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Nuclear structure explored by β-delayed decay spectroscopy of *spin-polarized* radioactive nuclei at TRIUMF ISAC-1

Intruder configurations in ^{29}Mg and ^{30}Mg, the nuclei in the region of island of inversion

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Abstract Spin-polarized radioactive nuclear beams at TRIUMF enable a new spectroscopic method which efficiently assigns spins and parities of the daughter levels by taking advantage of the asymmetric β-decay of the polarized parent nucleus. This method was successfully applied to structure studies of ^{29}Mg and ^{30}Mg in connection with the physics of the "island of inversion". In ^{29}Mg, two low-lying levels with intruder configuration were assigned. In ^{30}Mg, coexistence of spherical shape, prolate shape and γ-collectivity was strongly suggested.

Keywords Polarized RI beam · β-delayed decay spectroscopy · ^{29}Mg and ^{30}Mg · Island of inversion · Intruder configurations · Shape coexistence

ISAC and ARIEL: The TRIUMF Radioactive Beam Facilities and the Scientific Program.

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1 Introduction

One of the recent highlights in nuclear physics is the shell evolution in very neutron-rich nuclei with variation of neutron number. In particular, the exotic structure of nuclei around the "island of inversion" [1]. This very neutron-rich region of the nuclear chart with neutron numbers close to the magic number $N = 20$, has been attracting much attention for two decades. The significant fractions of intruder configurations in the ground and/or excited states should cause very different features from those of the magic-number nuclei close to the stability line. There have been many experimental and theoretical works to clarify which nuclei lie within the island of inversion and which level has structure with intruder configurations [2, 3].

However, the experimental information on these nuclei is rather limited. For many of the levels, spin and parity, which are the key quantities to understand the nuclear structure, have not been assigned. For example, in the case of ^{29}Mg whose structure will be discussed in the present work, only the ground-state spin-parity has been assigned [4, 5]. The levels in ^{30}Mg were placed with no spin-parity assignment by the β-delayed γ-spectroscopy of ^{30}Na [6]. A lifetime measurement proposed a 0_2^+ level at 1.788 MeV [7] and a conversion electron measurement confirmed this assignment [8]. The possible shape coexistence in this level is being discussed.

We have developed a powerful tool to assign spin-parity to the levels of the daughter nuclei in β-delayed decay spectroscopy at ISAC-1 at TRIUMF, where the world-highest polarization is available for radioactive alkali beams [9, 10]. This method takes advantage of asymmetric β-decay of the spin-polarized nucleus. The first successful application was performed in 2002 and 2004 on the β-delayed neutron-decay $^{11}\mathrm{Li}_{\mathrm{g.s.}} \xrightarrow{\beta} {}^{11}\mathrm{Be}^* \xrightarrow{\mathrm{n}} {}^{10}\mathrm{Be}^* \xrightarrow{\gamma} {}^{10}\mathrm{Be}_{\mathrm{g.s.}}$. We could firmly assign spins and parities of seven levels in ^{11}Be for the first time and reveal various types of cluster structure in ^{11}Be [11]. In the present work, the second also successful application in 2007 and 2010 to systematic studies of neutron-rich Mg isotopes is briefly discussed. More details are found in [12, 13].

2 Experimental

The principle of the method is based on an asymmetric β-decay shown by the following angular dependence, if we assume an allowed transition:

$$W(\theta) \simeq 1 + AP\cos\theta, \qquad (1)$$

where P, θ and A are the polarization of the parent nucleus, the emission angle of the β-ray with respect to the polarization direction and the asymmetry parameter characteristic of the β-transition, respectively. The essential point is that the asymmetry parameter A is a constant depending on the initial and final state spins, I_i and I_f, respectively, as shown in (2) and Table 1. Here, we ignored Fermi transition probabilities for the case of $I_f = I_i$, because in a very neutron-rich nucleus Fermi transitions result in highly excited states, whereas we are discussing a rather

Table 1 Asymmetry parameters for allowed β-decay of ^{29}Na and ^{30}Na

β-decay	I_i^π	I_f^π	A
$^{29}Na_{g.s.} \rightarrow {}^{29}Mg$		$1/2^+$	−1.0
	$3/2^+$	$3/2^+$	−0.4
		$5/2^+$	+0.6
$^{30}Na_{g.s.} \rightarrow {}^{30}Mg$		1^+	−1.0
	2^+	2^+	−0.33
		3^+	+0.67

low-excitation energy region. The large difference in A enables us to unambiguously assign I_f.

