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β decay of ^{32}Na

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The β-decay of ^{32}Na has been studied using β-γ coincidences. New transitions and levels are tentatively placed in the level scheme of ^{32}Mg from an analysis of γ-γ and β-γ-γ coincidences. The observation of the indirect feeding of the 2321 keV state in ^{32}Mg removes some restrictions previously placed on the spin assignment for this state. No evidence of a state at 2117 keV in ^{32}Mg is found. Previously unobserved weak transitions up to 5.4 MeV were recorded but could not be placed in the decay scheme of ^{32}Na.

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The structure of nuclei along the valley of stability is well understood in terms of the traditional magic numbers, corresponding to large gaps in single-particle energy levels of nucleons in realistic mean-field theories including a spin-orbit interaction. The evolution of the shell closures far from stability is, however, a subject of intense scrutiny. In particular, experimental studies have shown a breaking of magicity of the $N = 20$ [1–3] and the $N = 28$ [4,5] configurations for neutron-rich nuclei. Key nuclei in their respective regions, such as ^{32}Mg and ^{44}S, display large quadrupole collectivity arising from their prolate deformation. Over the years (and with the steady increase of computing power), shell model calculations have led to a better understanding of the magicity disappearance in certain regions of the nuclear chart (for a recent review, see Ref. [6] and references therein). In the case of the $N = 20$ shell closure, the so-called "island of inversion" around ^{32}Mg is due to low energy fp-intruder states competing with the standard sd-orbitals, giving rise to the deformed configurations.

Despite many experimental studies, significant features of the ^{32}Mg level scheme are still unknown. In fact, only the first excited state at 885 keV is firmly assigned as a 2^+ state [7]. The other excited states have, at best, only received a tentative assignment. Of interest is the location of the 4^+ state to shed some light on the origin of the observed deformation. Azaiez *et al*. [8] propose that this state is located at 2315(15) keV in agreement with a 2321 keV state previously observed in the β-decay of ^{32}Na [2]. Recently, a state in the vicinity of 2.31 MeV was also suggested in the two-proton knockout reaction of ^{34}Si, and assumed to be the 4^+ state [9]. However, conflicting evidence exists. With a tentative assignment of (3^-,4^-) for the ^{32}Na ground state, a 4^+ state in ^{32}Mg would not be strongly populated by the β-decay of ^{32}Na. Klotz *et al*. [2] have not observed any evidence that the 2321 keV state is populated from higher excited states. Moreover, an intermediate energy Coulomb excitation experiment similarly proposed the existence of a 2321 keV state, and suggested three possible assignments (not including 4^+), namely (1^-,1^+,2^+) [10]. Finally, the inelastic scattering of ^{32}Mg has led to the observation of an excited state, identified possibly as the 2321 keV excited state with a suggested spin and parity of 3^- [11]. Clearly, a new study of the β-decay of ^{32}Na is needed to help resolve the discrepancies in the ^{32}Mg level scheme.

The β-decay of ^{32}Na has been investigated at ISAC/TRIUMF with the 8π spectrometer, instrumented with the SCintillating Electron Positron Tagging ARray (SCEPTAR) [12] and a fast mylar tape transport system. Gamma rays were measured with the 8π spectrometer, an array of 20 high-purity germanium (HPGe) detectors [13], while beta particles were detected with SCEPTAR, a near 4π inner array of twenty 1.6 mm thick plastic scintillating detectors located 1.5 cm from the center of the 8π. Each plastic scintillator in SCEPTAR is in one-to-one correspondance with a HPGe detector of the 8π, i.e., each HPGe detector views the central focus of the array through primarily one SCEPTAR element.

