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Decay of the key 92-keV resonance in the ^{25}Mg(p,γ) reaction to the ground and isomeric states of the cosmic γ-ray emitter ^{26}Al

A. Kankainen[a,b,*], P.J. Woods[a], D.T. Doherty[a,c], H.M. Albers[d,1], M. Albers[d], A.D. Ayangeakaa[e,f], M.P. Carpenter[d], C.J. Chiara[d,g,2], J.L. Harker[d,g], R.V.F. Janssens[e,f], C. Lederer-Woods[a], D. Seweryniak[d], F. Strieder[h], S. Zhu[d,i]

[a] University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
[b] University of Jyvaskyla, P.O. Box 35, FI-40014 University of Jyvaskyla, Finland
[c] University of Surrey, Guildford GU2 7XH, United Kingdom
[d] Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA
[e] Department of Physics and Astronomy, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599-3255, USA
[f] Triangle Universities Nuclear Laboratory, Duke University, Durham, NC 27708-2308, USA
[g] Department of Chemistry and Biochemistry, University of Maryland, College Park, MD 20742, USA
[h] South Dakota School of Mines & Technology, Department of Physics, Rapid City, SD 57701, USA
[i] National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY 11973, USA

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ABSTRACT

The 92-keV resonance in the ^{25}Mg$(p,\gamma)^{26}$Al reaction plays a key role in the production of ^{26}Al at astrophysical burning temperatures of ≈100 MK in the Mg-Al cycle. However, the state can decay to feed either the ground, ^{26g}Al, or isomeric state, ^{26m}Al. It is the ground state that is critical as the source of cosmic γ rays. It is therefore important to precisely determine the ground-state branching fraction f_0 of this resonance. Here we report on the identification of four γ-ray transitions from the 92-keV resonance, and determine the spin of the state and its ground-state branching fraction $f_0 = 0.52(2)_{stat}(6)_{syst}$. The f_0 value is the most precise reported to date, and at the lower end of the range of previously adopted values, implying a lower production rate of ^{26g}Al and its cosmic 1809-keV γ rays.

The Mg-Al hydrogen-burning reaction cycle shown in Fig. 1 is triggered at temperatures above $T \approx 30$ MK. These conditions prevail in hydrogen-burning convective cores of massive main-sequence stars [1,2]. Studies by the INTEGRAL satellite mission have demonstrated that such massive stars are most likely the main source of the cosmic γ-ray emitter ^{26}Al, which is injected into the interstellar medium either from stellar winds in the quiescent burning phase, or by explosive burning in core collapse supernovae [3]. The Mg-Al cycle also occurs, at much higher temperatures $(0.1 - 0.4$ GK), in novae, which contribute to the budget of ^{26}Al material. Extinct ^{26}Al is evident in high ^{26}Mg/^{24}Mg isotopic abundance ratios found in carbonaceous chondrites [4] and presolar grains [5].

^{26}Al has a long-lived ground-state ($T_{1/2} = 0.7$ My) with a spin-parity $J^{\pi} = 5^+$, and a short-lived ($T_{1/2} = 6.35$ s) 0^+ isomeric state at 228 keV. At high temperatures the effective lifetime of ^{26}Al in the stellar plasma can be reduced significantly by thermal communication between the two states [6–8]. At temperatures below 0.4 GK, however, the thermal equilibrium is not established and the two states operate effectively as separate nuclear species in the reaction network [9]. The ground-state β-decay of ^{26}Al feeds dominantly the first excited state of ^{26}Mg, which de-excites and produces the 1.8-MeV γ-ray flux observed in satellite missions such as INTEGRAL. The superallowed Fermi β-decay of the isomeric state ^{26m}Al, on the contrary, feeds ≈100% the ground state of ^{26}Mg and does not contribute to the observed flux. When considering the astrophysical production of ^{26}Al, it is therefore critically important to know the fraction of the reaction yield that populates the ground state, known as the ground-state branching fraction f_0.

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[*] Corresponding author at: University of Jyvaskyla, P.O. Box 35, FI-40014 University of Jyvaskyla, Finland.
E-mail address: anu.kankainen@jyu.fi (A. Kankainen).

[1] Present address: GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany.

[2] Present address: U.S. Army Research Laboratory, Adelphi, Maryland 20783, USA.

