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STUDY OF INTERMEDIATE-SPIN STATES OF ^{98}Y*

M. Ramdhane[a], G.S. Simpson[a], F. Drouet[a], T. Malkiewicz[a]
A. Vancraeyenest[a], G. Gey[a], P. Alexa[b], G. Thiamova[a]
G. Kessedjian[a], C. Sage[a], T. Grahn[c], P.T. Greenlees[c]
K. Hauschild[c], A. Herzan[c], U. Jakobsson[c], P. Jones[c], R. Julin[c]
S. Juutinen[c], S. Ketelhut[c], A. Lopez-Martens[c], P. Nieminen[c]
P. Peura[c], P. Rahkila[c], S. Rinta-Antila[c], P. Ruotsalainen[c]
M. Sandzelius[c], J. Saren[c], C. Scholey[c], J. Sorri[c], J. Uusitalo[c]

[a]Laboratoire de Physique Subatomique et de Cosmologie
Université Joseph Fourier Grenoble, CNRS/IN2P3, Grenoble INP
53 rue des Martyrs, 38026 Grenoble Cedex, France
[b]Institute of Physics and Institute of Clean Technologies
VŠB — Technical University of Ostrava, 708 33, Ostrava, Czech Republic
[c]Department of Physics, PB 35, 40014 University of Jyväskylä, Finland

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The nuclear structure of the odd–odd nucleus ^{98}Y has been re-investigated by observing prompt γ rays emitted following the proton-induced fission of a ^{238}U target, using the JUROGAM-II multidetector array. New high-spin decays have been observed and placed in the level schemes using triple coincidences. The experimental level energies and γ-decay patterns are compared to GICM and QPRM calculations, assuming that this neutron-rich $N = 59$ isotone is spherical at low energies and prolate deformed at intermediate spins.

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1. Introduction

Nuclear shape evolution is now a highly topical issue in nuclear physics [1–3]. Especially interesting are those situations where nuclear structure and shapes change suddenly between neighboring nuclides. These effects are well-known in the neutron-rich isotopes with masses $A \sim 100$ [4, 5]. Several experimental [6–8] and theoretical [4, 5, 9, 10] studies are ongoing to better characterize the structural evolution of the ground and excited

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states in this mass region. The neutron-rich odd–odd ^{98}Y ($N = 39$, $Z = 59$) nucleus is of particular interest owing to its position on the border of a ground-state shape change. The spherical $N = 56$ subshell closure is still effective in ^{97}Y ($N = 58$) [11] while, with only two more neutrons, ^{99}Y ($N = 60$) has a strongly deformed ground state [12–14]. Shape coexistence in ^{98}Y has been reported. The spherical nature of the low-lying levels was proposed in a study of the β decay of ^{98}Sr to ^{98}Y [1] and was confirmed by calculations using the interacting-boson–fermion–fermion model (IBFFM) framework [15]. It was shown that levels of ^{98}Y below 500 keV could be described by coupling the $\pi p_{1/2}$ orbit to the lowest-lying spherical neutron levels of the neighboring isotones ($N = 59$) ^{97}Sr and ^{97}Zr. The best evidence for excited deformed states is a rather regular rotational band, with a band-head at 496 keV. This was among the very first rotational bands observed in this region [16]. The interpretation of deformed levels in ^{98}Y has long remained speculative due to the poor knowledge of the experimental levels. Only recently, significant progress has been achieved, mostly due to isomer and prompt-fission experiments.

2. Experimental procedure

Neutron-rich nuclei with $A \sim 100$ were produced via the proton-induced fission of a 74 mg/cm^2 thick ^{238}U target, giving an estimated fission rate of around 10^5 fission/s. The proton beam was delivered by the K130 cyclotron of the Accelerator Laboratory of the University of Jyväskylä (JYFL) with an energy of 25 MeV and an intensity of 0.1 pnA. The JUROGAM-II multidetector array, composed of 24 Clovers and 15 single-crystal Ge detectors, was used to detect prompt γ rays. The acquisition system was run in a total-data-readout mode. Event building and data sorting were done off-line using the GRAIN software package [17]. The detection of three, or more, unsuppressed Ge detector signals in a 150 ns time window was used to define an event. Events were sorted in to a three-dimensional cube, which was built and analyzed using the Radware software package. Since more than one hundred of nuclei are produced in this fission reaction, then a γ–γ–γ triple coincidence analysis is necessary to select transitions in a given nucleus. Level schemes can be extended by setting gates on known transitions in a nucleus and observing coincidence relations. The assignment of transitions to a particular nucleus can also be performed by setting gates on the most likely fission fragment partner, knowing that no protons and, on average, ~ 6 neutrons are evaporated by this fissioning system.

