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Spectroscopy on very neutron-rich nuclei beyond N = 20

H. Sakurai

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

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Abstract. Recent studies on nuclear structure by using radioactive isotope beams available at the RIKEN projectile-fragment separator (RIPS) are introduced. Special emphasis is given to two selected experiments from recent programs that highlight studies on the magicity loss observed for very neutron-rich nuclei beyond $N = 20$ in the "island-of-inversion" region; the particle stability of ^{31}F, and the low-lying excited states of ^{34}Mg.

PACS. 21.10.Dr Binding energies and masses – 23.20.Lv Gamma transitions and level energies – 25.60.-t Reactions induced by unstable nuclei – 25.70.Mn Projectile and target fragmentation

1 Introduction

Radioactive isotope (RI) beams, bringing out a high isospin degree of freedom, have given a great opportunity to investigate nuclei far from stability and to reveal out new phenomena and exotic properties in extreme conditions of isospin asymmetry.

Under the leadership of Prof. Ishihara, such potentials of the RI beam field have been demonstrated by the RI beam program at the RIKEN projectile-fragment separator (RIPS) [1]. RI beam intensities obtained at RIPS in the light mass region are the world highest level, which has been made possible by the combination of high-energy and high-intensity primary beams with RIPS. RIPS has large momentum and angular acceptances as well as a sizable maximum magnetic rigidity, hence has a high collecting power of projectile fragments. These features were adopted in taking into account energy dependences of RI beam intensities. Based on the intense RI beams, unique spectroscopic methods and techniques have been developed for nuclei with extreme isospin.

One of the manifestations of exotic properties in isotopes far from the stability line has been the magicity loss around $Z \approx 11$ and $N \approx 20$ region, *i.e.*, the so-called island-of-inversion region. A particular feature in this region is the tendency toward prolate deformation in spite of the effect of spherical stability due to the magicity of the neutron number of 20 [2]. As a matter of fact, large deformation has been experimentally suggested by 1) the extra enhancement of the binding energies from the mass measurements [3], 2) a very low energy of the first 2^+ state of ^{32}Mg reported by β-spectroscopy [4], and 3) a large $B(E2; 0^+_{\rm g.s.} \to 2^+_1)$ value deduced for ^{32}Mg by the intermediate-energy Coulomb excitation method [5]. Recently, the ^{31}Na isotope was studied by Coulomb excitation [6]. Such spectroscopy in the island-of-inversion region has been limited to the $N = 20$ isotones so far. Theoretically, the possible deformation in this region has attracted much interest and several recent works are reported using shell models [7–10] and mean-field approaches [9,11,12].

In this report, recent highlights of experimental results on the $N = 20$ magicity loss at RIKEN are introduced and reviewed. Experiments performed at RIPS have made attempts to extend the investigation beyond $N = 20$. Among them, two works are selected here; the particle stability of nuclei related to the character of the extra enhancement of binding energies, especially for ^{31}F [13], and properties of low-lying excited states of ^{34}Mg which provide more direct information on deformation [14].

2 Particle stability —mass spectroscopy

The experimental determination of the neutron drip line is essential for the understanding of the nuclear stability for extreme isospin asymmetry. An experimental difficulty in the search for new isotopes beyond the heaviest observed nuclei is the low production rates. These difficulties have been considerably reduced by the high luminosity obtained at RIPS.

The experiments of direct production and identification of extremely neutron-rich nuclei toward the neutron drip line have been performed by using ^{50}Ti, ^{48}Ca and ^{40}Ar beams [13,15,16]. In the series of the experiments, the nuclear chart in the light and extremely neutron-rich region has been changed drastically, as summarized in fig. 1. The highlights of the results [13,15] are the obtained clear evidence of particle stability for ^{31}Ne and ^{31}F as well as of particle instability for ^{28}O.