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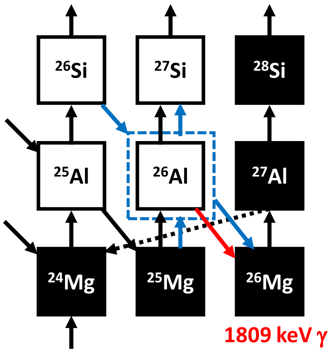

Fig. 1. The Mg-Al hydrogen-burning reaction cycle. The arrows indicate the reaction flow via proton captures and β-decays. The 1809-keV γ ray follows the β-decay of the ^{26}Al ground state ($J^{\pi}=5^{+}$, $T_{1/2}=0.7$ My) highlighted in red. The bypass routes related to ^{26m}Al ($J^{\pi}=0^{+}$, $T_{1/2}=6.35$ s) are shown in blue. The black squares indicate stable isotopes and β-unstable nuclei are shown in white.

The ^{25}Mg$(p,\gamma)^{26}$Al reaction plays the main role in the production of ^{26}Al in the Mg-Al cycle, and more generally, in determining the relative abundance of Mg/Al [10]. Considerable experimental efforts have gone into determining the ^{25}Mg$(p,\gamma)^{26}$Al reaction rate at low astrophysical energies where reactions on individual resonances play the dominant role (see Ref. [11] for a recent example and references therein). In the critical temperature region ≈100 MK, the rate is almost entirely dominated by a single resonance at 92 keV, corresponding to an excitation energy of 6399 keV in ^{26}Al. Underground measurements of the ^{25}Mg$(p,\gamma)^{26}$Al reaction performed by the LUNA collaboration at Gran Sasso have reported a first resonance strength value for this state [12]. However, Strieder et al. [12] comment that the ‘ground-state branching fraction is an important input parameter for the reaction rate’ (for the 92-keV resonance), but ‘available literature information’ is ‘contradictory’ (see Ref. [12] for a more detailed discussion). In fact, no γ-decay branches are listed for the 6399-keV excited state in the most recent data compilation [13]. Endt and Rolfs analyzed in detail spin-parity assignments of states near the proton threshold energy of ^{26}Al relevant for the ^{25}Mg$(p,\gamma)^{26}$Al reaction and assigned 2^{-} to the 6399-keV state [10]. This assignment is also given in the compilation of Endt [14]. The more recent ^{26}Al data compilation [13] also allows $J^{\pi}=1^{+}$ as a possibility. In the present paper, measurements of four γ-decay branches from the 6399-keV state are reported for the first time. These are used to derive the ground-state branching fraction and assign the spin of the resonance.

The experiment was performed using the ATLAS accelerator facility at Argonne National Laboratory. A 10-MeV ^{3}He beam was used to bombard an ≈ 840 μg/cm^{2}- thick ^{24}Mg target for approximately three days producing ^{26}Al nuclei via the single proton evaporation channel. De-excitation γ-rays were detected with the Gammasphere detector array, which has a near spherical geometry [15,16]. Energy and efficiency calibrations were performed with the standard ^{152}Eu and ^{60}Co calibration sources. In order to improve the energy calibration at the highest energies, an additional 6.129-MeV line in ^{16}O, from the ^{13}C$(\alpha,n)^{16}$O reaction, was also used. The trigger on Gammasphere was set to accept $\gamma-\gamma$ coincidence data. Fig. 2 presents the γ-decay level scheme showing the four identified γ-ray transitions from the 6399-keV state in ^{26}Al, and their connection to known lower-lying states in ^{26}Al [13]. Fig. 3 shows the γ-ray energy spectra including these four transitions obtained by gating on known lower-lying transitions. Transitions from other known levels near or above the proton threshold in ^{26}Al are also indicated in these spectra. We note that in Figs. 3(b) and (c), the peak including the transition from the 6399-keV state is too broad to be fitted as a single peak. The peak widths were fixed from the isolated single peaks in the same energy region. The double-peak fit yields a better agreement with the data, and is also required to match the known 4604.5-keV transition from the 6364-keV state in Fig. 3(b).

