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Letter

Revised decay properties of the key 93-keV resonance in the ^{25}Mg(p, γ) reaction and its influence on the MgAl cycle in astrophysical environments

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The γ-decay properties of an excited state in ^{26}Al at 6398.3(8) keV have been reexamined using the ^{11}B + ^{16}O fusion-evaporation reaction. This level represents a key 93.1(8)-keV resonance in the ^{25}Mg +p system and its relative branching to the ^{26}Al ground state, f_0, has been determined to be 0.76 ± 0.03 (stat.) ±0.10 (syst.). This is a significantly higher value than the most recent evaluation and implies a considerable increase in the production of cosmic γ rays from ^{26}Al radioactivity.

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The nucleosynthesis in the MgAl region is activated in several astrophysical scenarios, such as massive stars, asymptotic giant branch (AGB) stars, and classical novae [1–3]. This process defines the overall abundance of Mg and Al in our galaxy and, therefore, is expected to have a profound effect on a wide range of astronomical observables. In particular, variations in Mg-Al anticorrelations observed in globular clusters (GCs) are likely to be directly linked to the nucleosynthesis in the MgAl region. These variations indicate the existence of multiple populations of stars in GCs [4,5] and a detailed understanding of the nucleosynthesis may help to constrain the origin of this phenomenon—one of the most intriguing and open issues in stellar astrophysics.

In this regard, the abundance of the radioactive nucleus ^{26}Al in different stellar scenarios may provide unique insight. This relatively long-lived unstable isotope ($t_{1/2} = 7.2 \times 10^5$ yr) has been observed throughout the galaxy via its characteristic 1.809-MeV decay γ ray [6], and measurements by the COMPTEL and INTEGRAL satellite missions point to massive stars as being the likely source [7,8]. However, extinct ^{26}Al has also been inferred from large ^{26}Mg/^{24}Mg isotopic anomalies in primitive meteorites [9,10] and presolar grains [11], which, in turn, indicate that additional astrophysical production sites, such as AGB stars and classical novae, contribute to the overall galactic abundance. Consequently, it is important to obtain a detailed understanding of the ^{26}Al nucleosynthesis process in all of these environments.

A key difficulty in modeling ^{26}Al stellar nucleosynthesis relates to the existence of an isomer, ^{26m}Al ($t_{1/2} = 6.3$ s), located 228.305(13) keV [12] above the ground state, ^{26g}Al, that exhibits a superallowed β^+ decay directly to the ^{26}Mg ground state, bypassing emission of the characteristic 1.809-MeV γ ray. Moreover, at temperatures <0.15 GK, relevant for massive and AGB stars, the ground and isomeric levels of ^{26}Al are not in thermal equilibrium and, as such, must be entered into nuclear reaction networks as separate species [13]. Thus, it is essential to determine the population of ^{26g}Al, relative to that of ^{26m}Al, during the nucleosynthesis, in order to interpret the astronomical observations.

The production of ^{26}Al in astrophysical environments is expected to be governed by the ^{25}Mg(p, γ)^{26}Al reaction. This reaction is dominated by resonant capture to excited states located above the proton-emission threshold energy of 6306.33(6) keV in ^{26}Al [14]. Over the temperature range $T \sim 0.07$–0.15 GK, the rate is almost entirely determined by a single state at $E_x = 6398.3(8)$ keV [$E_r = 93.1(8)$ keV—corrected for nuclear mass differences [15]]. A previous direct measurement of the ^{25}Mg(p, γ) reaction at the LUNA underground laboratory [16] reported a resonance strength of $\omega\gamma = 2.9(6) \times 10^{-10}$ eV for the 93-keV level and a ground-state branching fraction, f_0, which is also an important input parameter for the stellar reaction rate, of $0.6^{+0.2}_{-0.1}$. However, the latter was based on simulations of BGO summing data and was lower than an earlier value of 0.80 ± 0.15 obtained in a ^{24}Mg(^{3}He, p) study [17]. More recently, Kankainen *et al.* performed a high-resolution γ-ray spectroscopy study of the 93-keV resonance using the Gammasphere array [18]. In that

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work [18], the ^{24}Mg(^{3}He, p) light-ion fusion reaction was used to populate proton-unbound levels in ^{26}Al and four γ-decay branches from the 93-keV resonance were observed at 1256.4(13), 3238.7(20), 4326.9(20), and 4638.0(21) keV, respectively. An angular distribution analysis of the 3239- and 4327-keV γ rays indicated a 2^- spin-parity assignment for the 93-keV resonance and the observed γ-ray intensities established a ground-state branching fraction of $f_0 = 0.52 \pm 0.02(\text{stat.}) \pm 0.06(\text{syst.})$ [18]. Intriguingly, in Ref. [18], the 4327-keV γ ray, which decays to the 2_2^+ state in ^{26}Al and strongly feeds the isomeric level, was found to represent the most intense decay branch of the 93-keV resonance—it is largely due to this fact that Kankainen *et al.* obtained a f_0 value at the lower end of all previously adopted values [16,17,19,20].