$$A \begin{cases} = -1 & (I_f = I_i - 1), \\ \backsimeq \dfrac{-1}{I_i + 1} & (I_f = I_i), \\ = \dfrac{I_i}{I_i + 1} & (I_f = I_i + 1). \end{cases} \tag{2}$$

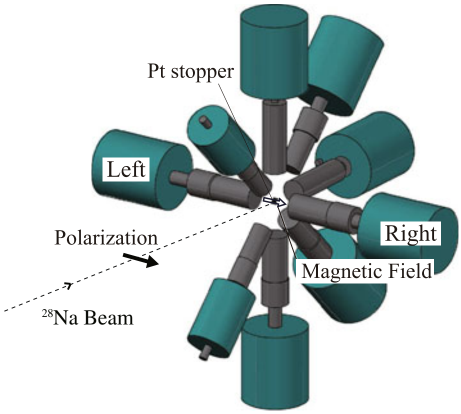
The AP value for each β-decay is obtained by comparing β-γ coincidence counts in the detectors at $\theta = 0°$ and 180°. In order to cancel out the spurious asymmetry due to instrumental asymmetry, the direction of polarization is reversed by flipping the laser helicity periodically. Note that the polarization P is common for all β-transitions. Therefore, once P is known, for example from the AP value of the β-transition to a spin-known level, the asymmetry parameters for other levels are obtained, i.e. the spin of the level is immediately assigned. For a daughter level which is also populated by γ-transitions from higher levels, it is easily shown that the effects on the asymmetry parameter are estimated and the asymmetry parameter for the specific β-transition is obtained, if the γ- and β-transition intensities are all known.

For the $^{29}Na^+$ and $^{30}Na^+$ beams, polarization of ∼50 % was achieved by using the collinear laser optical pumping technique at the polarized beam facility at ISAC-1 [9, 10]. The experiments were performed at the very end of a beamline named "OSAKA" which is located downstream of the polarized beam facility. The direction of polarization was perpendicular to the beam direction and in the horizontal plane.

Figure 1 shows the layout of detectors. The 30.4 keV polarized $^{29}Na^+$ or $^{30}Na^+$ was stopped on a thin Pt foil (10 μm thick) in vacuum. A static magnetic field of ∼530 mT was applied to preserve the polarization. The β-rays and the successive γ-rays were detected by 9 detectors surrounding the Pt foil. Each detector consisted of two thin plastic scintillators and a coaxial Ge detector to form a ΔE-ΔE-E detector telescope. This configuration enabled β-ray and γ-ray identification and their energy measurement. Two detectors ("Left" and "Right") placed on the polarization axis measured the asymmetry of β-decay.

The average beam intensities of ^{29}Na and ^{30}Na were 82 and 14 pps, respectively, at the Pt foil. A total of 1.7×10^7 ^{29}Na and 7.1×10^6 ^{30}Na were implanted into the foil during data-acquisition times of 56 and 142 hours, respectively. The polarization was determined from the measured AP-values to be $P(^{29}\mathrm{Na}) = 35 \pm 2$ % and $P(^{30}\mathrm{Na}) = 32 \pm 3$ %. The somewhat smaller polarization than the estimated beam polarization of ∼50 % may be due to spin-relaxation in the Pt foil.

Fig. 1 Schematic detector arrangement



3 Results

3.1 Structure of ^{29}Mg

Figure 2 shows the decay scheme of ^{29}Na revised by the present work. The decay intensities were determined by normalizing the well-established intensity of the 2224-keV γ-ray in the granddaughter ^{29}Al [14] and the neutron decay probability $P(1n) = 21.5(30)$ % [15]. Asterisks in the figure indicate new findings. It is seen that two new γ-transitions have been found and spins and parities (I^π) of seven levels have been assigned in ^{29}Mg for the first time. The I^π assignments for the two levels at 2.614 ($1/2^+$) and 3.223 ($3/2^+$) MeV, characterized by large β-decay branching ratios, were firmly assigned. Other I^πs in parentheses were determined based on the above-mentioned two assignments and detailed γ-transition paths and intensities. Note that the spins and parities of most of the ^{29}Mg states except for the two levels at 1.094 and 1.430 MeV were assigned. These levels are characterized by large log ft-values. It is interesting to note that the 3.985-MeV level which is located above the neutron threshold (3.672 MeV) decays to the ground state by γ-emission. This fact supports the $5/2^+$ assignment.

