Search for Isovector Giant Monopole Resonances via the Pb(^{3}He,tp) Reaction

R. G. T. Zegers,[1] A. M. van den Berg,[1] S. Brandenburg,[1] F. R. R. Fleurot,[1] M. Fujiwara,[2,3] J. Guillot,[4] V. M. Hannen,[1]
M. N. Harakeh,[1] H. Laurent,[4] K. van der Schaaf,[1] S. Y. van der Werf,[1] A. Willis,[4] and H. W. Wilschut[1]
[1]*Kernfysisch Versneller Instituut, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands*
[2]*Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567, Japan*
[3]*Japan Atomic Energy Research Institute, Advanced Science Research Center, Tokai 319-1195, Japan*
[4]*Institut de Physique Nucléaire, IN2P3, Université de Paris-Sud, Orsay Cedex, France*
(Received 26 October 1999)

The $^{\rm nat}$Pb(^{3}He, tp) reaction at $E(^3\text{He}) = 177$ MeV was studied to identify $2\hbar\omega$ isovector monopole strength in Bi isotopes. Monopole strength was found in the region $-45 < Q < -30$ MeV in the coincidence data. The cross section is compared with distorted-wave Born approximation calculations for non-spin-flip and spin-flip isovector monopole resonances. The observed spin-flip and non-spin-flip monopole strengths in the proton-decay channel amount to 20% of the respective non-energy-weighted sum rule.

PACS numbers: 24.30.Cz, 25.55.Kr, 27.80.+w

The existence of the isovector $2\hbar\omega$ giant monopole resonance in nuclei is a long-standing problem. In addition to its fundamental interest as a collective phenomenon at high excitation energy that can be described by microscopic models as a $2\hbar\omega$ $1p$-$1h$ excitation [1,2], the isovector giant monopole resonance has been invoked as the mediator for isospin-symmetry breaking and isospin mixing in nuclei [3,4]. Especially for the isobaric analog state (IAS) excited by (p,n)-type, isospin-changing ($\Delta T_z = -1$), charge-exchange (CE) reactions, the origin of the spreading width has been closely connected to the ($\Delta L = 0, \Delta S = 0$) isovector non-spin-flip giant monopole resonance (IVGMR). Therefore, the observation of the $2\hbar\omega$ giant monopole resonance provides a crucial test for microscopic theoretical model calculations with effective nucleon-nucleon interactions, and in $\Delta T_z = -1$ reactions would moreover give better insight into the isospin-mixing and spreading mechanism of the IAS.

Considerable effort has been devoted to identify the isovector $2\hbar\omega$ giant monopole resonances, non-spin-flip IVGMR and spin-flip IVSMR ($\Delta L = 0, \Delta S = 1$) in CE reactions. In previous experiments using the π charge exchange [5–7], ^{90}Zr(n,p) [8], (^{13}C, ^{13}N) [9,10], and ^{60}Ni(^{7}Li, ^{7}Be) reactions [11], identification of the IVGMR and IVSMR was seriously hampered by the large widths of the resonances in combination with the presence of a large, nonresonant, continuum background. This continuum background is due to quasifree (QF) processes with three-body final states, such as breakup (BU) combined with single-nucleon pickup and knockon (KO) charge exchange.

For $\Delta T_z = +1$ CE reactions the resonance region lies lower in excitation energy, final states have only one isospin ($T = T_0 + 1$; T_0 is the isospin of the target ground state), and competing $1\hbar\omega$ resonances such as the IVGDR ($\Delta L = 1, \Delta S = 0$) and IVSDR ($\Delta L = 1, \Delta S = 1, \Delta J = 0, 1, 2$) are absent or at least Pauli blocked. As a result only in the case of the (π^-, π^0) [5–7] and ^{60}Ni(^{7}Li, ^{7}Be) [11] reactions (both $\Delta T_z = +1$) strength has been found that could unambiguously be attributed to the IVGMR. The observation of the IVSMR in the studies of the ^{90}Zr(^{3}He, t) reaction at projectile energies of 600 and 900 MeV [12,13] and the (p,n) reaction at 795 MeV [14] was conjectured, but the interpretation was ambiguous, because of the QF continuum background. Also, an attempt to locate isovector monopole strength via the ^{124}Sn(^{3}He, $t + n$) reaction at 200 MeV failed [15].