Here, a ~5 pnA, 19-MeV beam of ^{16}O ions, delivered by the Argonne ATLAS accelerator, was used to bombard a ~300 μg/cm^2-thick target of ^{11}B for ~100 hr, in order to populate excited states in ^{26}Al via the one-neutron evaporation channel. The resulting γ-ray transitions were detected using the Gammasphere array [21,22] which, in this instance, consisted of 99 detectors operated in stand-alone mode. Data were sorted offline and both γ-γ and γ-γ-γ coincidence histograms were used to determine the properties of excited states in ^{26}Al. In particular, we find that the intensity of the γ-ray branch to the 2_2^+ excited state in ^{26}Al is markedly smaller than previously reported [18], leading to a significant increase in the ground state branching fraction of $f_0 = 0.76 \pm 0.03(\text{stat.}) \pm 0.10(\text{syst.})$. Energy and efficiency calibrations were obtained using standard ^{152}Eu and ^{56}Co sources, as well as a high-energy 6.129-MeV γ ray in ^{16}O. For strong transitions, an angular distribution analysis was performed by fitting γ-ray intensities as a function of detection angle with respect to the beam axis with the customary function $W(\theta) = A_0[1 + a_2P_2(\cos\theta) + a_4P_4(\cos\theta)]$. Finally, to test our methodology for obtaining accurate γ-ray branching ratios for excited states in ^{26}Al, the decay of the well-known 3159.89(1)-keV, 2_3^+ level [12] was investigated. In the current study, this level is observed to decay via 615-, 1088-, 1401-, 2102-, and 2743-keV γ rays to the 3_3^+, 1_3^+, 2_1^+, 1_1^+, and 3_1^+ excited levels in ^{26}Al, respectively. These transitions have been previously reported to represent branches of 1.40(5)%, 2.70(8)%, 14.7(4)%, 16.4(5)%, and 63.7(7)% [12]. In the present work, values of 2.31(3)%, 1.47(2)%, 11.1(1)%, 19.2(2)%, and 65.9(1)%, respectively, were obtained in agreement with the general trend of earlier compilation data [12]. Based on differences between observed ratios and previously reported values [12], as a weighted mean of overall branches, we estimate a ~13% systematic uncertainty in the extraction of branching ratios using the current methodology.

Table I presents a complete list of observed γ transitions de-exciting proton-unbound states in ^{26}Al while γ-γ and γ-γ-γ coincidence spectra of direct relevance for the decay of the 93-keV resonance in the ^{25}Mg(p, γ) reaction are displayed in Fig. 1. As can be seen in Fig. 1(a), a γ transition to the 2069-keV level in ^{26}Al is observed at 4327.7(10) keV. The energy of this γ ray is well matched to the previous value reported in Ref. [18] and indicates an excited state in ^{26}Al at 6398.3(8) keV, corresponding to a 93.1(8)-keV resonance in the ^{25}Mg$+p$ system. In addition, an angular distribution analysis of the 4328-keV transition, illustrated in Fig. 2, reveals a_2 and a_4 coefficients consistent with the 2^- assignment proposed in Ref. [18]. However, the presently observed intensity of the 4328-keV transition is significantly weaker than that of Ref. [18]. Furthermore, a triple coincidence spectrum, with gates placed on the 417- and 2743-keV γ rays in ^{26}Al, shown in Fig. 1(c), highlights an additional 3238.7(3)-keV

TABLE I. Observed γ decays from proton-unbound excited states in ^{26}Al. Excitation energies are adopted from Ref. [12].