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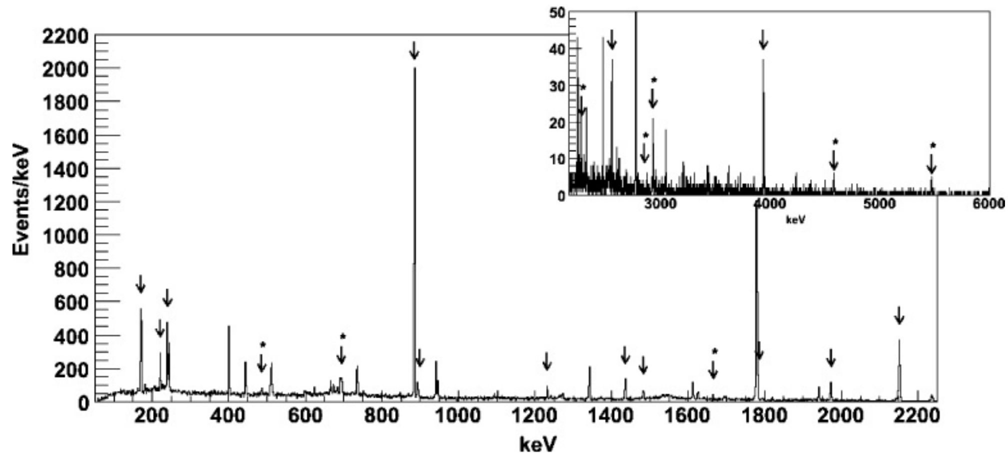

FIG. 1. Gamma spectrum obtained using both tape cycle data sets by requiring β-γ coincidences and after bremsstrahlung veto (see text), with known ^{30,31,32}Mg lines identified. Transitions identified by * are candidates for belonging to the level schemes of ^{30,31,32}Mg. (see table I)

Finally, the mylar tape intercepts the ion beam at the center of both arrays. The tape transport system is fully programmable and interfaced to ISAC beam controls. Such a combination provides a powerful selection tool both by requiring events in β-γ coincidences and by allowing the removal of long-lived progeny.

^{32}Na atoms were produced by bombarding a 22.4 g/cm^2 tantalum target with a 40 μA 500 MeV proton beam. An estimated 2–3 ^{32}Na atoms per second were extracted by surface ionization and delivered to the 8π experimental station, where they were implanted into the moving tape. During the 126 h of effective data taking, two settings were used for the tape transport operation. In the "continuous" mode, the mylar tape moved at a constant speed of 80 cm/s while beam was continuously delivered. In the "six-seconds" mode, the tape was held stationary for 6 sec while beam was delivered, then the beam was turned off and the tape was moved 45 cm out of the focus of the array. Data were first collected using a hardware event trigger requiring β-γ coincidences; the trigger was later upgraded to also include γ-γ coincidences.

In offline analysis, more event selections are made possible by the use of the SCEPTAR array. The neutron-rich nuclei of interest in this experiment decay with high Q-values, leading to the emission of high-energy electrons. When interacting in SCEPTAR, these high-energy electrons in turn produce bremsstrahlung photons in the direction of the HPGe detector colinear to the given SCEPTAR detector. This source of background is considerably reduced by vetoing β-γ coincidences occuring in a paired plastic scintillator/HPGe detector at a cost of losing 5% of the overall β-γ coincidences. Although the SCEPTAR elements are thin, it is possible to use the digitized energy loss information recorded by the detectors to discriminate against very low Q-value β decays, when the electrons are stopped rather than slowed down in SCEPTAR. This proved useful to remove the contributions from ^{28}Mg, the long-lived daughter of ^{28}Na originally delivered during beam tuning. The ^{28}Mg nuclei decay primarily (95%) through the 1373 keV state in ^{28}Al with a Q-value of only 460 keV. It is however not possible to reject the 1778.9 keV γ ray following the β-decay of ^{28}Al ($I_\gamma = 100\%$), because the Q-value of the decay is too large. This γ ray obscures the known 1783 keV transition in ^{32}Mg. A gate on the β-γ coincidence timing is also included in the offline analysis to reject uncorrelated events. The final γ ray spectrum is shown in Fig. 1. The spectrum shows no evidence of contributions from high-mass contaminants in higher charge states.