The experimental results were compared with the shell-model calculations with the universal *sd*-shell interaction B (USDB) [16]. It was found that the level energy, spin-parity and β-transition probability were well reproduced assuming all nucleons are in the *sd*-shell for all the positive-parity levels. However, the two spin-unassigned levels could not be explained by such calculations. This fact strongly suggests that these levels at 1.094 and 1.430 MeV are negative-parity levels with an intruder configuration. This result is consistent with the previous speculation [17]. In fact, the Monte Carlo Shell Model calculation taking into account the pf-shell configurations predicts $7/2^-$ and $3/2^-$ levels at 0.68 MeV and 1.01 MeV, respectively (Utsuno, private communication).

It becomes possible to compare the excitation energies of the negative-parity levels in neutron-rich Mg isotopes. Figure 3 shows the negative-parity levels in odd-mass Mg isotopes, assuming $7/2^-$ and $3/2^-$ assignments for the 1.430- and 1.094-MeV ^{29}Mg levels, respectively. It is clearly seen that the excitation energies of the negative-parity levels rapidly decrease at ^{29}Mg with the increase in neutron number. This is the experimental evidence for shell evolution in neutron-rich Mg isotopes.

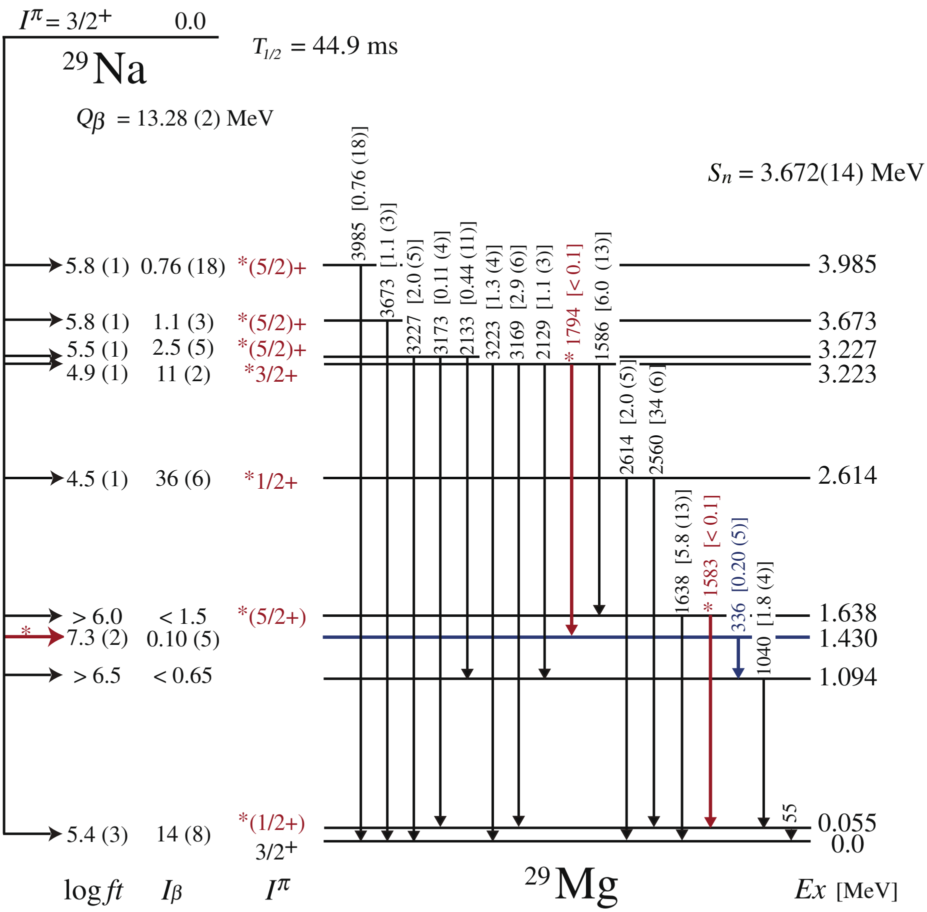
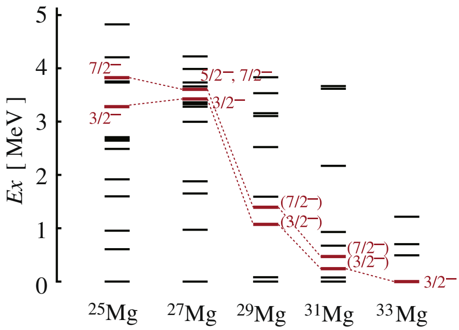


