C **89** 065805 [250]
- [251] Adsley P et al in preparation
- [252] Moss C E and Sherman J D 1976 Excitation energies of levels in ²⁷Al and ²⁸Si Nucl. Phys. A 259 413-22
- [253] Moss C E 1976 Excitation energies of levels in ²³Na, ²⁴Mg and ²⁶Mg *Nucl. Phys.* A **269** 429–42 [254] Adsley P, Laird A M and Meisel Z 2020 Status of the ²⁴Mg(*alpha*, γ)²⁸Si reaction rate at stellar temperatures Phys. Rev. C 102 015801
- [255] Chipps K A 2016 Resonances above the proton threshold in ²⁶Si Phys. Rev. C 93 035801
- [256] Richter W A, Alex Brown B, Signoracci A and Wiescher M 2011 Properties of ²⁶Mg and ²⁶Si in the sd shell model and the determination of the ${}^{25}Al(p, \gamma)$ ${}^{26}Si$ reaction rate Phys. Rev. C 83 065803
- [257] Liang P F et al 2020 Simultaneous measurement of beta -delayed proton and γ emission of ²⁶P for the ²⁵Al(p, γ)²⁶Si reaction rate *Phys. Rev.* C **101** 024305 [258] Bardayan D W *et al* 2002 Astrophysically important ²⁶Si states studied with the ²⁸Si(p, t)²⁶Si
- reaction Phys. Rev. C 65 032801
- [259] Caggiano J A, Bradfield-Smith W, Lewis R, Parker P D, Visser D W, Greene J P, Rehm K E, Bardayan D W and Champagne A E 2002 Identification of new states in ²⁶Si using the ²⁹Si(³He, ⁶ He)²⁶Si reaction and consequences for the ²⁵Al(p, γ)²⁶Si reaction rate in explosive hydrogen burning environments Phys. Rev. C 65 055801
- [260] Bell R A I, L'Ecuyer J, Gill R D, Robertson B C, Towner I S and Rose H J 1969 Excitation energies and lifetimes of levels in ²⁶Si Nucl. Phys. A 133 337-56
- [261] Parpottas Y, Grimes S M, Al-Quraishi S, Brune C R, Massey T N, Oldendick J E, Salas A and Wheeler R T 2004 Astrophysically important ²⁶Si states studied with the (³He, n) reaction and the ²⁵Al(p, γ)²⁶Si reaction rates in explosive hydrogen burning environments *Phys. Rev.* C 70 065805
- [262] Bardayan D W *et al* 2006 Astrophysically important ²⁶Si states studied with the ²⁸Si(p, t) ²⁶Si reaction. II. Spin of the 5.914-MeV ²⁶Si level and galactic ²⁶Al production *Phys. Rev.* C 74 045804
- [263] Canete L et al 2021 New constraints on the ${}^{25}Al(p, \gamma)$ reaction and its influence on the flux of
- cosmic γ rays from classical nova explosions *Phys. Rev.* C 104 L022802
 [264] Peplowski P N *et al* 2009 Lowest 1=0 proton resonance in ²⁶Si and implications for nucleosynthesis of ²⁶Al *Phys. Rev.* C 79 032801
- [265] Bennett M B et al 2013 Classical-nova contribution to the milky way's ²⁶Al abundance: exit channel of the key 25 Al (p, γ) ²⁶Si resonance *Phys. Rev. Lett.* **111** 232503

- [266] Perello J F et al 2022 Low-lying resonances in ²⁶Si relevant for the determination of the [200] Fereno J F et al 2022 Elow-lying resonances in Strenovant for the determination of the astrophysical ²⁵Al(p, γ)²⁶Si reaction rate *Phys. Rev.* C **105** 035805
 [267] Seweryniak D et al 2007 Level structure of ²⁶Si and its implications for the astrophysical reaction
- rate of 25 Al(p, γ) 26 Si Phys. Rev. C 75 062801
- [268] Komatsubara T et al 2014 Excited states above the proton threshold in ²⁶Si Eur. Phys. J. A **50** 136
- [269] Doherty D T et al 2015 Structure of resonances in the Gamow burning window for the ²⁵Al(p, γ ²⁶Si reaction in novae *Phys. Rev.* C **92** 035808
- [270] Hamill C B, Woods P J, Kahl D, Longland R, Greene J P, Marshall C, Portillo F and Setoodehnia K 2020 Study of the ${}^{25}Mg(d,p){}^{26}Mg$ reaction to constrain the ${}^{25}Al(p, \gamma){}^{26}Si$ resonant reaction rates in nova burning conditions Eur. Phys. J. A 56 36