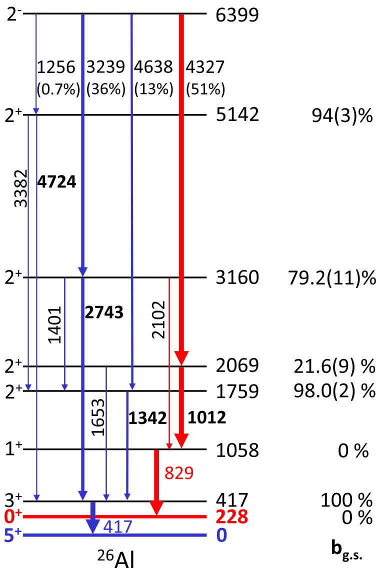

Fig. 2. γ-ray transitions and their branchings observed from the 6399-keV state together with the gating transitions (in bold). The transitions going dominantly to the ground state and the isomer are shown in blue and red, respectively. The transitions observed in this work from the 6398.64(21)-keV [13] state have uncertainties of around 2 keV (see Table 1) and result in $E_x=6398.0(20)$ keV. Other intense γ-ray transitions ($I_{\gamma}\geq 10\%$ in [13]) are also indicated for the relevant states. The fraction of transitions populating the ground state either directly or via cascades from each level ($b_{g.s.}$) is based on the intensities from Ref. [13].

Angular-distribution analyses were performed following the procedure outlined in Ref. [17]. Coincidence matrices were sorted where the energies of γ-rays detected at specific Gammasphere angles, $E_{\gamma}(\theta)$, measured with respect to the beam axis, were incremented on one axis, while the energies of γ-rays detected at any angle, $E_{\gamma}(\text{any})$, were placed on the other axis. Gates were placed on the $E_{\gamma}(\text{any})$ axis to clean the spectra and the intensities of the transitions of interest were extracted. As a consistency check, we compared the relative branch intensities of two transitions from the 6610-keV level (shown in Fig. 3(b) and (c)) with known literature values [13] and found them to be in good agreement. Fits to the measured yields at each angle were then performed. The standard angular distribution function $W(\theta)=a_0[1+a_2P_2(\cos\theta)+a_4P_4(\cos\theta)]$, where P_2 and P_4 are Legendre polynomials, was fitted to the data. The extracted coefficients, a_2 and a_4, contain information on the multipolarity of the transitions. Figs. 4(a)-(b) show angular distributions for the two most intense transitions (both to 2^{+} states) from the 6399-keV state, both well fitted as $\Delta J=0$ transitions. For comparison, in Figs. 4(c) and (d) fits are shown for known $\Delta J=0$ and $\Delta J=2$ transitions, respectively. $\Delta J=1$ (dipole) transitions have a negative a_2 parameter, and therefore exhibit an opposite trend compared to $\Delta J=0$ and $\Delta J=2$ (quadrupole) transitions (see e.g. Fig. 1 in Ref. [17]). The data support a $J=2$ assignment for the 6399-keV level, consistent with 2^{-} assignments deduced in Refs. [10,14], where for example transfer-reaction angular-distribution data support negative parity. We henceforth proceed on the basis that the spin-parity of the 6399-keV state is 2^{-}. This assignment rules out significant direct γ-branches to the ground and isomeric states, as high multipolarity transitions would be required. This is important for the ensuing analysis, as the present experiment is not sensitive to single γ-ray transitions since it requires $\gamma-\gamma$ coincidences.

