Excitation and Decay of the Isovector Giant Monopole Resonances via the ^{208}Pb(^{3}He, tp) Reaction at 410 MeV

R. G. T. Zegers,[1,2] H. Abend,[3] H. Akimune,[4] A. M. van den Berg,[5] H. Fujimura,[1] H. Fujita,[6] Y. Fujita,[6] M. Fujiwara,[1,2] S. Galès,[7] K. Hara,[1] M. N. Harakeh,[5] T. Ishikawa,[8] T. Kawabata,[8] K. Kawase,[1] T. Mibe,[1] K. Nakanishi,[1] S. Nakayama,[9] H. Toyokawa,[10] M. Uchida,[8] T. Yamagata,[4] K. Yamasaki,[4] and M. Yosoi[8]

[1]*Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan*
[2]*Advanced Science Research Center, Japan Atomic Energy Research Institute, Tokai, Ibaraki 319-1195, Japan*
[3]*College of Arts and Science, New York University, New York 10003*
[4]*Department of Physics, Konan University, 8-9-1 Okamoto Higashinda, Kobe, Hyogo, 658-8501, Japan*
[5]*Kernfysisch Versneller Instituut, Zernikelaan 25, 9747 AA Groningen, The Netherlands*
[6]*Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan*
[7]*Institute de Physique Nucléaire, IN2P3/CNRS, Université de Paris-Sud, 91406, Orsay Cedex, France*
[8]*Department of Physics, Kyoto University, Kyoto, Kyoto 606-8502, Japan*
[9]*Tokushima University, Tokushima, 770-8502 Tokushima, Japan*
[10]*Japan Synchrotron Radiation Research Institute, SPring-8, Sayo, Hyogo 679-5198, Japan*

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The excitation and subsequent proton decay of the isovector spin-flip giant monopole resonance (IVSGMR) is studied via the ^{208}Pb(^{3}He, t) reaction at 410 MeV. In the inclusive spectrum $(60 \pm 5)\%$ of the non-energy-weighted sum-rule strength for this $2\hbar\omega$ resonance was found in the region $29 < E_x(^{208}\mathrm{Bi}) < 51$ MeV. The central excitation energy and width of the IVSGMR are 37 ± 1 MeV and 14 ± 3 MeV, respectively. It is found that the branching ratio for proton decay is $(52 \pm 12)\%$ and that the deep neutron-hole states in ^{207}Pb are strongly fed.

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The isovector giant monopole resonance (IVGMR, $\Delta L = 0$, $\Delta S = 0$, $\Delta T = 1$) and the isovector spin-flip giant monopole resonance (IVSGMR, $\Delta L = 0$, $\Delta S = 1$, $\Delta T = 1$) have proven to be difficult to study experimentally. Both resonances are of fundamental interest as collective excitations at high excitation energies that are described microscopically by coherent $2\hbar\omega$ $1p$-$1h$ transitions [1]. Their properties provide crucial tests for microscopic model calculations with effective nucleon-nucleon interactions. The IVGMR mediates isospin mixing and isospin-symmetry breaking in nuclei [2,3]. A reliable measurement of the IVSGMR can shed light on the missing Gamow-Teller (GT) strength (40%) at low excitation energies [4]. One explanation is that due to mixing of $1p$-$1h$ with $2p$-$2h$ configurations via the strong tensor interaction, GT strength is pushed up in excitation energy [5,6]. Indication for this was found in the study of ^{90}Zr(p, n) at $E_p = 295$ MeV [7], where assumptions were made to subtract the contribution from the IVSGMR.

Evidence for the existence of the IVGMR has been found via the (π^-, π^0) [8] and ^{60}Ni(^{7}Li, ^{7}Be) $\Delta T_z = +1$ [9] charge-exchange reactions. Other studies to locate the IVGMR [10] have led to ambiguous results. This is due to the presence of the continuum in combination with the large widths of the IVGMR (10–15 MeV). Therefore, even in the cases where the IVGMR was found, extraction of resonance parameters was hampered. The existence of the IVSGMR was conjectured in studies of the (^{3}He, t) reaction at $E(^3\mathrm{He}) = 600$ and 900 MeV [11,12]. Also, a comparative study of the ($\vec{p}$, $\vec{n}$) reactions at 200 and 800 MeV [13] suggests the presence of the IVSGMR.