Fig. 2 Revised decay scheme of ^{29}Na. The physical quantities and decay paths marked by asterisks are ones newly found in the present work. The level at 1.430 MeV was observed in the β-decay of ^{29}Na for the first time (emphasized in *blue*). The γ-transition intensities per ^{29}Na β-decay are shown in units of percent, together with the γ-ray energies in keV. The β-decay to the first excited state at 55 keV was observed, but since its intensity could not be evaluated separately from that of the ground state, the summed intensity is shown

Fig. 3 Low-lying negative-parity levels in odd-mass Mg isotopes. The spin-parity assignments of the ^{31}Mg levels and ^{33}Mg$_{g.s.}$ are after [17] and [18, 19], respectively



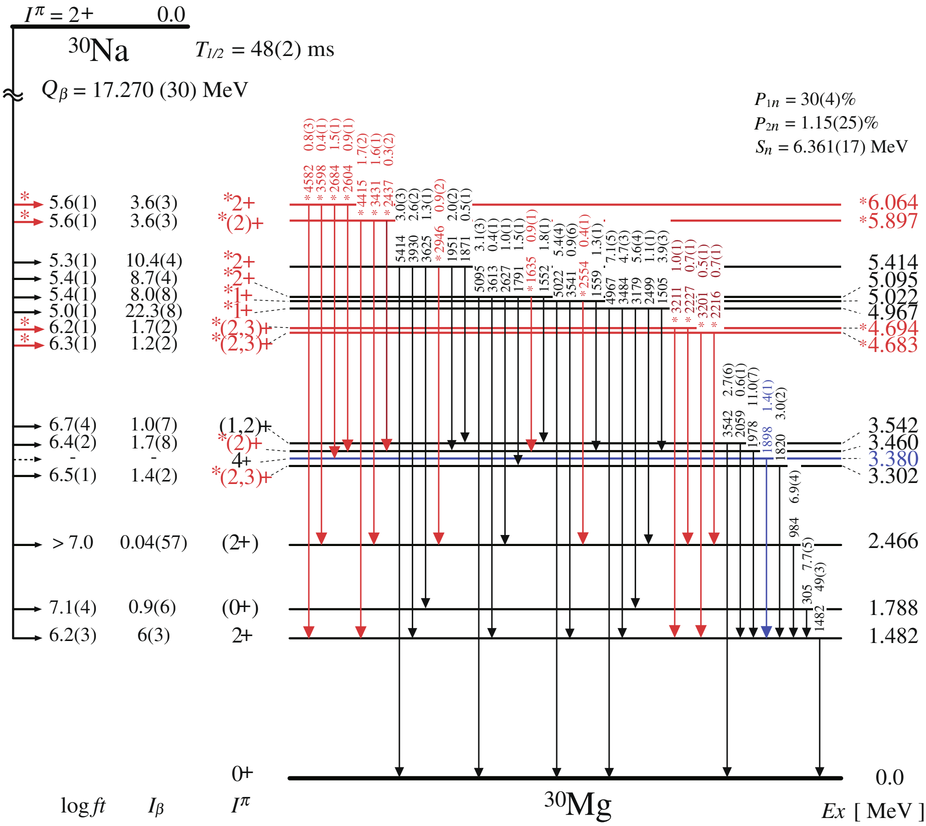


Fig. 4 Revised decay scheme of ^{30}Na. Asterisks denote new results achieved in the present work. The level at 3.380 MeV and the deexciting 1898-keV γ-ray (shown in *blue*), which were known in the ^{14}C(^{18}O,2p) reaction [22] , were observed in the β-decay of ^{30}Na for the first time

3.2 Structure of ^{30}Mg

Figure 4 shows the revised decay scheme of ^{30}Na established by the present work. The decay intensities were determined by referring to the known total β-decay probability $P(0n) = 69.2$ % [6]. It is seen that fourteen γ-transitions were newly found and detailed γ-γ analyses claimed four new levels at 4.683, 4.694, 5.897 and 6.064 MeV in ^{30}Mg. The confirmation of the new decay path 5.897→1.482 →g.s. eliminated the 4.415-MeV level [6] from the level scheme. It should be emphasized that the spins and parities of ten levels shown in *red* have been assigned for the first time. Among them five I^{π}s without parentheses were firmly assigned.

It is to be noted that the major part of β-decay goes to levels higher than 4.967 MeV. The fact that ^{30}Na$_{\text{g.s.}}$ has a deformed shape [20, 21] suggests a spherical nature of the low-lying levels and deformation of the high-lying levels in ^{30}Mg.