E_x [keV]	E_γ [keV]	a_2/a_4	J^π	E_r [keV]
6343	1212		(4)	38
	1638			
	1744	−0.34(6)/0.08(8)		
	2151			
	2747			
	3798			
	3978			
6364	2158		3^+	59
	2613			
	3818			
	3999	0.32(11)/0.20(14)		
	4295			
	4605			
	5946			
6398	1256		2^-	93
	3239	0.34(15)/ − 0.03(17)		
	4328	0.50(11)/ − 0.04(14)		
	4638			
6414	5356		$(0-2)^+$	109
6436	1304		$(3, 5^+)$	131
	1731			
	6018	0.29(6)/ − 0.33(9)		
6496	1790		$(3, 5^+)$	191
	4130	0.22(6)/ − 0.16(9)		
6551	1848		$(4^+, 5^-)$	246
	2876			
6598	1894	−0.36(11)/0.21(14)	5^+	293
	4053			
	4235			
6610	2418			
	3450			
	4851	−0.49(16)/−0.05(21)	3^-	305
	6193	0.18(4)/0.10(5)		
6695	3187		7	390
	3290			
6801	5042		3^+	496
	5743	0.34(8)/ − 0.07(10)		
6818	3143		4^+	513
	4273	−0.49(8)/0.05(8)		
	4453			
	4749	0.13(20)/0.38(24)		
	6401			
6874	4329		1^+	569
6875	4806	0.39(7)/0.11(11)	2^+	570
	6459			

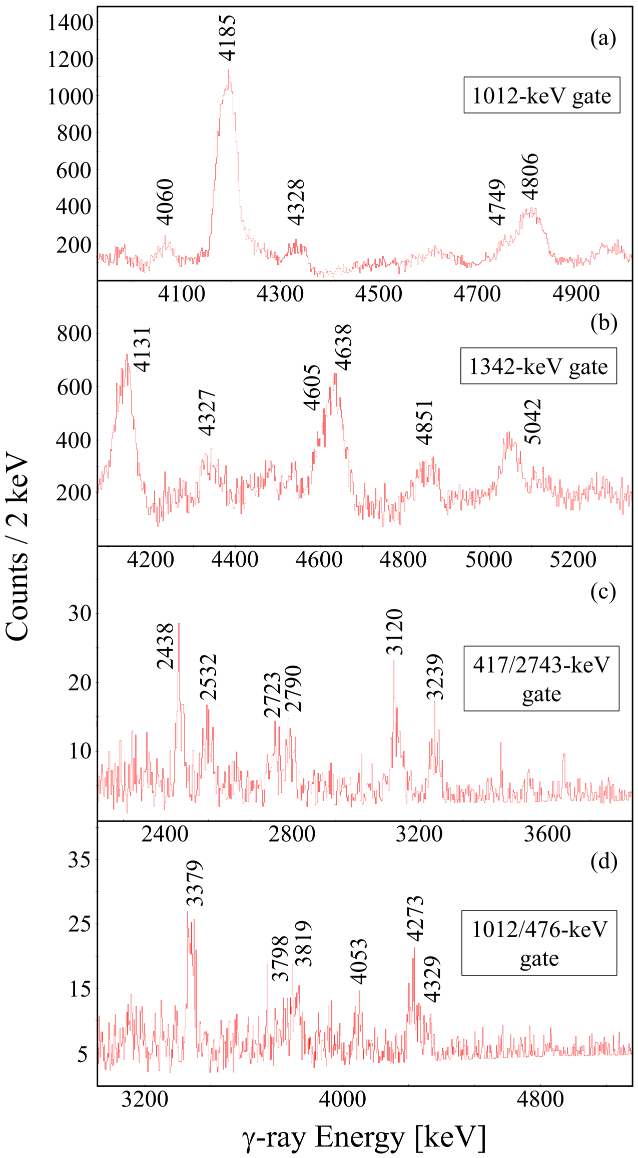

FIG. 1. (a) γ-γ coincidence spectrum with a gate placed on the 1012-keV transition from the 2^+, 2069-keV level in ^{26}Al. (b) γ-γ coincidence spectrum with a gate placed on the 1342-keV transition from the 2^+, 1759-keV level in ^{26}Al. (c) γ-γ-γ spectrum with gates placed on the 2743- and 417-keV transitions showing coincidences with the 2^+, 3160-keV level in ^{26}Al. (d) γ-γ-γ spectrum with gates placed on the 476- and 1012-keV transitions showing coincidences with the 3^+, 2545-keV level in ^{26}Al.

