

Proton-rich nuclear structure and mirror asymmetry investigated by β -decay spectroscopy of ^{24}Si

Y. Ichikawa^{1,2}, T. K. Onishi², D. Suzuki², H. Iwasaki², T. Kubo¹, V. Naik³, A. Chakrabarti³, N. Aoi¹, B. A. Brown⁴, N. Fukuda¹, S. Kubono⁵, T. Motobayashi¹, T. Nakabayashi⁶, T. Nakamura⁶, T. Nakao², T. Okumura⁶, H. J. Ong⁷, H. Suzuki², M. K. Suzuki², T. Teranishi⁸, K. N. Yamada¹, H. Yamaguchi¹ and H. Sakurai¹

¹RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

²Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan

³Variable Energy Cyclotron Centre, 1/AF, Bidham Nagar, Kolkata-700 064, India

⁴Department of Physics and Astronomy, and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824-1321, United States

⁵Center for Nuclear Study, University of Tokyo, RIKEN Campus, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

⁶Department of Physics, Tokyo Institute of Technology, 2-12-1 Oh-okayama, Meguro, Tokyo 152-8551, Japan

⁷Research Center for Nuclear Physics, Osaka University, 10-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan

⁸Department of Physics, Kyushu University, 6-10-1 Hakozaiki, Higashi, Fukuoka 812-8581, Japan

E-mail: ichikawa@ribf.riken.jp

Abstract. In order to investigate the characteristic properties of proton-rich nuclei, β -decay spectroscopy was carried out on ^{24}Si . The Gamow-Teller transition strength $B(\text{GT})$ of ^{24}Si to low-lying states in ^{24}Al was determined. Considering in particular the breaking of mirror symmetry for energy levels and $B(\text{GT})$, we discuss the behavior of a weakly-bound s -orbital proton by incorporating a recent experimental result.

1. Introduction

Protons and neutrons constitute the nucleus of atoms and are bound by the nuclear force, which is considered to be symmetrical for isospin. Based on the isospin symmetry of the nuclear force, the nuclear properties such as excitation energy and transition probability are also considered to be symmetrical between mirror nuclei. However the mirror symmetry can be broken by the Coulomb force. In a proton-rich nucleus, the Fermi surface of the proton orbital is pressed up by the Coulomb potential. Then, the binding energy becomes weaker than that in the mirror neutron-rich nucleus, leading to mirror asymmetry. The Thomas-Ehrman (TE) shift [1, 2] is known as this type of mirror asymmetry induced by a weakly-bound proton. Originally, the TE shift was interpreted as the reduction of Coulomb energy due to spatial expansion of an s -orbital proton occupying the outermost shell. The most significant case is seen in the mirror nuclei of ^{17}O and ^{17}F [3], where the $1/2^+$ states are the single-particle states of the $1s_{1/2}$ orbital, as shown in Fig. 1 (a).

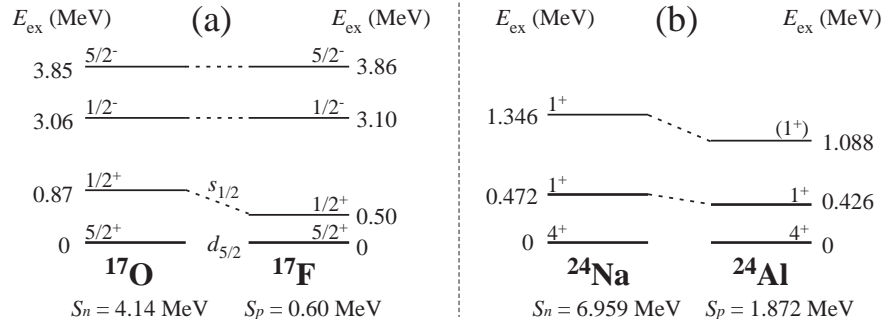


Figure 1. (a) Example of TE shift between ^{17}O and ^{17}F [3]. (b) Comparison of energy level between ^{24}Na [4] and ^{24}Al [5, 6, 7, 8, 9, 10, 11].

A TE shift is also seen between the low-lying states of ^{24}Na and ^{24}Al , which are $T_z = \pm 1$ mirror nuclei, as shown in Fig. 1 (b). While the energy difference between the first 1^+ (1_1^+) states is only 46 keV, the excitation energy of the second 1^+ (1_2^+) state in ^{24}Al is lower than that in ^{24}Na by 258 keV¹. This energy lowering in the 1_2^+ state of ^{24}Al suggests a TE shift, because excitation of a proton from the $d_{5/2}$ orbital to the $s_{1/2}$ orbital would be related to the 1_2^+ state according to a simple shell model.