In this Letter we present experimental results which, for the first time, identify $2\hbar\omega$ isovector monopole strength in the $\Delta T_z = -1$ channel, using the Pb(^{3}He, t) reaction at $E(^3\text{He}) = 177$ MeV around 0°. We employed a special method to suppress the QF background by measuring in coincidence the decay by proton emission at backward angles. This makes use of the fact that the QF continuum is largely due to BU and KO processes which are associated with forward-peaked high-energy protons [16,17].

In Bi isotopes, the IVGMR and IVSMR are expected both to peak at a Q value ≈ -40 MeV and to have a total width of $\sim$10 MeV [18]. Their doorway states have 1π(particle)-1ν(hole) configurations which have nonvanishing escape widths for direct proton decay into low-lying neutron-hole states. Both are excited with $\Delta L = 0$ angular-momentum transfer and must therefore have isotropic decay patterns. By requiring a coincidence between tritons around 0° and protons emitted at backward angles, the resonance-to-continuum ratio can be strongly improved. Furthermore, the branching ratios for proton decay of the IVSMR and IVGMR might be sizable as suggested by recent proton-decay results for the Gamow-Teller resonance (GTR) [19,20] and the spin-dipole resonance (IVSDR) [20,21] in ^{208}Bi (4.9% ± 1.3% and 13.4% ± 3.9%, respectively), both excited via the ^{208}Pb(^{3}He, t) reaction at 450 MeV. Calculations in an extended continuum RPA framework [22] show good agreement with the above results and predict a significantly higher proton branching ratio of ≥30% for both the IVGMR and IVSMR in ^{208}Bi [18].

A 177 MeV ^{3}He beam from the AGOR cyclotron at KVI was used to bombard a 7.8 mg/cm^{2} $^{\mathrm{nat}}$Pb target. Tritons were detected with the Big-Bite Spectrometer [23] which was set at $-1°$ with respect to the beam [i.e., the beam entered the spectrometer off center, along the concave (shorter-radius) edge of the dipole]. A focal-plane detector constructed at IPN Orsay [24] was used. It consists of four cathode-strip chambers for vertical and horizontal positions and angle determination and two plastic-scintillator planes for particle identification and triggering.

A special aperture was mounted in front of the entrance of the spectrometer to define the triton scattering angle. It has rectangular holes, centered at vertical scattering angles of $-2.9°$, 0°, and $+2.9°$, with vertical opening angles of 1.1°, 2.3°, and 1.1°, respectively. The horizontal opening angle was 3.8° and thus triton scattering-angles between 0° and ~4.7° were covered. The holes in the aperture cover angular regions that coincide with the maximum (0°) and minimum (~3°) in the angular distributions of the IVSMR and IVGMR (see Fig. 2). Data were taken between Q values of -15 and -48 MeV.

Protons were detected in a silicon-ball assembly consisting of 15 Si(Li) detectors of 5 mm thickness. The detectors were positioned at polar angles ranging from 95° to 160° with respect to the beam direction, and azimuthal angles between $-20°$ and $+40°$, at a distance of 10 cm from the target. Almost 6% of the full solid angle was covered. Protons with an energy higher than 30 MeV punch through the detectors and consequently deposit less than their full energy.

Figure 1 shows the measured triton singles and $t + p$ coincidence spectra. In both spectra, the isobaric analog state (IAS) is clearly observed. The branching ratio for proton decay from the IAS in Bi is determined to be 69% ± 3%, consistent with the result of 64% ± 4% obtained by weighting previously measured branching ratios of the IAS for various targets of Pb isotopes [25] according to their natural abundances. In the singles and coincidence spectra, a broad bump due to the IVGDR and the IVSDR is observed at $Q \approx -25$ MeV.

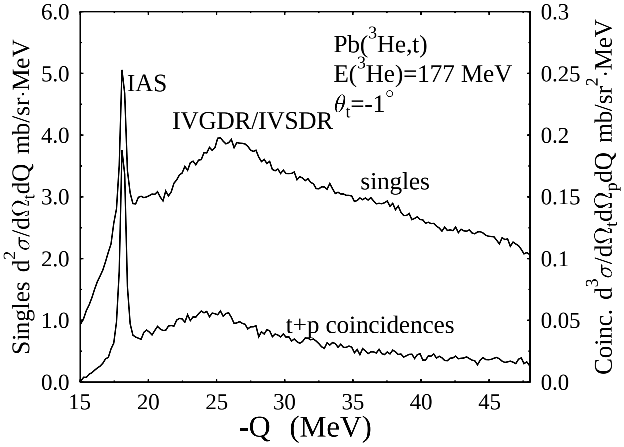

FIG. 1. Singles and $(t + p)$ coincidence Q-value spectra for the Pb(^{3}He, t) reaction at $E(^3\mathrm{He}) = 177$ MeV and $\theta_t = -1°$.