The IVGMR and IVSGMR in ^{208}Bi are expected to peak around 38 MeV [1,14,15]. Because their doorway states are of 1π(particle)-1ν(hole) configuration and the excitation energy far exceeds the Coulomb barrier, large escape widths for direct proton decay are expected [14]. Since monopole resonances are excited with $\Delta L = 0$ angular-momentum transfer, the decay is isotropic. On the other hand, the continuum is due to quasifree processes with three-body final states. In the (^{3}He, t) reaction, these are associated with forward-peaked high-energy protons. Therefore, by requiring coincidences between tritons near 0°, where the cross section for the monopole peaks, and protons at backward angles, the continuum contribution is suppressed [16,17].

Inspired by results for proton decay from the Gamow-Teller resonance (GTR) and isovector spin-flip giant dipole resonance (IVSGDR) in ^{208}Bi [18,19] where relatively high branching ratios of $(4.9 \pm 1.3)\%$ and $(13.4 \pm 3.9)\%$ were found, the above method was used to search for the IVSGMR and IVGMR. Evidence for the IVSGMR and IVGMR was found in the Pb(^{3}He, tp) reaction at 177 MeV [20,21]. At 177 MeV, the IVGMR and IVSGMR are expected to be excited with a ratio of 3 to 1. Since the two cannot be distinguished experimentally if no additional information on the spin transfer during the reaction is known, assignment of strength separately to each was difficult. Also, the Pb(^{3}He, t) singles cross section for the IVGMR and IVSGMR could not be obtained and the extracted branching ratio for proton decay was model dependent.

In this Letter, the results of a ^{208}Pb(^{3}He, tp) experiment at $E(^{3}\mathrm{He}) = 410$ MeV are presented. In contrast to the case of $E(^{3}\mathrm{He}) = 177$ MeV, at $E(^{3}\mathrm{He}) = 410$ MeV the spin-isospin term of the effective ^{3}He-nucleon interaction ($V_{\sigma\tau}$) is much larger than the isospin term (V_{τ}) [22] and the IVSGMR dominates the IVGMR by more than an order of magnitude. This is exemplified by the strong relative decrease of the excitation of the isobaric analog state (IAS) with respect to the GTR at higher bombarding energies. By improving the sensitivity of the triton-angle measurement in the current experiment, the IVSGMR was not only identified in the t-p coincidence data, but also in the triton singles' data, allowing for determination of the strength exhaustion and model-independent extraction of the partial branching ratios for proton decay.

A 410 MeV ^{3}He beam from the Research Center for Nuclear Physics (RCNP) ring cyclotron was used to bombard a 10.1 mg/cm^{2} ^{208}Pb target. Tritons were detected in the Grand Raiden spectrometer [23] which was set at -5.2 mrad with respect to the beam (i.e., the beam entered the spectrometer off center, along the shorter-radius edge). Three runs with different magnetic fields were taken to cover a large excitation-energy range (0–65 MeV). To determine the vertical component of the scattering angle, the "off-focus" mode was employed [24]. Angle calibrations were performed at each setting using a sieve slit. Angular resolutions obtained were 0.2° and 0.4° (FWHM) for the horizontal (θ_h) and vertical (θ_v) components of the scattering angle, respectively. To extract monopole contributions we compare spectra near 0° and small finite angles. Complete ray tracing was achieved for angular ranges $-0.23° < \theta_h < 1.14°$ and $-1.43° < \theta_v < 1.43°$ ($\theta_h = 0°, \theta_v = 0°$ is the beam axis), corresponding to a scattering-angle range between $0° and 1.8°$ and a solid angle of 1.2 msr. The determination of the vertical component of the scattering angle strongly improves the sensitivity of the experiment. The energy resolution for the detection of tritons was 200 keV.

Protons were detected in eight ΔE-E silicon detector [Si(Li)] arrays, placed at backward angles (four at 113° and four at 136° with respect to the beam axis). A total of 2% of the full solid angle was covered. Both the ΔE and E detectors were 5 mm thick. This setup enables unambiguous determination of the proton energy (E_p) even for very energetic ($>$ 30 MeV) protons that punch through the ΔE detector. The resolution in the final-state spectra is degraded in the latter case [from 0.5 to 1.1 MeV (FWHM)].