The particle stability of ^{31}Ne, which was confirmed by using an $80A$ MeV ^{50}Ti beam [15], was in contrast with

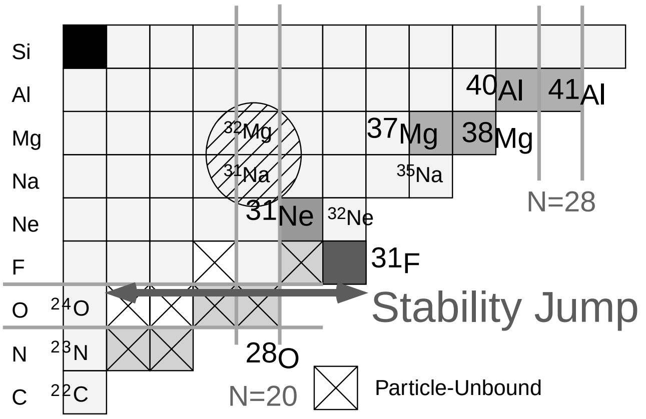

Fig. 1. Results obtained from the experiments at RIKEN [13, 15,16], searching for new isotopes toward the neutron drip line. The particle stability of ^{31}Ne [15], ^{37,38}Mg [16], ^{40,41}Al [16] and ^{31}F [13] has been established. In addition, clear evidence of particle instability has been obtained for ^{24,25}N, ^{27,28}O and ^{30}F [13]. It is remarkable that six additional neutrons can be bound by moving from oxygen to fluorine, where Z differs only by one. The sudden change in stability from oxygen to fluorine indicates an extra push of stability for the very neutron-rich fluorine isotopes.

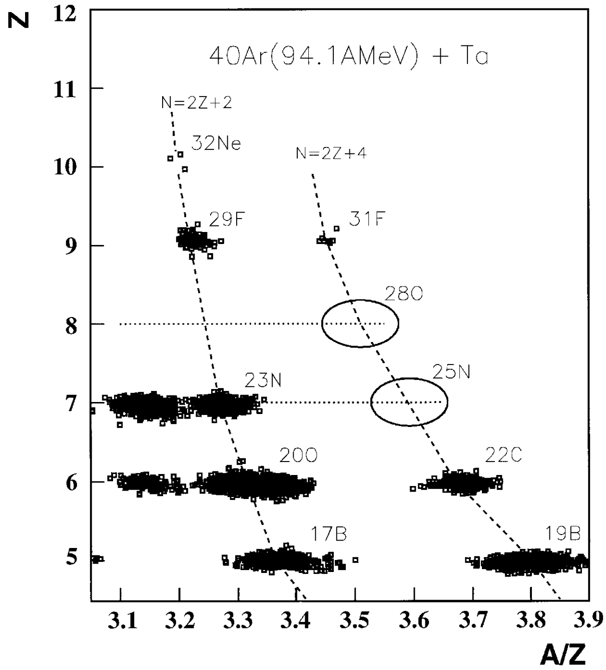

Fig. 2. Two-dimensional A/Z *versus* Z plot, which was obtained in the reaction of a 94.1 AMeV ^{40}Ar beam on a tantalum target [13]. A new isotope ^{31}F is clearly visible. No events associated with ^{25}N and ^{28}O as well as ^{24}N, ^{25,26,27}O were obtained. The dashed lines are drawn guides to the eye for the isotopes with the same neutron numbers, $N = 2Z + 2$ and $N = 2Z + 4$. Along the $N = 2Z+4$ line, the yields expected for ^{25}N and ^{28}O, which lie between ^{22}C (905 events) and ^{31}F (8 events), were estimated with fair reliability by the interpolation method.

most of the mass predictions as well as the previous experimental result [17]. ^{31}Ne is located at the deformation region. Thus, the extra stability of ^{31}Ne may be due to the deformation effect. Indeed, the particle stability of ^{31}Ne is predicted by two theoretical studies including deformation effects [18,19], which interestingly predict also the particle bound character of ^{31}F.

The discovery of the particle stability of ^{31}Ne motivated us to re-examine the location of the fluorine drip line, *i.e.*, to make an attempt for production and identification of ^{31}F by using a 94 A MeV ^{40}Ar beam [13]. The previously observed heaviest fluorine isotope, ^{29}F with $N = 20$ [20], had been in harmony with various mass predictions with or without deformation effects included, and had been suggested to be the drip line nucleus. We, however, observed a new isotope ^{31}F for the first time, as shown in fig. 2, and found that the heaviest isotope of fluorine has been extended up to ^{31}F with $N = 22$ beyond $N = 20$.