Calculations in plane-wave impulse approximation show that contributions to the coincidence spectra from quasifree processes decrease strongly at backward angles and more negative Q values and are very small and nearly angle independent for $\theta_p > 110°$ and $Q < -30$ MeV. This is confirmed in our present experiment. The measured coincidence yield for the backward-positioned proton detectors was indeed nearly angle independent, whereas the yield for the forward positioned detectors ($\theta_p = 96°$) was much larger. The data from these latter detectors have, therefore, been excluded in the analysis of the Q-value range of interest.

Cross sections for the ^{208}Pb(^{3}He, t)^{208}Bi reaction were calculated in the distorted-wave Born approximation (DWBA) framework using the code DW81 [26]. The cross sections of the resonances do not vary significantly among the Pb isotopes. An effective ^{3}He-nucleon (^{3}He-N) potential, consisting of isospin (V_τ), spin-isospin $V_{\sigma\tau}$, and isospin-tensor ($V_{T\tau}$) parts, each represented by a Yukawa potential, was used to describe the projectile-target interaction. At $E(^3\mathrm{He}) = 177$ MeV, i.e., ~60 MeV/u, contributions to the ^{3}He-N interaction from $V_{\sigma\tau}$ and V_τ are expected to be nearly equal [27]. The parameters for the effective potentials were taken from a preliminary analysis of the ^{12}C(^{3}He, t)^{12}N(g.s.) reaction at 200 MeV [28] and the ^{40}Ca(^{3}He, t)^{40}Sc($2_1^- + 5_1^-$) reaction at 197 MeV [29]. They are $V_{\sigma\tau} = -3.5$ MeV, $R_{\sigma\tau} = 1.415$ fm, $V_{T\tau} = -3.0$ MeV/fm^2, and $R_{T\tau} = 0.878$ fm. The value for V_τ was determined from the present experiment by fitting the cross section of the IAS. A value of $V_\tau = 3.5 \pm 0.1$ MeV, with the range $R_\tau = 1.415$ fm, was found in good agreement with previously extracted values for V_τ [30] at nearly the same bombarding energy.

Wave functions projected onto a complete $1p$-$1h$ basis were calculated in a normal-mode (NM) procedure [31]. In this formalism, the full strength [100% of the non-energy-weighted sum rule (NEWSR)] associated with single-particle multipole operators is exhausted. It should be noted that the strengths calculated for the IVSMR and IVGMR are a factor of 2 larger than the results from a Hartree-Fock random-phase approximation (HFRPA) calculation [1,2]. This is natural since the HFRPA approach takes ground-state correlations into account, in contrast to the NM calculations [2].

The results of the DWBA calculations for the IVSMR and IVGMR, as well as for the isovector giant quadrupole resonance (IVGQR, $J^\pi = 2^+$, $\Delta L = 2$) and IVGDR ($J^\pi = 1^-$, $\Delta L = 1$) are displayed in Fig. 2(a). The differential cross sections of the IVSMR and IVGMR peak at $\theta_t = 0°$, whereas the differential cross section

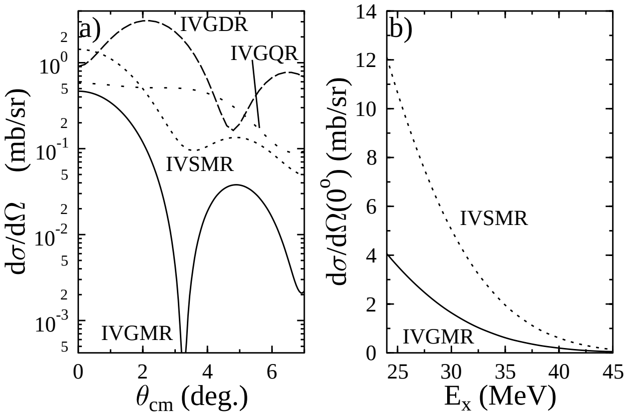

FIG. 2. (a) DWBA calculations, assuming full exhaustion of the NEWSR, for the IVGMR, IVSMR, IVGDR, and IVGQR excited via ^{208}Pb(^{3}He, t) at 177 MeV, with excitation energies of 35.0, 35.0, 22.8, and 31.4 MeV, respectively. (b) Calculated 0° cross sections of the IVGMR and IVSMR in ^{208}Bi for 100% NEWSR as a function of E_x.