The TE shift may affect the wave function in proton-rich nuclei. In addition to the original interpretation that the TE shift is the reduction of the Coulomb energy, a new interpretation has recently been put forward: the TE shift is regarded as lowering of the single-particle energy of the $s_{1/2}$ orbital [12]. Consequently the TE shift causes changes in the configuration in the wave function. For example, in the sd -shell region, the subshell gap between the $1s_{1/2}$ and $d_{5/2}$ orbitals may be quenched, then, the degree of configuration mixing is changed. The changes in configuration, especially increasing of the $1s_{1/2}$ -orbital component, may be a key to explaining the possible proton-halo structure such as reported in ^{17}Ne [13]. In this manner, the behavior of the s -orbital proton is important to understand characteristic properties of proton-rich nuclei. The large TE shift observed in the 1_2^+ state in ^{24}Al raises the question of whether there are changes in the configuration in the wave function associated with the TE shift in the low-lying states in ^{24}Al . Alternatively, is the energy-level asymmetry explained by the classical picture attributed to reduction of the Coulomb energy due to the spatial expansion of the weakly bound proton without changes in the configuration in the wave function?

The Gamow-Teller transition strength $B(\text{GT})$ provides a means of investigating the effects of the changes in the configuration in the wave function caused by the TE shift. Since the Gamow-Teller operator $\sigma\tau$ permits a nucleon's transition in one orbit only with spin flipping, $B(\text{GT})$ is sensitive to the orbital configuration in the wave functions. Therefore, if there is a change in configuration caused by the TE shift of the proton's $s_{1/2}$ -orbital, the change would be reflected in the mirror asymmetry of $B(\text{GT})$. $B(\text{GT})$ for the β decay of ^{24}Si [14] provides information on the configuration of the low-lying 1^+ states in ^{24}Al . Thus far, no experimental studies have been reported for the β decay to the low-lying bound 1^+ states.

In order to investigate the behavior of a weakly-bound s -orbital proton in terms of mirror asymmetry, we carried out the $B(\text{GT})$ measurement via the β -decay spectroscopy of ^{24}Si by measuring the β -delayed de-excitation γ rays from the low-lying bound states in ^{24}Al . This paper describes the results and discussion given in the previous paper [15] as well as some revisions through the incorporation of a recent experimental value used as a reference.

¹ The spin-parity of the state at 1.088 MeV was tentatively assigned to (1^+) , based on mirror symmetry for the spin-parity with the state at 1.346 MeV in ^{24}Na [6, 7, 8, 9, 10, 11].

2. Experiment

The experiment was performed at the RIKEN Projectile Fragment Separator (RIPS) facility [16]. The secondary beam of ^{24}Si was produced by projectile fragmentation of a 100-MeV/nucleon ^{28}Si beam with a primary target of $^{\text{nat}}\text{Ni}$. The secondary beam was identified event-by-event based on time-of-flight and energy-loss information. The beam was pulsed in order to measure the half-lives through the detection of β -delayed γ rays. The duration of the beam-on and beam-off periods was set to 500 ms.

The γ -ray setup consisted of an active beam stopper and a clover-type Ge detector equipped with BGO active counters and a plastic β -veto counter. The beam stopper was a plastic scintillator with a thickness of 5 mm placed at a tilted angle of 45 degrees with respect to the beam axis, which enabled determination of the absolute value of the branching ratio. The Ge detector was placed at a distance of 6.0 cm from the center of the stopper. The eight BGO counters surrounded the Ge detector to suppress the Compton background. The β -veto counter of a plastic scintillator with a thickness of 1 mm was located in front of the Ge detector to remove directly incident β rays. The experimental setup is described in further detail in Ref. [15].

In the γ -ray measurement, we observed two β -delayed γ rays of 0.426 MeV and 0.664 MeV emitted from the low-lying states in ^{24}Al . The 0.426-MeV and 0.664-MeV γ rays correspond to the de-excitations from the isomeric 1_1^+ state to the ground state [5] and from the state with spin-parity of (1^+) at 1.090 MeV to the 1_1^+ state [10], respectively. The half-life of the 0.664-MeV γ ray was determined to be 140.1(26) ms which was consistent with that of ^{24}Si [17, 18]. Based on the half-life, we confirmed that the 1.090-MeV state is populated by the β decay of ^{24}Si .