A relative efficiency curve was fit to data taken with ^{152}Eu, ^{133}Ba, and ^{56}Co sources immediately following the experiment. The curve was later complemented by the measurement of the known EC-decay [14] of ^{66}Ga. The ^{66}Ga source was produced at ISAC with a ZrC target, extracted by laser ionization and implanted in a stationary tape at the center of the arrays in the same experimental configuration as in the ^{32}Na β-decay measurement. The resulting relative efficiency curve spanned a range from 121 keV to 4806 keV and agreed well, once normalized, with predictions from GEANT4 [15] in the 1 to 5 MeV region (the GEANT simulation did not take threshold effects into account, leading to some disagreement at low energy). Efficiencies for γ rays higher than 4.8 MeV were extrapolated from the GEANT efficiency curve.

The intensities from this work are compared to those found by Klotz *et al.* [2] and by Guillemaud-Mueller *et al.* [16] in Table I. Reasonably good agreement is found with some exceptions. Disagreements observed with Ref. [2] at low and high energy could be explained by systematic errors in their efficiency calibration. In our work and in Ref. [2], the γ ray at 1783 keV is obscured by a different contaminant (^{28}Al in present work), and so the intensity remains referenced from the earlier work [16]. A notable disagreement at 1973 keV may be attributed to the observed presence of the contaminant ^{128}In in [2]: ^{128}In β-decays to ^{128}Sn with $t_{1/2} = 0.72$ s, and includes a 20% γ branch at 1973.86 keV. A fraction (as much as 50%) of the intensity indicated for the 221 keV transition

TABLE I. Gamma transition energies and relative intensities following the β-decay of ^{32}Na. Comparison with intensities from [2] and [16]. All intensities are normalized to the 885 keV transition in ^{32}Mg (100). The ratio of intensities from two tape-cycling modes is shown, providing a qualitative argument that these transitions may belong to level schemes of the immediate daughters of ^{32}Na (see text).

	E_γ(keV)[a]	I_γ	[2]	[16]	Ratio: $\frac{6s}{\text{cont}}$
^{32}Mg	486.1[b]	1.3(3)	–	–	1.3(6)
	693.5[b,c]	[c]	[c]	[c]	
	885.0	100	100	100	1.00
	1231.7[d]	3.8(5)	4.8(17)	4.9(14)	0.8(3)
	1436.1	9.8(7)	9.8(25)	10.2(20)	1.1(2)
	1665.6[b]	2.4(4)	–	–	0.6(3)
	1783[e]	–	–	8.3(20)	–
	1972.9	11.6(8)	19.7(25)	14.3(25)	1.0(2)
	2151.7	47.0(17)	48.5(37)	52.6(60)	0.9(1)
	2268.5[b]	2.5(3)	–	–	0.7(2)
	2550.7	6.4(6)	10.2(25)	9.1(20)	1.3(2)
	3934.5	12.0(8)	18.3(37)	13.3(30)	0.6(1)
^{31}Mg	170.8	9.6(6)	21.9(35)	9.0(25)	1.0(1)
	220.8[f]	3.9(4)	8.9(18)	4.4(14)	1.3(3)
	239.9	9.5(6)	9.7(11)	27.6(32)	1.0(1)
	693.5[c]	[c]	[c]	[c]	[c]
	894.1	4.1(5)	5.1(26)	4.3(10)	1.5(3)
^{30}Mg	1483.0	4.2(5)	4.9(22)	2.0(17)	0.8(3)
Unplaced	2869.2(8)	1.1(2)	–	–	1.2(5)
	2925.8(6)	3.3(4)	–	–	1.5(4)
	4575(3)	2.4(4)	–	–	0.8(4)
	5470(3)	3.3(6)	–	–	0.9(4)

[a]Uncertainty is $\pm$0.5 keV unless otherwise specified.
[b]Assigned to ^{32}Mg in this work.
[c]Doublet: centroid energy given (see text for details); transitions in ^{31,32}Mg - total intensity: I_γ: 6.9(6); [2]: - ; [16]: 3.8(16); Ratio: 1.1(2).
[d]Possible doublet - See text.
[e]Not extracted due to the presence of ^{28}Mg (see text).
[f]See text for details.

in ^{31}Mg may come from the β-decay of ^{32}Mg to ^{32}Al, which decay scheme contains two 222 keV transitions [17]. Analysis of γ-γ coincidences suggests that this contribution may be small in our case, because most of our data were taken in "continuous mode", where the progeny decays were partly rejected. Finally, a significant disagreement is observed for the 240 keV transition in ^{31}Mg with [16].