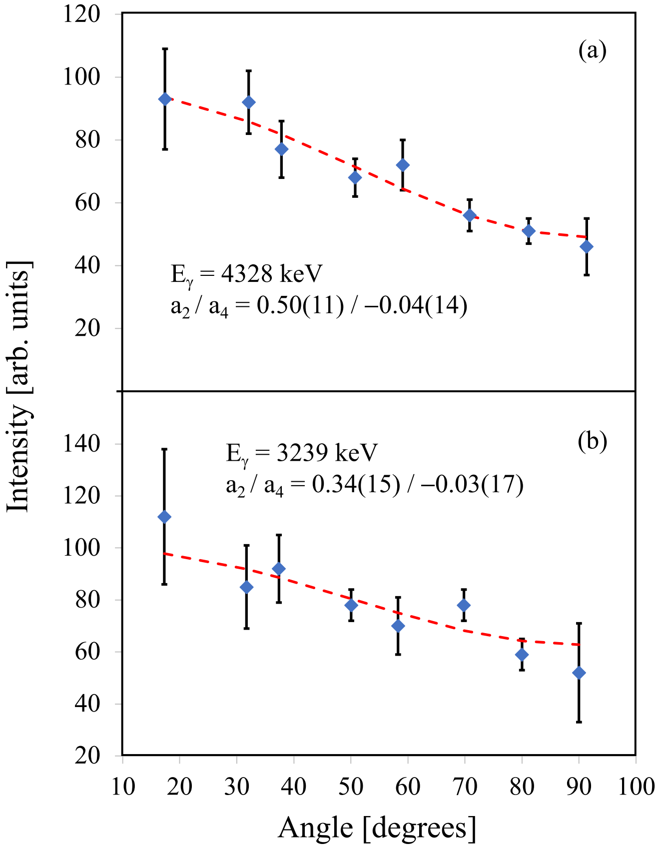

FIG. 2. Observed angular distributions of (a) the 4330-keV transition and (b) 3239-keV γ decay from the 93-keV resonance in the ^{25}Mg$+p$ system. The measured angular distributions are consistent with a 2^- spin-parity assignment for the 93-keV resonant state.

branch from the 6398-keV level as being the strongest primary decay transition, in disagreement with Ref. [18]. A plausible explanation for this discrepancy is that the 1012-keV coincidence gate in Ref. [18] appears to be strongly fed by the higher-lying 3^+, 2545-keV level. This is in contrast to the current work, as can be seen by comparing Fig. 1(a) given here with Fig. 3(a) of Ref. [18]. Exploring this matter further, we find a nearly degenerate 4329-keV decay, from a known 1^+, 6874-keV level in ^{26}Al [12], to the 2545-keV excited state, as highlighted in Fig. 1(d). Given the intensity of the neighboring 4273-keV γ ray, also seen in Fig. 1(d), in the 1012-keV coincidence spectrum of Ref. [18], we conclude that the extracted intensity of the 4328-keV transition in that work [18] was likely contaminated by the newly reported 4329-keV line, as illustrated in Fig. 3. This is particularly unfortunate, as the angular distributions of γ decays from the 1^+, 6874-keV and 2^-, 6398-keV levels to the 3^+, 2545-keV and 2^+, 2069-keV levels, respectively, would be almost indistinguishable.

A summary of the presently observed γ de-excitation paths from the 93-keV resonance in ^{26}Al, together with their relative branching ratios, is given in Table II. The extracted branching ratios have been combined with known decay properties of lower-lying states in ^{26}Al [12] in order to deduce a ground-state branching fraction, f_0, of 0.76 ± 0.03. The error quoted here is purely statistical, and we note that the authors of Ref. [18] estimate an additional systematic uncertainty of ± 0.06, due to unobserved weak decay branches. However, based on a comparison between previous and present branching ratios for the known 3160-keV excited state in ^{26}Al [12], we estimate a slightly higher systematic uncertainty of ± 0.10 for the present f_0 value. This leads to an expected overall ground-state branching fraction of $f_0 = 0.76 \pm 0.03(\text{stat.}) \pm 0.10(\text{syst.})$. Finally, although outside the scope of the present study, we note, for completeness, that the current data indicate a similar f_0 value for the nearby 59-keV resonant state in