- [271] de Séréville N et al 2011 Spectroscopic study of ²⁶Si for application to nova gamma-ray emission Proceedings of Science NIC XI 212
- [272] Timofeyuk N K, Descouvemont P and Johnson R C 2006 Relation between proton and neutron asymptotic normalization coefficients for light mirror nuclei and its relevance for nuclear astrophysics *Eur. Phys. J.* A **27** 269–76 [273] Wrede C 2009 Thermonuclear ²⁵Al(p, γ)²⁶Si reaction rate in classical novae and Galactic ²⁶Al
- Phys. Rev. C 79 035803
- [274] Cyburt R H et al 2010 the jina reaclib database: its recent updates and impact on type-i x-ray bursts Astrophys. J. Suppl. Ser. 189 240-52
- [275] Van der Zwan L and Geiger K W 1981 Cross Sections for the ${}^{25}Mg(\alpha,n){}^{28}Si$ Reaction for $E_{\alpha} < 4.8$ MeV Nucl. Sci. Eng. **79** 197–201
- [276] Anderson M R, Mitchell L W, Sevior M E and Sargood D G 1983 $^{25}Mg(\alpha,n)^{28}Si$ and $^{26}Mg(\alpha,n)^{29}Si$ as neutron sources in explosive neon burning Nucl. Phys. A 405 170–8
- [277] Wieland O 1995 Diploma Thesis
- [278] Iliadis C, Champagne A, Chieffi A and Limongi M 2011 The effects of thermonuclear reaction rate variations on ²⁶Al production in massive stars: a sensitivity study Astrophysical Journal Supplement 193 16
- [279] Tomlinson J R et al 2015 Measurement of 23 Na(alpha, p) 26 Mg at energies relevant to 26 Al production in massive stars Phys. Rev. Lett. 115 052702
- [280] Avila M L et al 2016 Experimental study of the astrophysically important ²³Na(alpha, p)²⁶Mg and ²³Na(alpha, n)²⁶Al reactions Phys. Rev. C 94 065804
- [281] Howard A M, Munch M, Fynbo H O U, Kirsebom O S, Laursen K L, Diget C A and Hubbard N J 2015 ²³Na(alpha, p)²⁶Mg reaction rate at astrophysically relevant energies Phys. Rev. Lett. 115 052701
- [282] Rauscher T, Thielemann F-K, Görres J and Wiescher M 2000 Capture of $/\alpha$ particles by isospinsymmetric nuclei *Nucl. Phys.* A **675** 695–721 [283] Hubbard N J *et al* 2021 New experimental ²³Na(α ,p) ²⁶Mg reaction rate for massive star and type
- ia supernova models Astrophys. J. 912 59
- [284] Dillmann I, Heil M, Käppeler F and Plag F K 2006 R und Thielemann. KADoNiS-the karlsruhe astrophysical database of nucleosynthesis in stars AIP Conf. Proc. 819 123
- [285] Weigmann H, Macklin R L and Harvey J A 1976 Isobaric analog impurities from neutron capture and transmission by magnesium Phys. Rev. C 14 1328-35
- [286] Massimi C et al 2012 Resonance neutron-capture cross sections of stable magnesium isotopes
- and their astrophysical implications *Phys. Rev.* C 85 044615
 [287] Massimi C *et al* 2017 Neutron spectroscopy of ²⁶Mg states: constraining the stellar neutron source ²²Ne(α, n)²⁵Mg *Phys. Lett.* B 768 1–6
- [288] Koning A J, Rochman D, Sublet J-C, Dzysiuk N, Fleming M and van der Marck S 2019 Tendl: complete nuclear data library for innovative nuclear science and technology Nucl. Data Sheets 155 1-55
- [289] Mengoni A, Otsuka T and Ishihara M 1995 Direct radiative capture of p-wave neutrons Phys. Rev. C 52 R2334-8
- [290] Reifarth R, Fiebiger S, Göbel K, Heftrich T, Kausch T, Köppchen C, Kurtulgil D, Langer C, Thomas B and Weigand M 2018 Treatment of isomers in nucleosynthesis codes Int. J. Mod. Phys. A 33 1843011
- [291] Coc A, Porquet M-G and Nowacki F 1999 Lifetimes of ²⁶Al and ³⁴Cl in an astrophysical plasma Phys. Rev. C 61 015801