Cross sections for the ^{208}Pb(^{3}He, t) reaction at 410 MeV were calculated in distorted-wave Born approximation (DWBA) using the code DW81 [25]. Optical-model parameters determined at $E(^{3}\mathrm{He}) = 450$ MeV [26] were used. For the tritons, the potential-well depths were taken 85% of the depths for the ^{3}He particles [27]. An effective ^{3}He-N potential with isospin (V_{τ}), spin-isospin ($V_{\sigma\tau}$), and isospin-tensor ($V_{T\tau}$) terms, each represented by a Yukawa potential, was employed to describe the projectile-target interaction. The value of V_{τ} was determined from the present data by fitting the IAS ($E_x = 15.16$ MeV) cross section [see Fig. 1(a)]. V_{τ} was the only fit parameter and found to be 0.73 ± 0.01 MeV. From the known ratio of $V_{\sigma\tau}/V_{\tau}$ at $E(^{3}\mathrm{He}) = 450$ MeV [18], $V_{\sigma\tau}$ was determined to be 2.1 ± 0.2 MeV. $V_{T\tau}$ was chosen to be -2.0 MeV/fm^{2} but is uncertain. The $T\tau$ interaction becomes increasingly small near zero momentum transfer and, therefore, near 0° the DWBA calculations are insensitive to its value. Wave functions projected on a complete $1p$-$1h$ basis were calculated in a normal-mode (NM) procedure [21,28]. In this formalism, 100% of the non-energy-weighted sum rule is exhausted. For resonances at higher excitation energies, like the IVSGMR, this leads to an overestimation of the strength compared to more sophisticated [1,14,15] approaches. As shown in Fig. 1(a) the cross sections of the IVSGMR and IVGMR ($E_x = 40$ MeV) peak at 0° and the IVSGMR is much more strongly excited than the IVGMR. Also shown are our experimental results for the IAS, which are nicely reproduced by DWBA, the combined IVSGDR (three components with $J^{\pi} = 0^{-}, 1^{-}, 2^{-}$ MeV) and isovector giant dipole resonance (IVGDR, $J^{\pi} = 1^{-}$) at an average excitation energy of 21 MeV and the isovector giant quadrupole resonance (IVGQR, $\Delta L = 2, \Delta S = 0$, located at $E_x = 33$ MeV). By subtracting differential cross sections at small finite angles (1°–2°) from those near 0°, one can differentiate the contributions from monopole and dipole excitations. Quadrupole contributions are canceled out. In the present analysis, differential cross sections in angular bins defined by the arrows in Fig. 1(a) are used. Figure 1(b) shows that the differential cross section of the

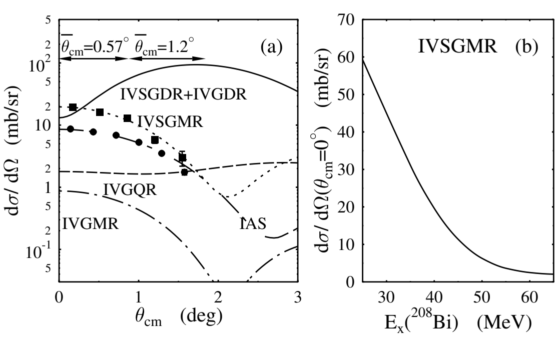

FIG. 1. (a) DWBA calculations for the IAS, IVSGMR, IVGMR, IVSGDR + IVGDR, and IVGQR, assuming full strength exhaustion. The circles are the measured cross sections for the IAS in this experiment, and the squares indicate the measured angular distribution for the IVSGMR, divided by the extracted degree of strength exhaustion (0.60). The error bars are mostly smaller than the symbol sizes. (b) IVSGMR cross section assuming full strength exhaustion as a function of E_x, as used for determination of the strength exhaustion from the data.

IVSGMR at 0° drops rapidly as a function of E_x due to the increasing transferred momentum.

In Fig. 2(a), the measured ^{208}Pb(^{3}He, t) double-differential cross sections for the most forward angles are compared with those at small finite angles. Figure 2(b) shows the difference between the two. The $\Delta L = 0$ IAS and GTR give clear positive contributions to the difference and the IVSGDR a negative contribution. For $E_x >$ 29 MeV an excess in cross section at forward angles is found. The continuum background also peaks at forward angles, but the angular dependence is shallow [29] and has a smooth dependence on E_x. Therefore, the area below the dashed line in Fig. 2(b) is identified as the contribution due to the continuum and the area above the dashed line as the contribution due to the IVSGMR. By using the calculated angular distribution for the IVSGMR [Fig. 1(a)] its differential cross section at 0° was extrapolated from the difference in each E_x bin. These were then divided by the calculated 0° cross section [Fig. 1(b)] to obtain the NM-strength exhaustion [S_{NM}; Fig. 2(e), open data points]. For the IVSGMR $(60 \pm 5)\%$ of the full normal-mode strength is exhausted in the region $29 < E_x < 51$ MeV, where the minor contribution from the IVGMR (3%) has been taken into account. A fit between $E_x = 32$ and 51 MeV with a Lorentzian leads to a peak position and width of the IVSGMR of 37 ± 1 MeV and $\Gamma = 14 \pm 3$ MeV, respectively. By combining the difference-of-angles method using five 0.36°-wide angular bins, the angular distribution of the resonance was extracted and the consistency with the DWBA calculation for the IVSGMR checked. The result is indicated by the squares in Fig. 1(a), where the data points have been divided by the measured degree of strength exhaustion (0.60) for the IVSGMR to enable a comparison with the DWBA calculation in which full exhaustion is assumed. A good consistency is found.