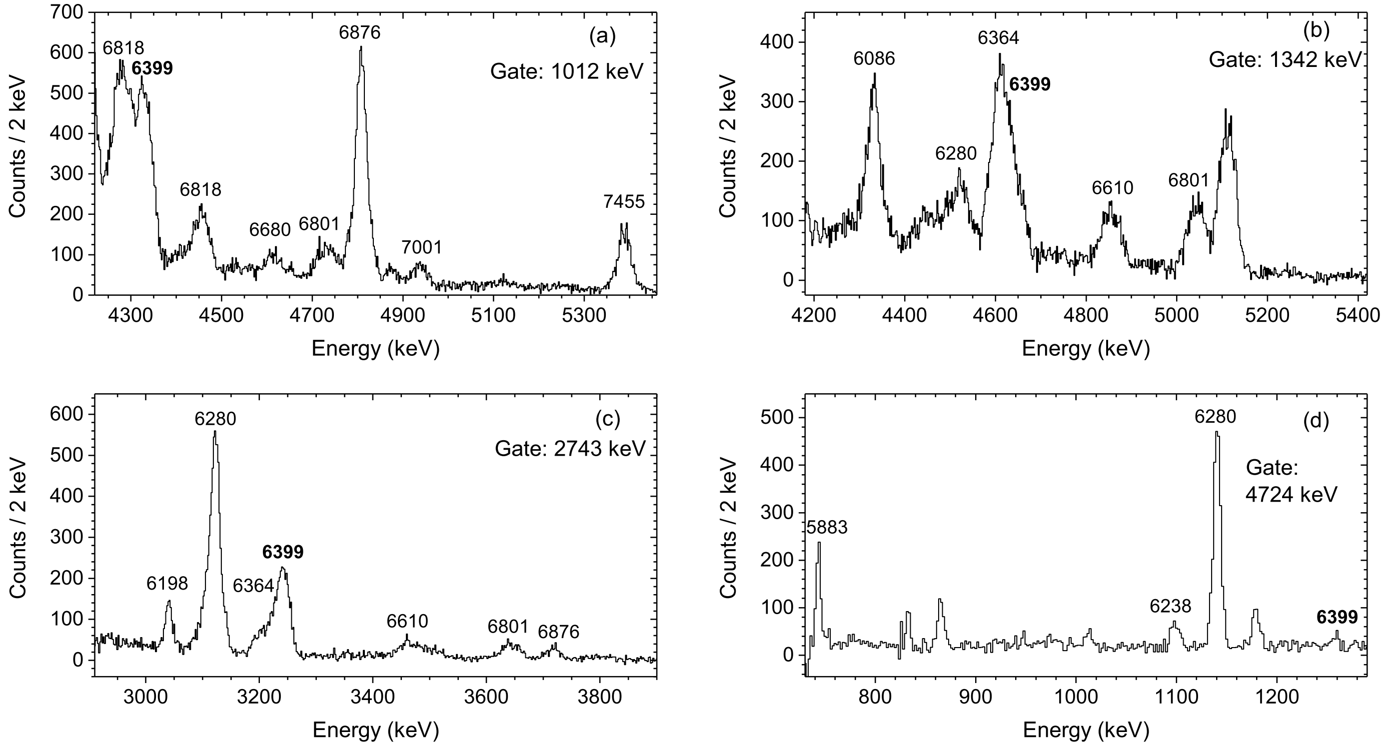

Fig. 3. Transitions observed from the 6399-keV state. Gates at γ-ray energies of (a) 1012 keV, (b) 1342 keV, (c) 2743 keV, and (d) 4724 keV have been applied to observe transitions to 2^+ states at 2069 keV, 1759 keV, 3160 keV, and 5142 keV, respectively. The peaks have been labelled with excitation energies corresponding known excited states in ^{26}Al.

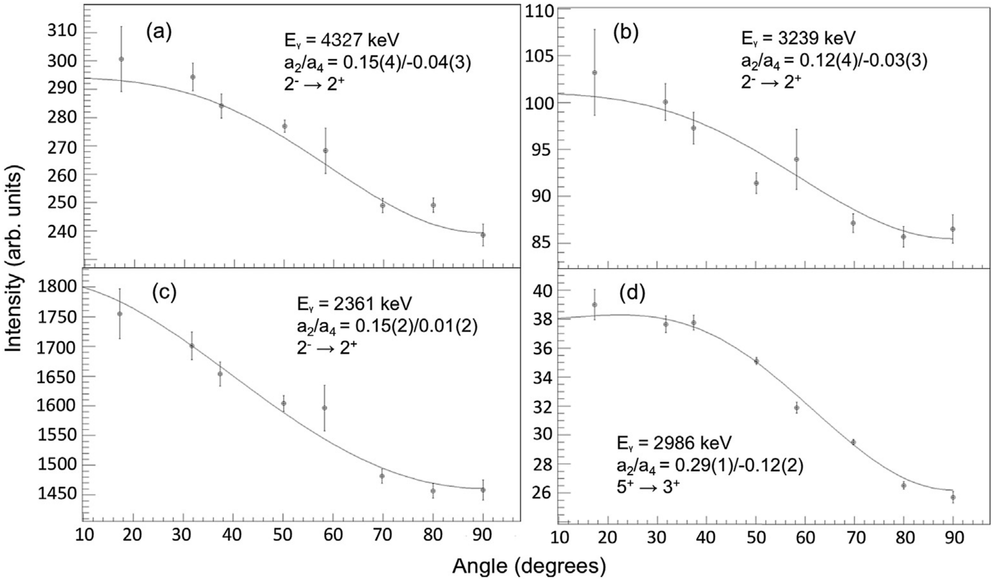

Fig. 4. Angular distributions for (a) 4327-keV transition from the 6399-keV state to the 2^+ state at 2069 keV, (b) 3239-keV transition from the 6399-keV state to the 2^+ state at 3160 keV, (c) a known $\Delta J = 0$ transition (4431 keV, $2^- \to$ 2069 keV, 2^+), and (d) a known $\Delta J = 2$ transition (3402 keV, $5^+ \to$ 417 keV, 3^+).