At the same time, a clear evidence of the particle instability of ^{28}O was obtained. The question of the possible stability of the double magic nucleus, ^{28}O, has attracted much attention, even though the particle instability of ^{25,26}O beyond ^{24}O had been clearly shown by two experiments [17,21]. The expectation for ^{28}O to be stable stems from an enhanced stability anticipated from the double magicity or the deformation. The stability of ^{28}O has been discussed in several theoretical papers based on both shell-model and mean-field approaches, which however yielded conflicting results. A previous attempt to search for ^{28}O had been made by using a ^{36}S beam [22]. In that work, no events of ^{28}O were observed, and the particle instability of ^{28}O was obtained from a comparison with the larger estimated yield for particle-stable ^{28}O. The yield estimate was made by means of an extrapolation method using the results of heavier isotones of $N = 20$. Such extrapolation may, however, involve some ambiguities since the Z, A dependence of the production cross-sections is not well understood theoretically. In order to reduce the possible uncertainty, an interpolation method was applied for the isotopes with $N = 2Z + 4$ as illustrated in fig. 2, and to deduce clearly the expected yield of ^{28}O [13]. It was also concluded that the ^{24,25}N and ^{30}F isotopes are particle-unbound.

It has been confirmed that the heaviest nitrogen and oxygen isotopes are ^{23}N and ^{24}O with the same neutron number, $N = 16$, while the heaviest isotope of fluorine has been extended up to ^{31}F with $N = 22$, as shown in fig. 1. It is remarkable that six additional neutrons can be bound by moving from oxygen to fluorine, where Z differs only by one.

Theoretically, two studies [18,19], which include the deformation effects, predict the particle stability of ^{31}F and ^{31}Ne. However, one of them, the FRDM mass formula [18] does not predict the particle instability of ^{26}O. Another theoretical work in a shell-model approach [19] demands strong configuration mixing between the *sd* and *fp* shells to explain properties of nuclei in the deformation region, but gives an over-binding to ^{28}O.

A recent work in the Monte Carlo shell-model calculation by Utsuno *et al.* [10] reproduces fairly well the measured S_{2n} values for very neutron-rich even-even isotopes in the $Z = 8$–12 region, which predicts, for instance, the particle-unbound character of ^{26,28}O. According to the calculation, the energy gap between $2s_{1/2}$ and $1d_{3/2}$ increases at $N = 16$ for the oxygen isotopes when the neutron number is increased [23]. This leads to the appearance of the new magic number 16 near the neutron drip line [24].

The fact of the particle instability of ^{28}O may suggest a large shell gap between $2s_{1/2}$ and $1d_{3/2}$ beyond $N = 16$. Concerning the fluorine isotopes, on the other hand, one additional proton into fluorine should play a key role to bring out the deformation or the mixing of *sd* and *fp* shells, hence to enhance the binding energies for the very neutron-rich fluorine isotopes. Besides such qualitative arguments, however, no quantitative attempts have been made so far to reproduce all of the experimental findings of particle stability and instability obtained in this region, especially for the particle stability of ^{31}F.

3 Spectroscopy for low-lying excited states

More direct information on deformation can be obtained from the properties of the low-lying excited states. The powerful method for in-beam γ-ray spectroscopy with RI beams has been the intermediate-energy Coulomb excitation. This method developed at RIKEN by Motobayashi *et al.* [5] allows us to determine $E(2_1^+)$ and $B(E2; 0^+_{\rm g.s.} \to 2_1^+)$ for very neutron-rich even-even nuclei even with relatively low-intensity RI beams.

Intriguing aspects of this method, which are to be compared with the traditional Coulomb excitation at sub-Coulomb barrier energies, are the following two points [25]. First, even in intermediate-energy reactions at several $10A$ MeV the Coulomb part in $E2$ excitations is dominant in comparison with the nuclear part when Z numbers of projectiles are chosen to be larger than 10 and heavy targets like Pb are used. Secondly, such high-energy RI beams allow us to use thick secondary targets and to detect ejectiles efficiently due to the kinematical focusing, which bring out high reaction rates for relatively low-intensity RI beams.

Since the virtue of the Coulomb excitation method at intermediate energies was shown, this method has been extensively employed for a large variety of even-even isotopes. Especially in the light and neutron-rich region, a great contribution has been made by Glasmacher *et al.* at MSU [6,26,27]. So far, such spectroscopy on low-lying excited states is only limited to the case of the $N = 20$ isotones among the isotopes in the island-of-inversion region.