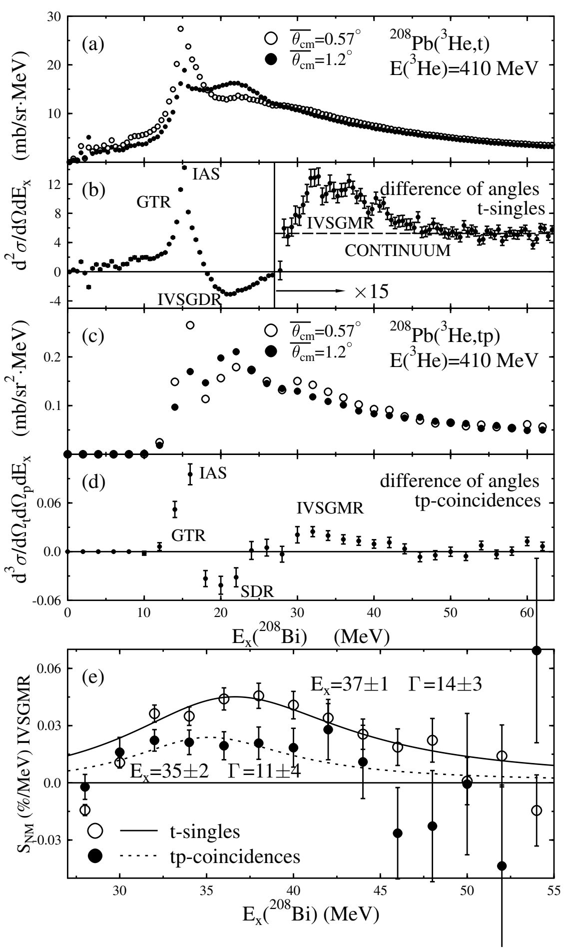

FIG. 2. (a) ^{208}Pb(^{3}He, t) double-differential cross sections at $\overline{\theta}_{cm} = 0.57°$ and $\overline{\theta}_{cm} = 1.2°$. (b) The singles difference-of-angle spectrum. The data above $E_x = 27$ MeV have been multiplied by a factor of 15. (c) ^{208}Pb(^{3}He, tp) triple-differential cross sections at $\overline{\theta}_{cm} = 0.57°$ and $\overline{\theta}_{cm} = 1.2°$. (d) The coincidence difference-of-angle spectrum. (e) Strength-exhaustion distribution of the IVSGMR and fits with Lorentzians for the singles and coincidence data.

The error bar in the strength exhaustion indicates statistical errors only. Systematic errors arise from the following: (i) The extrapolation of the continuum to lower excitation energies (~30 MeV) where, however, the effect on the extracted strength is small and estimated to be 5%. (ii) The presence of high-lying GT strength. If the measured monopole cross section at high excitation energies is fully attributed to GT strength, it would exhaust the GT sum rule by 200%, and only 40% is missing at lower excitation energies. Also, since the high-lying GT strength is spread out over a large excitation-energy range, the procedure of removing the continuum cancels (part of) the GT strength in the region of the IVSGMR and makes its contribution negligible. (iii) Missed IVSGMR strength due to cancellation by the tail of the IVSGDR. Estimation of this is difficult since only a limited angular range was covered. However, a simple approximation based on the shape of the difference spectrum indicates that about 10% of the IVSGMR strength could have been missed due to the tail of the IVSGDR. Since the IVSGDR affects the IVSGMR distribution mostly at lower excitation energies, the range below 32 MeV was not used for fitting the IVSGMR with a Lorentzian. (iv) Uncertainties in the optical potential used for the DWBA calculations. These are estimated to be 10% of the cross section.