Branching ratios to the 1.090-MeV state was determined to be $b_2 = 0.239(15)$. In the deduction of the branching ratio b_1 to the 1_1^+ state, a reference value of the γ -transition ratio I_γ was needed. In the paper [15], a value of $I_\gamma = 0.82(3)$ taken from Ref. [19] was used, then b_1 was determined to be 31(4)%. However very recently, the γ -transition ratio has been remeasured and determined to be $I_\gamma = 0.696(7)$ [20]. Using this value, b_1 is revised to 41.0(44)%.

In Ref. [15] the decay scheme of ^{24}Si was reconstructed by combining the results of the delayed γ -ray measurement as well as a delayed proton measurement carried out at the same time using separate setups. The branching ratios to the unbound states are also changed with the new result; These ratios were derived from the relative intensities of the delayed protons via renormalization using the total branch to the unbound state that was the complement of the total branch to the bound state. The decay scheme of ^{24}Si , in which the branching ratios are derived using both the previous and new I_γ values, is shown in Fig. 2. The deduced $\log ft$ values and $B(\text{GT})$ are shown in Table 1.

The β -decay spectroscopy has an advantage for the spin-parity assignment in terms of $\log ft$. The spin-parity of the 1.090-MeV state has been suggested to be (1^+) [6, 7, 8, 9, 10, 11]. The transition to the 1.090-MeV state has a $\log ft$ value of 4.45 which is appropriate for an allowed transition. Due to the observation of the allowed transition, it is possible to firmly establish the spin-parity for this state as 1^+ . Thus, the 1.090-MeV state has been confirmed to be the 1_2^+ state.

Among the changes in the decay scheme that incorporates the new result, the superallowed transition to the isobaric analog state (IAS) is remarkable. In the case of β decay of an even-even nucleus such as ^{24}Si , a superallowed transition to a 0^+ IAS is a pure Fermi transition, because a Gamow-Teller transition is forbidden for $0^+ \rightarrow 0^+$ by the selection rule for spin-parity. The expected ft value for the pure Fermi transition of $T_z = -2$ nuclei is 1.536×10^3 sec which corresponds to $B(\text{F}) = 4$. The branching ratio with the previous I_γ value was 12.7(9)% from which the ft value was derived to be $1.2(1) \times 10^3$ sec. It was a problem that such an anomalously fast ft value could not be explained by the Fermi transition to an IAS alone. However the ft value derived from the branching ratio of 9.9(9)% with the new I_γ value has been deduced to be 1.5(1) sec which is consistent with the expected ft value for a pure Fermi transition.