Concerning the possible deformation of ^{34}Mg, one of the interesting features observed in the mass systematics is that the sudden enhancement of S_{2n} binding energy at ^{34}Mg along $N = 22$ is larger than at ^{32}Mg along $N = 20$ [28]. This may suggest that ^{34}Mg has a larger deformation than ^{32}Mg. An experimental attempt to determine the $E(2_1^+)$ and $B(E2; 0^+_{\rm g.s.} \to 2_1^+)$ values was once performed for ^{34}Mg [27], but due to the low statistics, no significant results have been deduced so far. Theoretically, several works are reported based on either shell-models or mean-field approaches. The recent shell-model calculation [10] predicts a larger deformation of ^{34}Mg than of ^{32}Mg. In order to clarify the basic mechanism for the occurrence of the anomalous deformation, it should be desirable to extend experimental studies beyond ^{32}Mg.

To find whether and how deformation evolves in the isotopes with $N = 22$, in-beam γ-ray spectroscopy on ^{34}Mg has been made with an alternative method, *i.e.*, the RI beam fragmentation method by Yoneda *et al.* [14].

The RI beam fragmentation method is a modified scheme of the fragmentation method originally proposed by Azaiez *et al.* [29], which incorporates the projectile fragmentation reaction to populate excited nuclei. As compared to the Coulomb excitation method, the fragmentation method affords a better access to higher excited states, and hence opens a possibility to determine the $E(4_1^+)/E(2_1^+)$ ratio. On the other hand, in general, in-beam γ-spectroscopy techniques with heavy loading of γ detectors suffer from strong γ-ray yields from other fragmentation products, which tend to overwhelm the limit of counting rate acceptable for γ-ray detection. This is particularly disturbing when one tries to study isotopes very far from the original projectile, whose relative yields are very small. To remove this difficulty, we have introduced a modified scheme of the fragmentation method. Namely, the ^{34}Mg isotope was produced in two steps: an RI beam of ^{36}Si was first produced from the ^{40}Ar primary beam, and the ^{34}Mg isotope was produced in the subsequent projectile fragmentation of ^{36}Si. In this scheme, ^{34}Mg differs from the secondary projectile only by two nucleons so that they share a fairly large fraction of the total γ-ray flux.

The ^{36}Si RI beam produced via the projectile fragmentation at RIPS was transported to a secondary target of ^{9}Be to be further fragmented to make ^{34}Mg nuclei. The fragments produced were detected and identified with a parallel-plate avalanche counter as well as four sets of counter telescopes. Gamma-rays from fragments in flight were detected with an array of the NaI(Tl) scintillators surrounding the secondary target. Further experimental details can be found in ref. [14]

Doppler corrected γ-ray energy spectra obtained in coincidence with even-even isotopes, of which transitions are known, were first examined to observe the systematic behavior of population in the fragmentation products. For most of the isotopes observed, two γ-lines appeared strongly. The strongest transition always corresponds to the $2_1^+ \to 0^+_{\rm g.s.}$ transition and the next strongest one is in most cases attributed to the $4_1^+ \to 2_1^+$ transition. This suggests that the excited states along the yrast line tend to be favorably populated in the fragmentation reaction. This trend, which was also observed in the ^{36}S + ^{9}Be reaction [29], may be used to tentatively assign the γ-transition.