Several previously unobserved γ transitions are found with intensity greater than $\sim$1% relative to the 885 keV transition in ^{32}Mg (see Fig. 1 and Table I). Gamma transitions, for which the intensity is attenuated by more than a factor of 2 under the β-energy cut, are rejected as belonging to a low Q-value decay, such as ^{28}Al. Next, the ratio of intensities of the two tape modes is considered. The "continuous" operation mode favors the detection of the β-decay of ^{32}Na over its longer-lived progeny, while the "six-seconds" mode yields a much larger contribution of progeny decays. The ratio of intensities I_{6s}/I_{cont} is expected to increase with the lifetime of the parent. Indeed, this

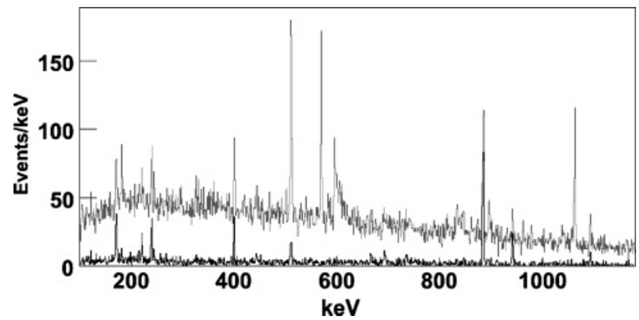

FIG. 2. Projections of γ-γ (light) and β-γ-γ (dark) coincidence data sets for selected runs.

ratio (normalized for the 885 keV γ ray in ^{32}Mg) is measured to be respectively: 1.0(2) for ^{32}Na, 1.9(3) for ^{32}Mg and 3.6(5) for ^{31}Mg for known γ rays following the decay of their respective parent. A ratio near unity is therefore considered a good indication that the given transition belongs to the decay of ^{32}Na. Eight γ rays are found to satisfy this condition.

Finally, γ-γ and β-γ-γ coincidences are inspected for placement of those eight transitions in the decay scheme of ^{32}Na. An offline 50 ns coincidence gate is set to select the γ coincidence events. As shown in Fig. 2, the β-γ-γ coincidence spectrum displays considerably less background than the γ-γ coincidence spectrum, allowing more in-depth coincidence analysis despite the overall low statistics collected in this experiment.

Three of the new transitions are found to be in coincidence with known transitions and also match the energy difference of known energy levels in ^{32}Mg. The 1666 keV line is in coincidence with the 885 keV transition and fits the energy difference between the known 2551 and 885 keV states. Similarly, the 486 keV line is in coincidence with the 885 keV γ ray and is placed as a 3037 to 2551 keV transition. Finally, the 2269 keV line is observed in coincidence with the aforementioned 1666 keV transition and is assigned as a transition between the 4820 and the 2551 keV states.

A 693.4 keV γ has been seen but not placed by Guillemaud-Mueller *et al.* [16]. Recently, Mach *et al.* assign this transition to ^{31}Mg as an $11/2^- \rightarrow 7/2^-$ transition from a new level at 1154 keV to the previously seen 461 keV level [18]. β-γ-γ coincidences observed in this work support the placement as made by Mach *et al.* (see Fig. 3(a)). However, the coincidence spectrum also suggests another slightly higher-energy line (about 695 keV) may belong in the ^{32}Mg decay scheme, as the same coincidence gate produces coincidences with the 885 keV (see Fig. 3(a)). As additional evidence, this transition is also seen in γ-γ coincidences with the 1973 keV γ ray, another known transition in ^{32}Mg (see Fig. 3(b)). The individual contributions of both transitions cannot be extracted, thus only the intensity of the doublet state is reported in Table I. To explain the coincidences observed with the 695 keV transition, it is proposed that it results from the decay of a new level at 3553 keV to the known 2858 keV level, which subsequently decays by the sequential emission of both the 1973 keV and 885 keV γ rays observed in coincidence.