of the IVGQR and QF continuum are flat near $\theta_t = 0°$. The angular distribution of the IVGDR and also the three components of the IVSDR with $J^\pi = 0^-, 1^-, 2^-$ [not shown in Fig. 2(a)] have a minimum at 0°. Figure 2(b) shows the cross sections of the IVSMR and IVGMR at 0° as a function of excitation energy, E_x. They decrease strongly with increasing E_x.

In order to emphasize monopole strength at low, i.e., very negative, Q values, the difference Q-value spectrum between events with average triton scattering angle $\bar{\theta}_t = 1.4°$ and $\bar{\theta}_t = 3.2°$ was constructed, making use of the angle-defining aperture described above. In Fig. 3(a) the spectra at $\bar{\theta}_t = 1.4°$ and $\bar{\theta}_t = 3.2°$ are shown for $-48 < Q < -27$ MeV; in Fig. 3(b) the difference is shown. Excess cross section is present at forward angles which is an indication for monopole strength. Events belonging to this excess are isotropically distributed over the proton detectors, as expected for monopole excitations. The result is shown in Fig. 4, where the excess is displayed as a function of polar angle θ_p [Fig. 4(a)] and azimuthal angle ϕ_p [Fig. 4(b)]. The distribution is consistent with isotropy.

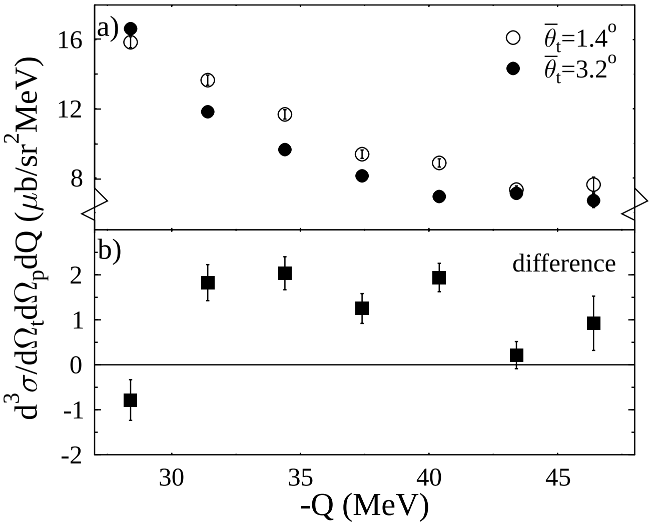

FIG. 3. (a) Coincidence spectra for the Pb(^{3}He, tp) reaction at 177 MeV for $\bar{\theta}_t = 1.4°$ and $\bar{\theta}_t = 3.2°$. (b) The difference between the spectra in (a).

Therefore, the excess in cross section at $\bar{\theta}_t = 1.4°$ with respect to $\bar{\theta}_t = 3.2°$ is attributed to monopole transitions. In order to determine the exhaustion of the NEWSR for the IVGMR and the IVSMR, the experimental results were compared with the DWBA calculations by folding the latter over the opening angle of the spectrometer, and taking into account the E_x (or Q-value) dependence as shown in Fig. 2(b). The experimental cross section was integrated over the full proton solid angle. The ratio between the folded DWBA cross sections for the IVSMR and IVGMR is approximately 3 over the whole Q-value range. Furthermore, we assume that the branching ratios for proton decay are the same for the IVGMR and IVSMR. This is expected [18] since both resonances have similar structure and strength distribution as a function of excitation energy [2]. The strength distribution in terms of exhaustion of the NEWSR, peaking at $Q \approx -41$ MeV, is shown in Fig. 5. If a Lorentzian fit to the data points is made, a width of 11 MeV is found. Between $Q = -30$ and -45 MeV, a fraction of 0.20 ± 0.04 of the NEWSR for the IVGMR and IVSMR is found in the proton-decay channel.