3. Experimental results

Previous studies have reported the level scheme of ^{98}Y up to spin 10^- [18]. In order to expand the level scheme, different combinations and sums of gates were set on the known transitions of this nucleus. An example spectrum made using two different double gates is shown in Fig. 1. It can be seen in the spectrum that the most intense transitions of ^{98}Y are present along with several ones belonging to the complementary Xe nuclei, as well as uranium X rays originating from protons interacting with ^{238}U target.

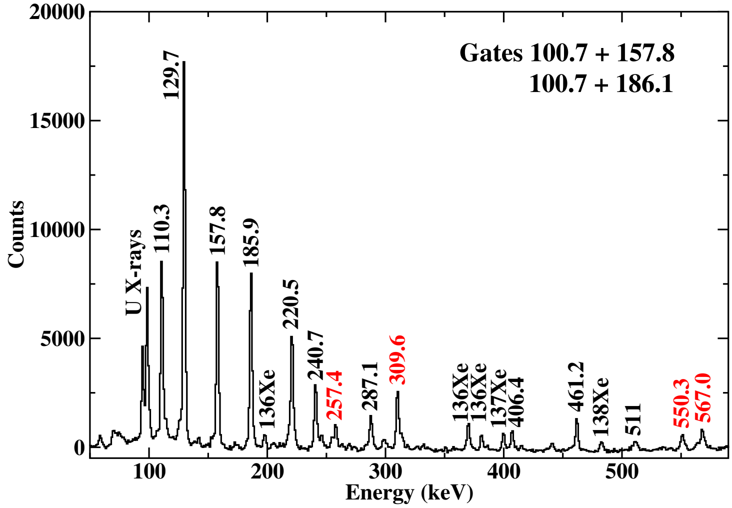

Fig. 1. (Color online) A summed γ-ray spectrum of prompt transitions in ^{98}Y, obtained by setting double gates on the 100.7 keV γ-ray along with the 157.9, and 186.1 keV decays. Four new transitions are present and are marked in gray (red).

Four new transitions were observed and were then placed in the level scheme based on their observed coincidence relations and relative intensities. These transitions have been determined to belong to the nucleus ^{98}Y with many checks made in order to eliminate the possibility that either they belong to Xe complementary fission partner nuclei, or that they belong to a contaminant with similar transition energies. These new transitions have energies of 257.4, 309.6, 550.3, and 567.0 keV and allow the rotational band based on the 4^- isomer to be extended.

The energies of the excited states of ^{98}Y are plotted against $J(J+1)$ in Fig. 2. Here, one can clearly see that the new (11^-) and (12^-) levels, marked in gray (red), lie close to a straight line drawn through the established rotational sequence. It is also clear from this plot that both the low-spin states and the 10^- isomer [18] are far from the line. The presence of the

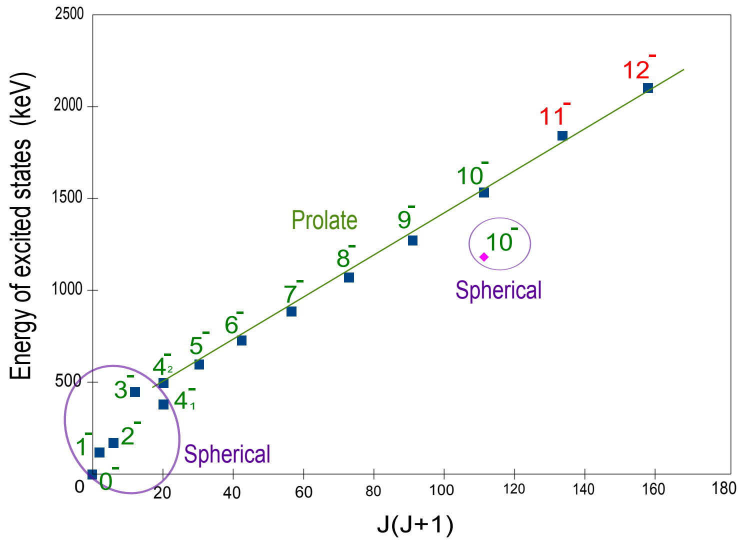

Fig. 2. Plot of experimental level energy *versus* $J(J+1)$.

10^- isomer, and any states on top of it do not perturb the energies of the $J \geq 10^-$ members of 4^- rotational band. This is in agreement with the previous spherical $[\pi g_{9/2} \nu h_{11/2}]_{10^-}$ assignment for the 10^- isomer [18].