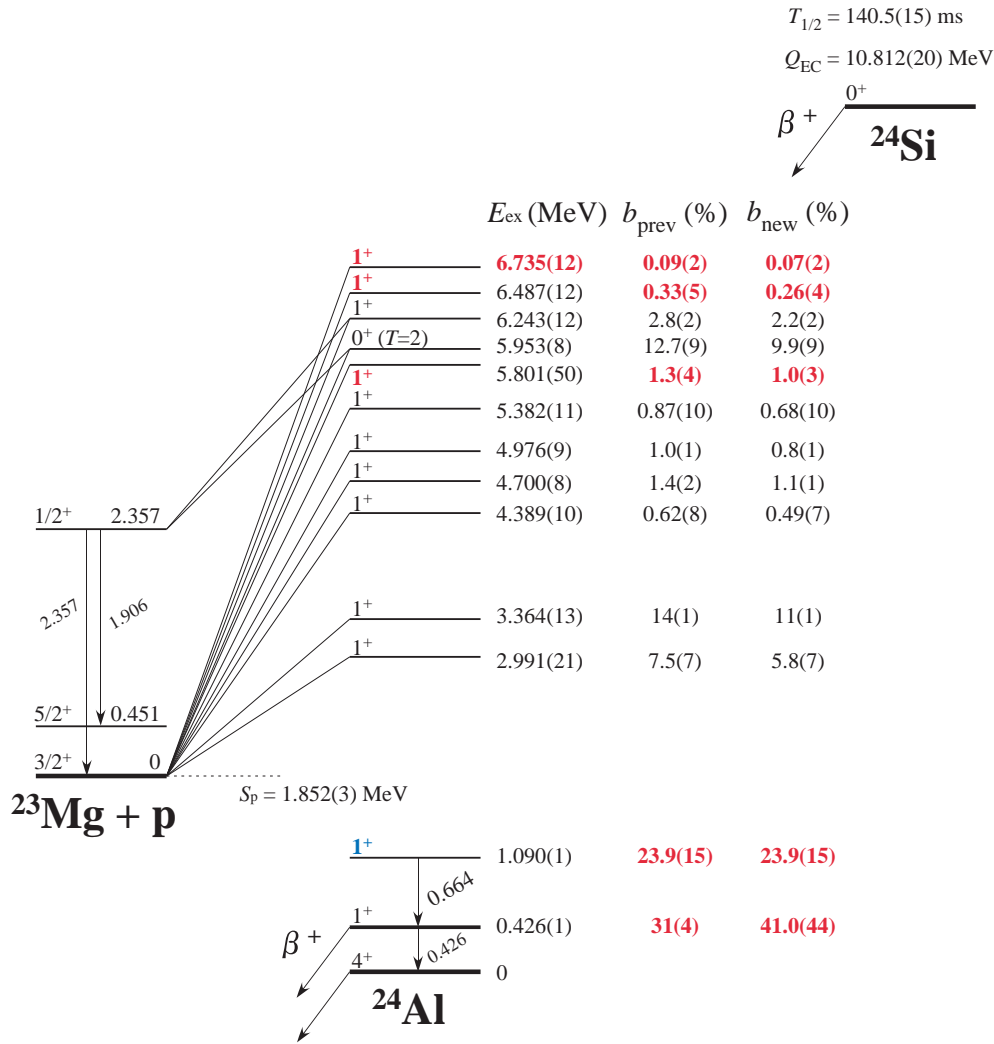


Figure 2. Decay scheme of ^{24}Si . Energy levels E_{ex} and spin-parities J^π are shown. b_{prev} and b_{new} represent the branching ratios derived using the γ -transition ratio from the 1_1^+ state of $I_\gamma = 0.82(3)$ [19] and $I_\gamma = 0.696(7)$ [20], respectively. Red and blue characters denote the newly determined and the firmly fixed values, respectively, in this work.

3. Discussion

In Ref. [15], the mirror asymmetry for Gamow-Teller transition is discussed based on the results using the previous γ -transition ratio $I_\gamma = 0.82(3)$. However, the new value $I_\gamma = 0.696(7)$ requires this mirror asymmetry, as well as the decay scheme described above, to be reevaluated. In this section, first we summarize the discussion of the previous result in Ref. [15], and then we incorporate the new result into the discussion.

With the previous result, $B(\text{GT})$ of ^{24}Si to the low-lying 1_1^+ and 1_2^+ states in ^{24}Al were deduced to be 0.13(2) and 0.14(1), respectively. The deduced $B(\text{GT})$ were compared with that of its mirror case of ^{24}Ne , that were 0.167(4) and 0.155(9) [4]. Then the ratios of $B(\text{GT})$, here defined as $B(\text{GT}^+)/B(\text{GT}^-)$, were determined to be 0.78(11) and 0.90(8) for the 1_1^+ and 1_2^+ states, respectively. The $B(\text{GT})$ asymmetries appear both in the 1_1^+ and 1_2^+ states, although the large TE shift is observed only in the 1_2^+ state. Instead, the degree of the asymmetry is larger in the 1_1^+ state than that in the 1_2^+ state. The appearance of $B(\text{GT})$ asymmetry in both

Table 1. Obtained branching ratio b , $\log ft$ value and $B(\text{GT})$. The subscripts of “prev” and “new” denote the results with previous $I_\gamma = 0.82(3)$ [19] and new $I_\gamma = 0.696(7)$ [20], respectively. The state of 5.953 MeV is the IAS of the ground state of ^{24}Si .