The microscopic structure of giant resonances can be well studied via the direct decay by particle emission. However, due to low statistics and the fact that high-energy protons punch through the proton detectors and thus deposit less energy, it was not possible in the present experiment to separate decay into different channels (statistical, direct, semidirect). Only an upper limit for decay by direct proton emission (i.e., proton emission to single-neutron-hole states) could be extracted, with a result corresponding to a 0.08 ± 0.04 fraction of the NEWSR. Statistical decay by proton emission is calculated to be very small (0.1%), which is due to the Coulomb barrier and the data

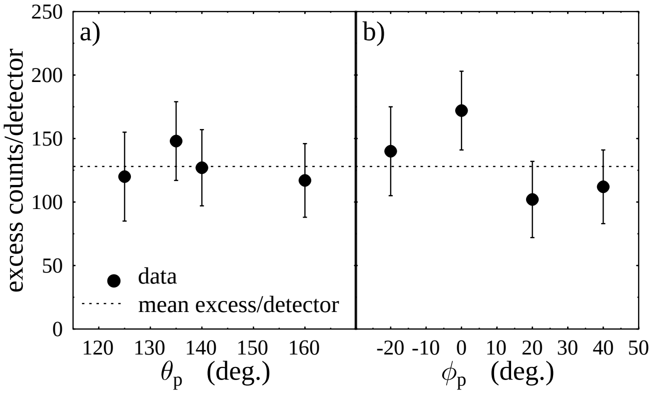

FIG. 4. Excess in counts (see Fig. 3) per proton detector at $\bar{\theta}_t = 1.4°$ with respect to $\bar{\theta}_t = 3.2°$. (a) As a function of θ_p; (b) as a function of ϕ_p.

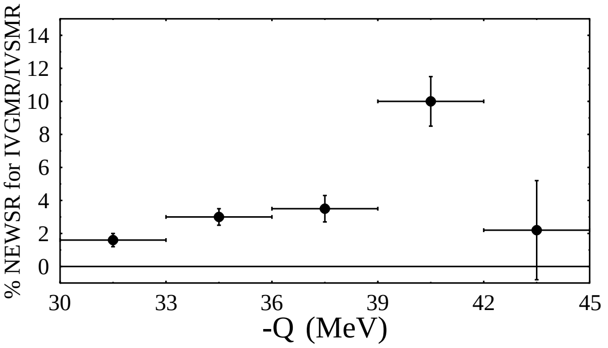

FIG. 5. Exhaustion of the NEWSR for the IVGMR and IVSMR as a function of Q. The data point between $Q = -45$ and -48 MeV has a large error (the exhaustion in this bin is 20% ± 15%) and is not included in the figure.

thus suggest that a considerable fraction of the measured proton coincidences is due to semidirect decay.

In the above analysis we assumed that the IVGMR and IVSMR are superimposed on a background with a flat triton angular distribution; possible interference from other resonances was neglected. The IVGQR has a flat angular distribution and thus will not contribute to the difference spectrum of Fig. 3(b). The tails of the IVGDR and IVSDR into the Q-value region $Q < -30$ MeV could, however, interfere with monopole contributions. Interference from the dipole resonances was estimated to lead possibly to a 20% reduction of the experimentally observed monopole cross section between $Q = -30$ and -45 MeV shown in Fig. 3(b). We also checked to which extent the monopole strength in the range between $Q = -30$ and -45 MeV could be due to high-lying GT strength. If the monopole cross section would be completely due to GT strength, 52% of the GT sum rule would be exhausted in the proton-decay channel only. However, the total GT strength, i.e., in all decay channels, missing at low excitation energies is 40% of the GT sum rule [32]. Since the branching ratio for proton decay is much smaller than 1, it is concluded that the observed monopole cross section in the Q-value range $-30 < Q < -45$ MeV cannot be due to GT strength for more than a small fraction. The cross section calculated in DWBA in the Q-value range $-30 < Q < -45$ MeV for the GTR (assuming that the full missing GT strength, i.e., 40% of the GT sum rule is in this Q-value region) is only 15% of that of the total measured cross section of the IVGMR and IVSMR.