Conjecturing a linear dependence between strength and cross section, the extracted strength in the NM calculation corresponds to $(68 \pm 7)\%$ exhaustion for the IVSGMR in the Tamm-Dancoff approximation [15], $(103 \pm 9)\%$ exhaustion in continuum RPA [14] and $210\% \pm 16\%$ exhaustion in Hartree-Fock RPA [1]. It should be noted that in the latter case a different form for the multipole operator is chosen.

In Figs. 2(c) and 2(d), the t-p coincidence results are presented. The layout is similar to Figs. 2(a) and 2(b). In the coincidence spectrum the continuum is suppressed, and in the difference spectrum between forward and backward angles [Fig. 2(d)] no excess of counts is seen

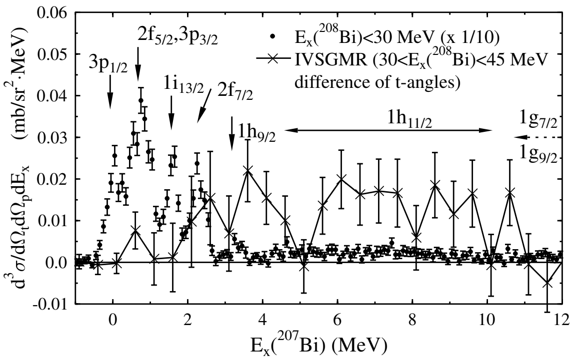

FIG. 3. The ^{207}Pb final-state spectra for proton decay from the IVSGMR (crosses/lines) and for all events with $E_x(^{208}\mathrm{Bi}) <$ 30 MeV (dots; scaled by a factor of 0.1).

for $E_x > 45$ MeV, proving that such a feature in the singles spectrum was due to the continuum. The strength distribution for the tp coincidences was determined in a similar manner as for the singles results [see Fig. 2(e), filled data points], but have larger statistical uncertainties. The extracted peak position ($E_x = 35 \pm 2$ MeV) and width ($\Gamma = 11 \pm 4$ MeV) are consistent with those determined from the singles data. Proton decay from the IAS to neutron-hole states in ^{207}Pb has been studied in the past [18,30]. Our results are consistent with those. The branching ratio for proton decay from the IVSGMR amounts to $(52 \pm 12)\%$. A value of 66% was predicted [14], with especially the $1i_{13/2}$ hole state [$E_x(^{207}\mathrm{Pb}) = 1.63$ MeV] being strongly fed. However, from Fig. 3, where the final-state spectrum is shown for decay from the IVSGMR [difference of final-state spectra at $\overline{\theta}_{cm}(t) = 0.57°$ and $\overline{\theta}_{cm}(t) = 1.2°$ for $30 < E_x(^{208}\mathrm{Bi}) < 45$ MeV], no decay to this state is found. For comparison, the final-state spectrum for $E_x(^{208}\mathrm{Bi}) < 30$ MeV, where the hole states can be distinguished, is also plotted. Strong feeding [$(13 \pm 5)\%$] from the IVSGMR of the $2f_{7/2}$ and $1h_{9/2}$ states is found. By comparing with results of the ^{208}Pb(^{3}He, α) [31] reaction, structures at higher $E_x(^{207}\mathrm{Pb})$ are identified as the $1h_{11/2}$ and the $2g_{7/2}/2g_{9/2}$ deep-hole states, with branching ratios of $(22 \pm 8)\%$ and $(17 \pm 8)\%$, respectively. For the latter case, the final-state energies are beyond the horizontal scale of Fig. 3. The complete measurements of the branching ratios provides crucial information to confront and improve microscopic models. The statistical proton decay from the IVSGMR is expected to be small: about 1% calculated with the code CASCADE [32]. These protons have an energy of about 9 MeV independent of excitation energy and are easily identified. We find a branching ratio of $(3 \pm 3)\%$ for such protons, consistent with the expectation.

In conclusion, the IVSGMR is identified using the ^{208}Pb(^{3}He, t) reaction at 410 MeV. A total of $(60 \pm 5 \pm 14)\%$ of the NM strength is found, where the first error is statistical and the second the combined systematical one. The branching ratio for proton decay from the IVSGMR is $(52 \pm 12)\%$. In contrast to prediction, no evidence for feeding of the $1i_{13/2}$ final state was found. Instead, the deep-hole states in ^{207}Pb are strongly populated.

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