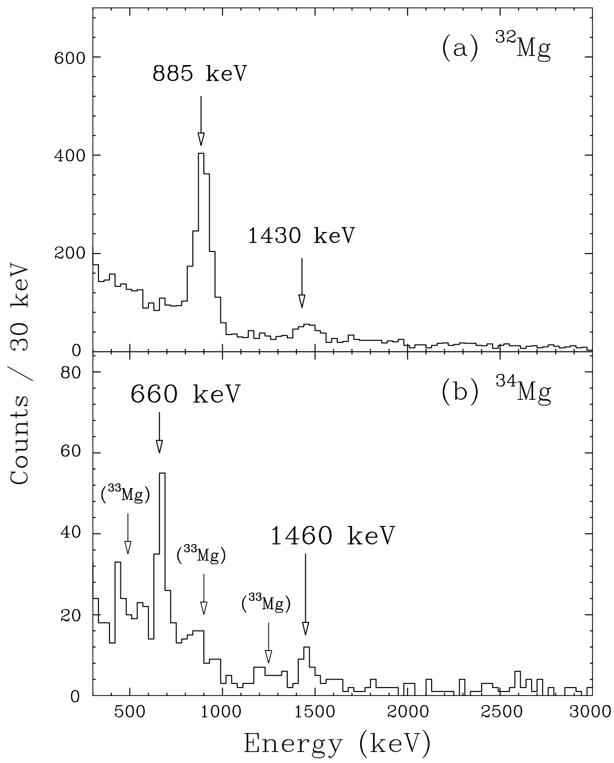

Fig. 3. Doppler corrected γ-ray energy spectra associated with ^{32}Mg (a) and ^{34}Mg (b), obtained from in-beam γ-ray spectroscopy using the RI beam fragmentation technique [14]. In spectrum (b) two sharp peaks can be seen at energies of 660 keV and 1460 keV.

The γ-ray energy spectra for ^{32}Mg and ^{34}Mg fragments are shown in fig. 3. In the spectrum for ^{32}Mg, one can see two prominent peaks around 885 keV and 1430 keV. The strongest peak at 885 keV corresponds to the known $2_1^+ \to 0_{\text{g.s.}}^+$ transition. According to an analysis of γ-γ coincidence, the coincidence relation between the two lines was confirmed. These results are in good agreement with the earlier experimental results obtained in the spectroscopy following the ^{36}S + ^{9}Be fragmentation reaction [29].

The γ-ray energy spectrum for ^{34}Mg, as shown in fig. 3 (b), clearly exhibits two significant γ-lines at 660(10) keV and 1460(20) keV to be attributed to ^{34}Mg. The spectrum involves some contamination peaks due to the adjacent nucleus ^{33}Mg [14,30]. According to the systematics of the γ-ray intensities, the strongest line at 660 keV can be assigned to the $2_1^+ \to 0_{\text{g.s.}}^+$ transition, resulting in $E(2_1^+) = 660$ keV. As for the next strongest line, the assignment is less certain. However, it is plausible that the line corresponds to the $4_1^+ \to 2_1^+$ transition. With this assignment, the value of $E(4_1^+)$ is 2120 keV.

The $E(2_1^+)$ value of ^{34}Mg can be compared with those of other Mg isotopes. Among the isotopes, the energy of 660 keV is the lowest. The small $E(2_1^+)$ value of ^{34}Mg, which is even smaller than that of ^{32}Mg, suggests a very large deformation for ^{34}Mg. The resulting value of the $E(4_1^+)/E(2_1^+)$ ratio is about 3.2, close to the limit for rotation nuclei, 10/3.

These results are compared with the predictions from the recent theoretical works [8–10]. Among them, the quantum Monte Carlo shell-model calculation [10] reproduces the experimental results very well, and the value of $E(2_1^+) = 620$ keV is predicted for ^{34}Mg. The predicted value of the $E(4_1^+)/E(2_1^+)$ ratio is 3.0, also in good agreement with the experimental results. These results are all suggestive that ^{34}Mg is indeed a very well-deformed nucleus. Recently the $B(E2)$ value was measured with the intermediate-energy Coulomb excitation method at RIPS [31]. The preliminary result indicates a $B(E2)$ value fairly larger than that of ^{34}Mg, further supporting a large deformation of ^{34}Mg.

4 Summary

The exotic properties of very neutron-rich nuclei beyond $N = 20$ in the island-of-inversion region have been observed on the basis of the high luminosity obtained at RIPS as well as the newly developed spectroscopic technique. The particle stability of ^{31}F and the particle instability of ^{28}O have indicated a stability jump manifested in the very neutron-rich fluorine isotopes. The energies of low excited states for ^{34}Mg were observed via the in-beam gamma spectroscopy with the RI beam fragmentation method, suggesting that ^{34}Mg has a larger deformation than ^{32}Mg.

Spectroscopic methods developed at not only RIKEN, but also other RI beam facilities will be naturally applied in the RIKEN future program, called RI Beam Factory (RIBF) project. The RIBF project was proposed to further promote research fields by utilizing RI beams which are now being used at RIPS. At RIBF, the range of radioactive nuclei will be expanded up to U, to enforce the advantage of RI beams. According to the expansion of available beams toward heavier nuclei, studies on the nuclear structure of very neutron-rich nuclei at $N = 50$ and 82 will be possible.

This work described here represents the efforts of many people, whom I have tried to adequately reference. In particular, most of the experiments presented here have been performed in collaboration with University of Tokyo, Rikkyo University and RIKEN. A part of the experiments for particle stability [13,16] has been performed under the JINR-RIKEN collaboration.