Table 1 lists the four observed transitions from the 6399-keV state in ^{26}Al, and their relative intensities. These intensities are combined with the known branching ratios from the lower-lying states [13] in the observed decay cascades shown in Fig. 2, to deduce a ground-state branching fraction of 0.52(2), where the error is mainly statistical, stemming from the determined peak areas and uncertainties in the known γ-ray transition intensities. A key additional systematic uncertainty relates to possible weak unobserved branches from the 6399-keV level. In order to explore this, we consider the effect of excluding the weakest observed branch from the 6399-keV level, for which the decay sequence predominantly leads to the ground state. The effect of its removal is to reduce the derived ground-state branching fraction value by an amount of 0.06. Since other possible branches are likely to be weaker than this, and not necessarily feeding dominantly either the ground or isomeric state, we consider ±0.06 to be a reasonable estimate of this systematic uncertainty, giving a value for $f_0 = 0.52(2)_{stat}(6)_{syst}$.

Table 1
Observed transitions from the 6399-keV state and their relative intensities I_γ. The transitions were gated with the dominant γ-ray transitions (1342 keV, 1012 keV, 2743 keV and 4724 keV) originating from the final states at energies E_f with spin-parity J_f^π, and a fraction $b_{g.s.}$ of transitions populating the ground state (either directly or via cascades).

E_γ (keV)	I_γ (%)	E_f, J_f^π [13]	$b_{g.s.}$ (%)
4638.0(21)	12.7(7)	1759.034(8), 2^+	98.00(17)
4326.9(20)	51.2(23)	2069.47(3), 2^+	21.6(9)
3238.7(20)	35.5(17)	3159.899(13), 2^+	79.2(11)
1256.4(13)	0.69(12)	5141.68(6), 2^+	93.8(32)
In total	100(2)		52(2)

The 92-keV resonance strength value measured at LUNA for the ^{25}Mg$(p,\gamma)^{26}$Al reaction is $\omega\gamma = 2.9(6) \times 10^{-10}$ eV [12]. For the production of ^{26g}Al in reaction-rate calculations, this needs to be multiplied by f_0 and the electron screening enhancement factor, f_{esc}, calculated to be 1.25 in Ref. [12]. Although not observing discrete γ-ray transitions from the 92-keV resonance, Strieder et al. performed a simulation analysis on their BGO summing crystal data to adopt a value for $f_0 = 0.6^{+(2)}_{-(1)}$ [12], which is consistent with the more precise value reported here. Prior to the LUNA measurement, the most recent analyses of the low-energy ^{25}Mg$(p,\gamma)^{26}$Al reaction rate had assumed values of 0.61 [18] and 0.85 [10] for f_0 of this state, with no error given. An even earlier study of the ^{24}Mg$(^3$He$, p\gamma)^{26}$Al reaction [19,20] reported a 3^+ assignment for a state at 6400(3) keV and a value for $f_0 = 0.8(2)$ (in Table 1 of Ref. [20]). The spin assignment is in disagreement with the present study, as are the branch intensities (e.g. the main gamma branch observed here dominantly feeding the isomer was not observed in Ref. [19]), and these data were not adopted in subsequent data compilations [13,14].

In summary, four γ-ray branches have been identified for the key 92-keV resonance in the low-energy ^{25}Mg$(p,\gamma)^{26}$Al reaction. These data have been used to determine the spin of the resonance, and to derive the most precise value yet for the ground-state branching fraction f_0; the latter is required for the accurate calculation of the production of the cosmic γ-ray emitting species, ^{26g}Al. The value for f_0 is the lowest yet reported, although broadly consistent with previous adopted values. It would imply a lower production rate of ^{26g}Al and consequently a less intensive cosmic 1809-keV γ-ray flux than the previous calculations of the Mg-Al cycle.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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