4. Discussion

The experimental results were compared to theoretical calculations performed with two types of collective models, the Generalized Intermediate Coupling Model (GICM) [19] and the Quasi-Particle Rotor Model (QPRM) [20]. These are shown in Fig. 3. Within the GICM, the nucleus ^{98}Y is modeled as a system of two odd nucleons coupled to a vibrating ^{96}Sr even–even core. The configurations of the odd neutron and proton are the same as that used in Ref. [18]. The comparison of calculations and data shows that the states of spins 0^-, 1^-, 2^-, 4_1^-, 3^- are in a good agreement with experimental results, since they differ by not more than 100 keV. However, at higher spins and, therefore, at higher excitation energies, the calculated excitation energies are well above the experimental ones. We notice the presence of predicted spherical 4_2^-, $5_{1,2}^-$ and 6_1^- states which cannot be assigned to any experimental states.

The QPRM calculations are presented on the right part of Fig. 3. In this calculation, intrinsic states result from the inclusion of four types of interactions simultaneously: the average Nilsson field, the pairing and quadrupole–quadrupole residual interactions and a recoil term. The Coriolis force must

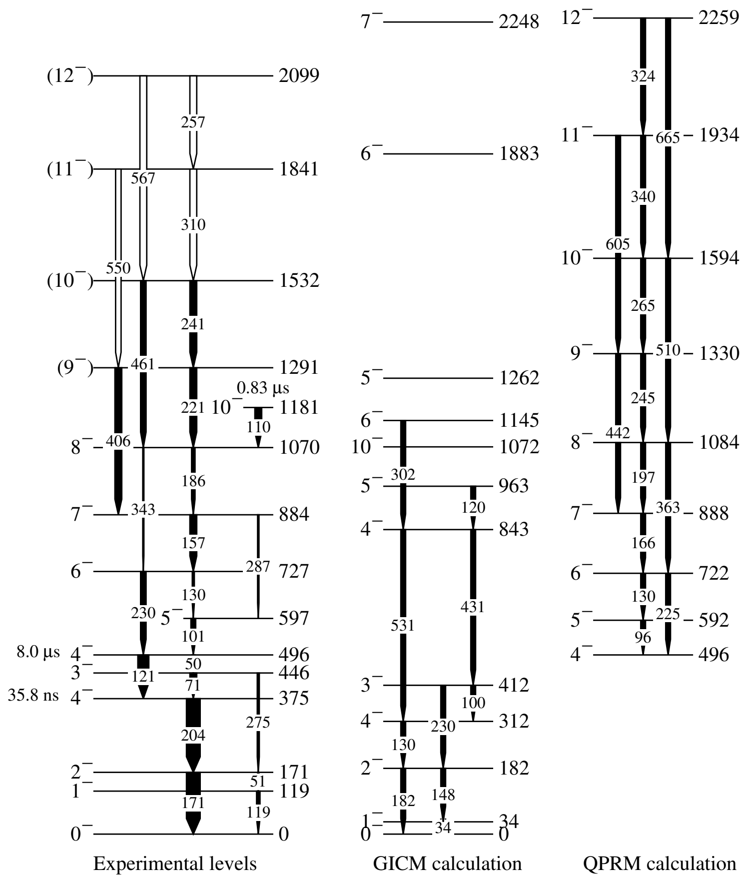

Fig. 3. Experimental and calculated level schemes of ^{98}Y.

be added in order to reproduce the spectrum of excited states. The energy levels of the rotational band and its staggering are fairly well-reproduced using a quadrupole deformation parameter $\epsilon_2 = 0.32$ and a Coriolis attenuation factor of 0.55. The $J^\pi = 4_2^-$ to 10^- members of the rotational band are predicted to have $\pi 5/2^+[422] \times \nu 3/2^-[541]$ two-quasiparticle components, in agreement with the results of the IBFFM calculation [18]. For members of the band with spin higher than $J^\pi = 10^-$, the configuration of the band is different, the dominant two-quasiparticle component being $\pi 5/2^+[422] \times \nu 1/2^-[550]$.

5. Conclusion

The rotational band of ^{98}Y has been extended up to spin $J^{\pi} = (12^{-})$ by the prompt γ-ray spectroscopy of fission fragments produced by the proton-induced fission of a ^{238}U target. The energies of low-spin states below 500 keV are well-reproduced in GICM calculation, and excited states with energies above 500 keV are correctly predicted by QPRM calculations. The members of the rotational band with spins $\geq 10^{-}$ are not perturbed by the presence of a 10^{-} μs isomer, in agreement with the proposed spherical nature of this state.

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