E_{ex} (MeV)	b_{prev} (%)	b_{new} (%)	$\log ft_{\text{prev}}$	$\log ft_{\text{new}}$	$B(\text{GT})_{\text{prev}}$	$B(\text{GT})_{\text{new}}$
0.426(1)	31(4)	41.0(44)	4.49(6)	4.37(4)	0.13(2)	0.17(2)
1.090(1)	23.9(15)	23.9(15)	4.45(3)	4.45(3)	0.14(1)	0.14(1)
2.991(21)	7.5(7)	5.8(7)	4.45(4)	4.56(5)	0.14(1)	0.11(1)
3.364(13)	14(1)	11(1)	4.06(4)	4.16(5)	0.34(3)	0.26(4)
4.389(10)	0.62(8)	0.49(7)	5.06(5)	5.17(6)	0.03(1)	0.3(1)
4.700(8)	1.4(2)	1.1(1)	4.60(5)	4.70(5)	0.10(1)	0.08(1)
4.976(9)	1.0(1)	0.8(1)	4.62(5)	4.72(6)	0.10(1)	0.07(1)
5.382(11)	0.87(10)	0.68(10)	4.51(5)	4.62(6)	0.12(2)	0.09(1)
5.801(50)	1.3(4)	1.0(3)	4.14(12)	4.25(12)	0.28(9)	0.22(7)
5.953(8)	12.7(9)	9.9(9)	3.07(3)	3.18(4)		
6.243(12)	2.8(2)	2.2(2)	3.57(4)	3.68(4)	1.03(9)	0.80(8)
6.487(12)	0.33(5)	0.26(4)	4.36(6)	4.47(7)	0.17(3)	0.13(2)
6.735(12)	0.09(2)	0.07(2)	4.79(10)	4.90(10)	0.06(2)	0.05(1)

states indicates the configuration changes in both states, because the energy-level asymmetry is mainly sensitive to the s -orbital component, while the $B(\text{GT})$ asymmetry is sensitive to the change in configuration mixing between the s - and d -orbital components.

In order to clarify the mechanism of the $B(\text{GT})$ asymmetry from a microscopic perspective, the experimental $B(\text{GT})$ were compared with theoretical ones. The theoretical $B(\text{GT})$ were calculated in the sd -shell model space with the universal sd -shell (USD) Hamiltonian [21]. This Hamiltonian is isospin invariant and $B(\text{GT})$ values for the mirror decays are equal. In addition to USD, calculation for the mirror asymmetry were carried out with the Hamiltonian [22] that takes into account the Coulomb interaction together with charge-independence breaking and charge-asymmetry breaking of strong interactions. Furthermore, the effect of weak binding energy is considered by lowering the single-particle energy of the $1s_{1/2}$ proton orbital by 500 keV relative to the neutron single-particle energy. It was determined to reproduce the experimental TE shift in the 1_2^+ state in ^{24}Al . The experimental $B(\text{GT})$ asymmetry was reproduced by taking into account the effect of weak binding energy. Therefore the $B(\text{GT})$ asymmetry in the 1_1^+ state is attributed to the lowering of the $1s_{1/2}$ orbital. For the 1_2^+ states, the changes of some amplitudes are accidentally cancelled out, thus the $B(\text{GT})$ asymmetry is not significant.

Here, let us survey the change of results with the new γ -transition ratio $I_\gamma = 0.697(7)$. The branching ratio to the 1_2^+ state is not changed. On the other hand, the branching ratio to the 1_1^+ state is revised to be $b_1 = 41.0(44)\%$. Using this result, the $B(\text{GT})$ to the 1_1^+ state is deduced to be $B(\text{GT}) = 0.17(2)$. By comparing with the mirror case, $B(\text{GT}) = 0.167(4)$, the $B(\text{GT})$ ratio is determined to be 1.0(1). With the previous I_γ value, the 1_2^+ state had mirror asymmetry of $B(\text{GT})$ by 22(11)%, that indicated a change in configuration in the wave function associated with the TE shift. However, the $B(\text{GT})$ asymmetry is not observed with the new I_γ value. Thus, the mirror asymmetry of the energy level of the 1_2^+ state in ^{24}Al is mainly attributed to the “classical TE shift”, that is, lowering of the Coulomb energy due to the spatial expansion of the weakly bound proton, rather than the lowering the $s_{1/2}$ -orbital energy causing a change in configuration in the wave function.