Note that the branching ratio of the second forbidden transition ^{30}Na$_{\text{g.s.}}(2^+) \rightarrow$ ^{30}Mg$(0_2^+$, 1.788) was evaluated to be 0.9(6) % (log $ft = 7.1(4)$), whereas no β-decay intensity was claimed in the previous work [7]. This fact suggests deformation of the

Table 2 The γ-transition intensities deexciting the 4.967-MeV level (1^+)

	$E_x^f(I_f^\pi)$	0.0 (0_1^+)	1.482 (2_1^+)	1.788 (0_2^+)	2.466 (2_2^+)	3.460 (2^+)
	$\sigma\lambda$	M1	M1	M1	M1	M1
I_γ	Experiment	1.0	0.66(7)	0.878(8)	0.15(2)	0.55(5)
	Weisskopf est.	1.0	0.35	0.26	0.13	0.03

Both the experimental and Weisskopf estimates are normalized to those of the ground state transition

Table 3 The γ-transition intensities deexciting the 5.414-MeV level (2^+)

	$E_x^f(I_f^\pi)$	0.0 (0_1^+)	1.788 (0_2^+)	1.482 (2_1^+)	2.466 (2_2^+)	3.460 (2^+)
	$\sigma\lambda$	E2	E2	M1	M1	M1
I_γ	Experiment	1.0	0.43(6)	1.0	0.35(8)	0.79(9)
	Weisskopf est.	1.0	0.13	1.0	0.42	0.12

Both the experimental and Weisskopf estimates are normalized to those of the ground state transition

0_2^+ level. This result is consistent with the small transition rate of the 0_2^+ level to the ground state [8], which is known to be spherical [17]. It is also worth noting that the 0_2^+ level is populated by γ-transitions from two higher levels 5 times more than the β-transition, and that the two higher levels are associated with large β-transition probabilities. Namely, (i) the largest β-transition (22.3 %) goes to the 4.967-MeV level (1^+), then leads to the 0_2^+ level with 5.6 % intensity, and (ii) the next largest one (10.4 %) goes to the 5.414-MeV level (2^+) and finally to the 0_2^+ level (0.9 %). The fact that $^{30}Na_{g.s.}$ is well deformed suggests that these two levels also have intruder configurations to a large extent. However, we could not find the deexciting γ-ray from the possible 2^+ state of the rotational band on the 0_2^+ state.

Tables 2 and 3 compare the observed γ-transition probabilities from the 4.967-MeV and 5.414-MeV levels, respectively, with the Weisskopf estimates. It is found that the transitions 4.967 (1^+)$\rightarrow$ 3.460 (2^+) and 5.414 (2^+)$\rightarrow$ 3.460 (2^+) show a very large enhancement from the Weisskopf estimates. This fact suggests that the 3.460-MeV level also has a deformed shape with an intruder configuration.

Note that the β-decay intensity to the second 2^+ level at 2.466 MeV was found to be less than the experimental sensitivity in the present work, whereas the previous work reported 3.7 % [6]. On the contrary, the β-decay to the first 2^+ level at 1.482 MeV was observed with 6(3) % intensity. Since the 2_1^+ level is interpreted to be spherical [17], the unobserved β-decay intensity to the 2_2^+ level suggests its non-spherical nature, but different deformation from $^{30}Na_{g.s.}$. This level is likely the 2^+ band head of the γ-band predicted by a calculation of large-amplitude collective motion, based on the constrained Hartree-Fock-Bogoliubov plus local quasiparticle random-phase approximation (CHFB+LQRPA) method [23].

4 Summary

We have investigated the structures of ^{29}Mg and ^{30}Mg by taking advantage of TRIUMF's spin-polarized radioactive nuclear beams of ^{29}Na and ^{30}Na, respectively. Because of high polarization of the beams and detailed decay intensities, we could assign spins and parities to seven levels in ^{29}Mg and ten levels in ^{30}Mg for the first time. Since all positive-parity levels in ^{29}Mg were consistent with the shell model calculations with the USDB Hamiltonian, the two unassigned levels at 1.430 and 1.094 MeV associated with large log ft-values were assigned negative-parity with an intruder configuration. In ^{30}Mg, five levels at 1.788 (0_2^+), 2.466 (2_2^+), 3.460 (2^+), 4.967 (1^+), and 5.414 (2^+) MeV exhibited a non-spherical nature. From the β- and γ-branching ratios, we propose that the 1.788-, 3.460-, 4.967- and 5.414-MeV levels have a deformed shape and the 2.466-MeV level is the 2^+ band head of the γ-band.

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