References

1. T. Kubo *et al.*, Nucl. Instrum. Methods B **70**, 309 (1992).
2. X. Campi *et al.*, Nucl. Phys. A **251**, 193 (1975).
3. C. Thibault *et al.*, Phys. Rev. C **12** 644 (1975); N.A. Orr *et al.*, Phys. Lett. B **258** 29 (1991); Z.G. Zhou *et al.*, Phys. Lett. B **260** 285 (1991); F. Sarazin *et al.*, Phys. Rev. Lett. **84**, 5062 (2000).
4. C. Detraz *et al.*, Phys. Rev. C **19** 164 (1979); D. Guillemand-Mueller *et al.*, Nucl. Phys. A **426**, 37 (1984).

5. T. Motobayashi *et al.*, Phys. Lett. B **346**, 9 (1995).
6. B.V. Pritychenko *et al.*, Phys. Rev. C **63**, 011305 (2001).
7. E.K. Warburton, J.A. Becker, B.A. Brown, Phys. Rev. C **41**, 1147 (1990).
8. E. Caurier *et al.*, Phys. Rev. C **58**, 2033 (1998).
9. P.-G. Rainhard *et al.*, Phys. Rev. C **60**, 014316 (1999).
10. Y. Utsuno *et al.*, Phys. Rev. C **60**, 054315 (1999).
11. Z. Ren *et al.*, Phys. Lett. B **380** 241 (1996); G.A. Lalazissis *et al.*, Nucl. Phys. A **628** 221 (1998); J. Terasaki *et al.*, Nucl. Phys. A **621**, 706 (1997).
12. R. Rodríguez-Guzmán *et al.*, Phys. Lett. B **474**, 15 (2000).
13. H. Sakurai *et al.*, Phys. Lett. B **448**, 180 (1999).
14. K. Yoneda *et al.*, Phys. Lett. B **499**, 233 (2001).
15. H. Sakurai *et al.*, Phys. Rev. C **54**, (1996) R2802.
16. H. Sakurai *et al.*, Nucl. Phys. A **616**, 208c (1997).
17. D. Guillemaud-Mueller *et al.*, Phys. Rev. C **41**, 937 (1990).
18. P. Möller *et al.*, At. Data Nucl. Data Tables **39**, 185 (1995).
19. A. Poves, J. Retamosa, Nucl. Phys. A **571**, 221 (1994).
20. D. Guillemaud Mueller *et al.*, Z. Phys. **332**, 189 (1989).
21. M. Fauerbach *et al.*, Phys. Rev. C **53**, 647 (1996).
22. O. Tarasov *et al.*, Phys. Lett. B **409**, 64 (1997).
23. T. Otsuka *et al.*, Nucl. Phys. A **685**, 100c (2001).
24. A. Ozawa *et al.*, Phys. Rev. Lett. **84**, 5493 (2000).
25. T. Motobayashi, *Proceedings Tours Symposium on Nuclear Physics II, Tours, France, 1994*, edited by H. Utsunomiya, M. Ohta, J. Galin, G. Münzenberg (World Scientific, Singapore, 1994) p. 61.
26. H. Scheit *et al.*, Phys. Rev. Lett. **77** 3967 (1996); T. Glasmacher *et al.*, Phys. Lett. B **395** 163 (1997); R.W. Ibbotson *et al.*, Phys. Rev. Lett. **80** 2081 (1998); T. Glasmacher, Annu. Rev. Nucl. Part. Sci **48**, 1 (1998).
27. B.V. Pritychenko *et al.*, Phys. Lett. B **461**, 322 (1999).
28. H. Sakurai, Contribution to the *Shell Model 2000, Wako, Japan, March, 2000.*
29. F. Azaiez *et al.*, *Nuclear Structure '98, Gatlinburg, Tennessee 1998*, edited by C. Baktash, AIP Conf. Proc. Vol. **481** (AIP, New York, 1998) p. 243; M. Belleguic *et al.*, Phys. Scr. Topical Issues T **88**, 122 (2000).
30. G. Walter *et al.*, Contribution to the *5th International Conference on Radioactive Nuclear Beams, Divonne, France, April 2000*, to be published.
31. H. Iwasaki *et al.*, Phys. Lett. B **522**, 227 (2001).