4. Summary

We carried out β -decay spectroscopy of the proton-rich ^{24}Si nucleus. Two β transitions to the low-lying bound states in ^{24}Al were observed for the first time. Through the comparison of the energy level and $B(\text{GT})$ of the mirror nuclei of ^{24}Al and ^{24}Na , the contribution of a weakly-bound s -wave proton to the nuclear structure was investigated. With the previous value of the γ -transition ratio $I_\gamma = 0.82(3)$ [19], deriving the branching ratio to the 1_1^+ state in ^{24}Al to be $b_1 = 31(4)\%$, the $B(\text{GT})$ asymmetry appears both in the 1_1^+ and 1_2^+ states in ^{24}Al , which indicates changes in the configuration in the wave function caused by the TE shift of the single-particle energy of the $s_{1/2}$ orbital. However with the new value $I_\gamma = 0.696(7)$, the branching ratio was revised to $b_1 = 41.0(44)\%$. The mirror asymmetry for $B(\text{GT})$ in the 1_1^+ state disappeared. Therefore, the TE shift in the 1_2^+ state can be understood from the classical picture, in which the lowering of the Coulomb energy is due to the spatial expansion of a weakly-bound proton. By considering the accuracy of the experiment and the consistency with other experimental results (see Ref. [20]), the new value should be adopted as the γ -transition ratio. The configuration change in the wave function associated with the TE shift, which was the focus of this work, may not occur in the case of ^{24}Al . However the notion of the configuration change might be a key to understanding various interesting phenomena reported for proton-rich nuclei, such as anomalously large reaction-cross-sections in ^{17}Ne [13] and an anomalous magnetic moment in ^9C [23] which cannot be explained without considering the breaking of the mirror symmetry in the nuclear structure.

Acknowledgements

The experiment was carried out at the RIKEN Accelerator Research Facility operated by the RIKEN Nishina Center and CNS, University of Tokyo. This work is supported by Grant-in-Aid for Scientific Research No.15204017 in Japan, NSF grant PHY-0758099 in the United States and the Japan-US Theory Institute for Physics with Exotic Nuclei (JUSTIPEN). Y. I. acknowledges Special Postdoctoral Researchers Program at RIKEN.

References

- [1] R. G. Thomas, Phys. Rev. **88**, 1109 (1952).
- [2] J. B. Ehrman, Phys. Rev. **81**, 412 (1951).
- [3] A. Bohr and B. R. Mottelson, *Nuclear Structure*, Vol. I (W.A. Benjamin, New York, 1969).
- [4] R. E. McDonald *et al.*, Phys. Rev. **181**, 1631 (1969).
- [5] A. J. Armini *et al.*, Phys. Lett. **21**, 335 (1966).
- [6] G. C. Kiang *et al.*, Nucl. Phys. **A499**, 339 (1989).
- [7] M. B. Greenfield *et al.*, Nucl. Phys. **A524**, 228 (1991).
- [8] B. D. Anderson *et al.*, Phys. Rev. C **43**, 50 (1991).
- [9] S. Kubono *et al.*, Nucl. Phys. **A588**, 521 (1995).
- [10] G. Lotay *et al.*, Phys. Rev. C **77**, 042802(R) (2008).
- [11] R. G. T. Zegers *et al.*, Phys. Rev. C **78**, 014314 (2008).
- [12] L. V. Grigorenko *et al.*, Phys. Rev. Lett. **88**, 042502 (2002).
- [13] W. Geithner *et al.*, Phys. Rev. Lett. **101**, 252502 (2008).
- [14] J. Äystö *et al.*, Phys. Lett. **B82**, 43 (1979).
- [15] Y. Ichikawa *et al.*, Phys. Rev. C **80**, 044302 (2009).
- [16] T. Kubo *et al.*, Nucl. Instrum. Methods Phys. Res. B **70**, 309 (1992).
- [17] S. Czajkowski *et al.*, Nucl. Phys. **A628**, 537 (1998).
- [18] V. Banerjee *et al.*, Phys. Rev. C **63**, 024307 (2001).
- [19] J. Honkanen *et al.*, Phys. Scr. **19**, 239 (1979).
- [20] K. Matsuta *et al.*, Proceedings of the 24th International Nuclear Physics Conference (INPC), TRIUMF at the University of British Columbia, Vancouver, Canada, to be published (2010).
- [21] B. A. Brown and B. H. Wildenthal, Ann. Rev. of Nucl. Part. Sci. **38**, 29 (1988).
- [22] W. E. Ormand and B. A. Brown, Nucl. Phys. **A491**, 1 (1989).
- [23] K. Matsuta, *et al.*, Hyperfine Interactions **97/98**, 519 (1996).