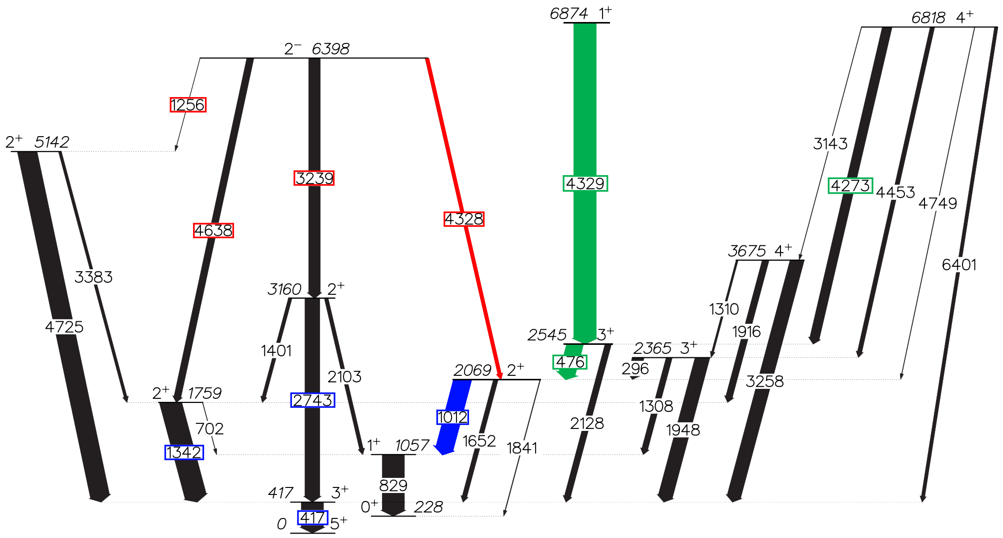

FIG. 3. Partial level scheme of ^{26}Al. The transition energies in color refer to: (red) primary decays of the 6398-keV level; (blue) Gating transitions in the present study; (green) side-feeding (contaminant) transitions. The colored arrows mark the key transitions impacting the present revision of the ground state branching ratio: notice that the contaminant 4329-keV transition (green), shown here in Fig. 1(d), has almost the same energy as the 4328-keV primary transition (red). A significant population of the 6874-keV level will therefore contaminate the peak near 4328 keV that is observed in the coincidence spectrum gated on the 1012-keV transition (blue), as can be seen in Fig. 3(a) of Ref. [18].

the ^{25}Mg $+p$ system of $0.75 \pm 0.03(\text{stat.}) \pm 0.10(\text{syst.})$. Our results agree with previously reported values of 0.81 [23] and 0.75 [17,19,20].

In order to accurately estimate the contribution of specific astrophysical environments to the observed galactic abundance of ^{26}Al cosmic γ rays, it is necessary to multiply the strengths of resonances in the ^{25}Mg(p,γ) reaction by their respective ground-state branching fractions, f_0. In the case of massive stars and AGB stars, the 93-keV resonance is expected to play a critical role in determining the production rate of ^{26}Al. A previous direct measurement of this resonance established a strength of $2.9(6) \times 10^{-10}$ eV [16] and the most recent γ-ray spectroscopy study reported an f_0 value of 0.52(6) [18]—the uncertainty quoted here is the quadrature sum of the statistical and systematic uncertainties. Our newly obtained value, $f_0 = 0.76(10)$, is 46% higher than that of Ref. [18]. This would imply a more efficient production of the cosmic γ-ray emitting ground state of ^{26}Al in the H-burning regions of massive stars and AGB stars than previously expected [24] and, therefore, a greater contribution of such environments to the overall galactic abundance of ^{26}Al.

On the other hand, our present angular distribution measurements of γ-decay transitions from the 93-keV resonance match those reported in Ref. [18] well. Hence, our current study confirms a spin-parity assignment of 2^- for this state. In this regard, previous indirect investigations of the astrophysical ^{25}Mg(p,γ) reaction have also determined strengths for the 93-keV resonance of 1.16×10^{-10} eV [25] and 2.2×10^{-10} eV [26], based on a 2^- assignment, in good agreement with the direct measurement of Ref. [16].

In summary, the present γ-ray spectroscopy study of the astrophysically important nucleus ^{26}Al has obtained new information on the γ-decay properties of the 93-keV resonance in the ^{25}Mg(p,γ) reaction. In particular, evidence is presented for a revision of the ground-state branching fraction of this state in comparison to the most recent value of Ref. [18]. Further constraints on the branching fraction could be made by a new measurement of the ^{25}Mg$(^3$He$,d)^{26}$Al reaction in normal kinematics, incorporating a high-resolution γ-ray array. This reaction is known to populate the key resonant state of interest, and would provide a definitive measure of the γ-decay branching ratios, independent of γ-γ coincidence relationships.

TABLE II. γ-decay properties of the 93-keV resonance in the ^{25}Mg(p,γ) reaction.

E_x [keV]	E_r [keV]	J^π	E_γ [keV]	b (%) [a]	E_f [keV] [12]	$b_{\text{g.s.}}$ (%) [b]	$\omega\gamma$ (eV) [16]
6398.3(8)	93.0(8)	2^-	1256.0(30)	1.12(39)	5141.68(6)	93.8(32)	$2.9(6) \times 10^{-10}$
			3238.7(3)	54.3(11)	3159.899(13)	79.2(11)	
			4327.7(10)	15.4(4)	2069.47(3)	21.6(9)	
			4638.3(15)	29.1(12)	1759.034(8)	98.00(17)	

[a] Primary branching ratios for decays from the 6398-keV state.
[b] Secondary branching ratios to the ^{26}Al ground state [18].

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