In conclusion, monopole strength at high excitation energies has been found in the Pb(^{3}He, tp) reaction that can be attributed to the IVGMR and IVSMR in Bi isotopes. The observed strength in the proton-decay channel exhausts 20% of the NEWSR for the spin-flip and non-spin-flip monopole strengths. This would correspond to 100% of the NEWSR if a branching ratio of 0.2 for proton decay were assumed. Possible underestimation of the cross section of the IVGMR and IVSMR by 20% due to interference from dipole excitations and a possible overestimation of the cross section by 15% due to the presence of high-lying GT strength cannot be excluded.

This work was performed as part of the research program of the "Stichting voor Fundamenteel Onderzoek der Materie" (FOM) with financial support from the "Nederlandse Organisatie voor Wetenschappelijk Onderzoek" (NWO).

[1] N. Auerbach and A. Klein, Nucl. Phys. **A395**, 77 (1983), and references therein.
[2] N. Auerbach and A. Klein, Phys. Rev. C **30**, 1032 (1984).
[3] T. Suzuki, H. Sagawa, and G. Colò, Phys. Rev. C **54**, 2954 (1996), and references therein.
[4] J. Jänecke, M. N. Harakeh, and S. Y. van der Werf, Nucl. Phys. **A463**, 571 (1987), and references therein.
[5] A. Erell *et al.*, Phys. Rev. C **34**, 1822 (1986).
[6] A. Erell *et al.*, Phys. Rev. Lett. **52**, 2134 (1984).
[7] F. Irom *et al.*, Phys. Rev. C **34**, 2231 (1986).
[8] T. D. Ford *et al.*, Phys. Lett. B **195**, 311 (1987).
[9] C. Bérat *et al.*, Nucl. Phys. **A555**, 455 (1993).
[10] I. Lhenry, Nucl. Phys. **A599**, 245c (1996).
[11] S. Nakayama *et al.*, Phys. Rev. Lett. **83**, 690 (1999).
[12] C. Ellegaard *et al.*, Phys. Rev. Lett. **50**, 1745 (1983).
[13] N. Auerbach, F. Osterfeld, and T. Udagawa, Phys. Lett. B **219**, 184 (1989).
[14] D. L. Prout *et al.*, in *Proceedings of the Eighth International Symposium on Polarization Phenomena in Nuclear Physics, Bloomington, 1995*, edited by E. J. Stephenson and S. Vigdor, AIP Conf. Proc. No. 339 (AIP, New York, 1995), p. 458.
[15] R. G. T. Zegers *et al.*, Phys. Rev. C **61**, 054602 (2000).
[16] N. Matsuoka *et al.*, Nucl. Phys. **A337**, 269 (1980).
[17] E. H. L. Aarts *et al.*, Phys. Lett. **102B**, 307 (1981).
[18] M. L. Gorelik, V. A. Rodin, and M. H. Urin (private communication); (to be published).
[19] M. N. Harakeh *et al.*, Nucl. Phys. **A577**, 57c (1994).
[20] H. Akimune *et al.*, Phys. Rev. C **52**, 604 (1995).
[21] H. Akimune *et al.*, Phys. Rev. C **61**, 011304(R) (1999).
[22] E. A. Moukhai, V. A. Rodin, and M. H. Urin, Phys Lett. B **447**, 8 (1999).
[23] A. M. van den Berg, Nucl. Instrum. Methods Phys. Res., Sect. B **99**, 637 (1995).
[24] E. Plankl-Chabib, Ph.D. thesis, Université Paris XI, Orsay, 1999 (unpublished), and references therein.
[25] J. Bordewijk, Ph.D. thesis, Rijksuniversiteit Groningen, 1993 (unpublished).
[26] R. Schaeffer and J. Raynal, computer code DWBA70, SPtH, 1970 (unpublished); extended version DW81 by J. R. Comfort, University of Pittsburgh, 1981 (unpublished); updated version (1986).
[27] W. G. Love and M. A. Franey, Phys. Rev. C **24**, 1073 (1981).
[28] J. Jänecke *et al.* (to be published).
[29] S. L. Tabor *et al.*, Nucl. Phys. **A422**, 12 (1984).
[30] J. Jänecke *et al.*, Phys. Rev. C **48**, 2828 (1993).
[31] M. A. Hofstee *et al.*, Nucl. Phys. **A588**, 729 (1995); S. Y. van der Werf, computer code NORMOD, KVI Groningen, 1991 (unpublished).
[32] C. Gaarde *et al.*, Nucl. Phys. **A369**, 258 (1981).