Further evidence for the 3553 keV level exists. A gate placed around the 1436 keV transition shows coincidences

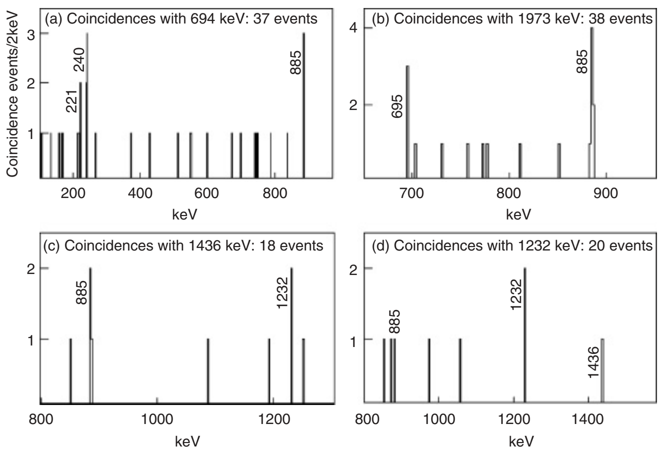

FIG. 3. Coincidence spectra using both tape cycle data sets supporting the evidence of a new state at 3553 keV and possibly another one at 4785 keV in ^{32}Mg. The total number of events in each coincidence spectrum is indicated in the title together with the transition around which the gate was placed. Spectra labeled (a),(c) and (d) are obtained in β-γ-γ coincidences, while spectrum (b) is obtained using γ-γ coincidences only (see text).

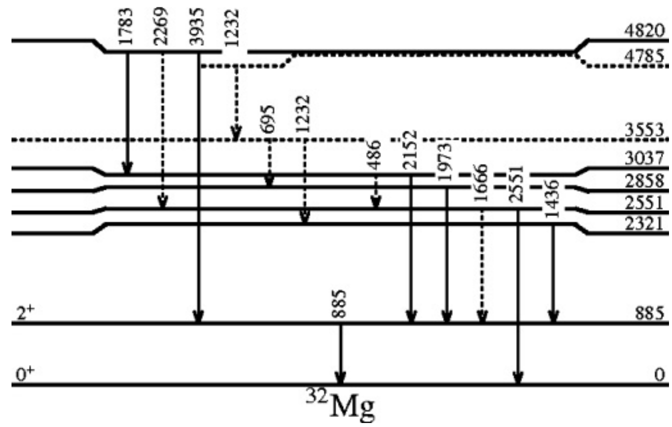

FIG. 4. Decay scheme in ^{32}Mg as observed in this work. The dashed lines indicate the new transitions and levels. Energies are in keV.

with the 885 and the 1232 keV γ rays (see Fig. 3(c)). The latter coincidence is not possible from the decay scheme of ^{32}Mg proposed by Klotz *et al.*, where the 1232 keV and the 1436 keV transitions correspond to the decay of a 2117 keV and the 2321 keV states, respectively, to the first excited state in ^{32}Mg. At present, there is no further published evidence of the existence of a 2117 keV state in ^{32}Mg. It is therefore suggested that the 2117 keV state postulated by Klotz *et al.* may not exist and that the 1232 keV transition results instead from the decay of the new 3553 keV state to the known 2321 keV state in ^{32}Mg. The observation of a feeding of the 2321 keV state from a higher energy level is of importance as it shows that the β-decay to the 2321 keV state does not necessarily have to be an allowed transition and therefore does not restrict this state to be of negative parity. No evidence of the decay of the 2321 keV state to the ground state could be found in this work. Moreover, the 1232 keV transition is also found in coincidence with itself (see Fig. 3(d)), suggesting the existence of an even higher excited state at 4785 keV in ^{32}Mg. No coincidence is observed with the 695 keV γ ray originating from the 3553 keV level, which could have constituted supporting evidence for the existence of such a state. Figure 4 includes the new transitions and the new levels at 3553 keV and at (tentatively) 4785 keV. No other significant (β-)γ-γ coincidences are observed to help in the placement of the remaining four lines identified as possibly belonging to the immediate β-decay scheme of ^{32}Na.

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