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“Bi-modal” isoscalar giant dipole strength in ^{58}Ni

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Abstract

The strength distribution of the isoscalar giant dipole resonance (ISGDR) in ^{58}Ni has been obtained over the energy range 10.5–49.5 MeV via extreme forward angle scattering (including 0°) of 386 MeV α particles. We observe a “bi-modal” E1 strength distribution for the first time in an $A < 90$ nucleus. The observed ISGDR strength distribution is in reasonable agreement with the predictions of a recent RPA calculation.

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The compressional-mode giant resonances in the atomic nuclei—the isoscalar giant monopole resonance (ISGMR) and the isoscalar giant dipole resonance (ISGDR)—provide a direct method to obtain the incompressibility of the nucleus and of nuclear matter (K_{nm}) [1]. Although ISGMR has been investigated extensively for a large number of nuclei in the past, the exotic ISGDR has been identified only in a few nuclei and the location of ISGDR is not systematically established over the wide mass region. One major concern with ISGDR data had been that the nuclear incompressibility extracted from the centroid of the ISGDR strength distribution was significantly different from that obtained from the ISGMR data. In recent work, this ambiguity has been resolved for ^{208}Pb by a more precise, background-free measurement of ISGDR strength distribution, and the value of K_{nm} obtained from the ISGMR data is now consistent with that from the ISGDR data for ^{208}Pb [2].

The experimentally-observed ISGDR strength distribution in all $A \geqslant 90$ nuclei has a “bi-modal” structure [3–6], in agreement with predictions of recent theoretical work [7–10]. Of these, only the high-energy (HE) component depends on K_{nm} and, hence, is of interest from the point of view of determining an experimental value for this important parameter. The low-energy (LE) component, which is quite small in comparison with the HE component, is located much higher in excitation energy than the expected $1\hbar\omega$ component of the ISGDR, previously identified by Poelhekken et al. [11]. As well, it is lower in energy than the isovector giant dipole resonance (IVGDR) which can be excited in inelastic α scattering via Coulomb excitation; in the event, the full expected IVGDR strength is subtracted out in the analysis of all aforementioned data. The exact nature of this component is not fully understood yet, although suggestions have been made that it might represent the “toroidal” or “vortex” modes; Refs. [12,13] provide a review of the recent experimental and theoretical results on ISGDR.

For ^{58}Ni, there has been only one recent measurement, wherein a concentrated ISGMR and isoscalar giant quadrupole

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resonance (ISGQR) strength distribution has been observed, but the ISGDR strength is reported to be spread more or less uniformly over $E_x = 12$ to 35 MeV [14]. This observation leaves a few open questions: Is the ISGDR strength fragmented in light nuclei such as ^{58}Ni? Are we missing the resonance strength distribution because of experimental limitations? In an attempt to answer these questions, we have carried out measurements on excitation of isoscalar giant resonances in ^{58}Ni. In this Letter, we report our results on the ISGDR strength distribution in ^{58}Ni. We find that the ISGDR in this nucleus has a "bi-modal" structure as well, similar to that in the medium- and heavy-mass nuclei, and that the experimentally observed ISGDR strength is in reasonable agreement with predictions of a recent RPA calculation.

The $^{58}\mathrm{Ni}(\alpha, \alpha')$ experiment at $E_\alpha = 386$ MeV was performed at the ring-cyclotron facility of Research Center for Nuclear Physics (RCNP), Osaka University. Details of the experimental measurements and data analysis procedures have been provided in Refs. [2,4]; only the salient points are elaborated upon below. α-particles, inelastically scattered off a 5.8 mg/cm^2-thick ^{58}Ni target, were momentum analyzed in the spectrometer, Grand Raiden [15], and detected in the focal-plane detector system comprised of two multi-wire drift-chambers and two scintillators, providing particle identification as well as the trajectories of the scattered particles. The scattering angle at the target and the momentum of the scattered particles were determined by the ray-tracing method. The $^{58}\mathrm{Ni}(\alpha, \alpha')$ spectra were measured in the angular range of 0° to 8.5° for two excitation-energy-bite settings of the spectrometer ($E_x = 5.0$–35.0 MeV and $E_x = 22.0$–52.0 MeV). The primary beam was stopped at one of four different Faraday cups, depending on the scattering angle and the excitation energy bite of the spectrometer. The vertical position spectrum obtained in the double-focused mode of the spectrometer was exploited to eliminate the instrumental background due to Coulomb scattering of the beam at the target and subsequent rescattering by the edges of the entrance slit, the yoke, and walls of the spectrometer [2,4]. Fig. 1 shows an excitation energy spectrum for the $^{58}\mathrm{Ni}(\alpha, \alpha')$ reaction at $\theta_{\mathrm{avg.}} = 0.69°$ after subtraction of the instrumental background. A prominent "bump" corresponding to (ISGMR + ISGQR) in ^{58}Ni is observed at $E_x = 10$–25 MeV and another bump (ISGDR + the high-energy octupole resonance (HEOR)) is visible as a shoulder at $E_x \sim 33$ MeV. There is an underlying continuum in the high excitation-energy region in the spectrum. Since there is no sound theoretical basis to estimate and subtract the physical continuum from the excitation energy spectrum, it is reasonable to assume that the continuum background remaining after elimination of the instrumental background is the contribution from the higher multipoles and the three-body channels resulting, for example, from knockout reactions. In the present work, a multipole-decomposition (MD) analysis has been performed to extract giant resonance strengths, by taking into account the transferred angular momentum up to $\Delta L = 7$. The cross-section data were binned in 1-MeV energy intervals to reduce the statistical fluctuations. For each excitation-energy bin from 10.5 MeV to 49.5 MeV, the experimental angular distribution $\sigma^{\mathrm{exp}}(\theta_{\mathrm{c.m.}}, E_x)$ has been fitted by means of the least-square method with the linear combination of calculated distributions $\sigma^{\mathrm{cal}}(\theta_{\mathrm{c.m.}}, E_x)$ defined by

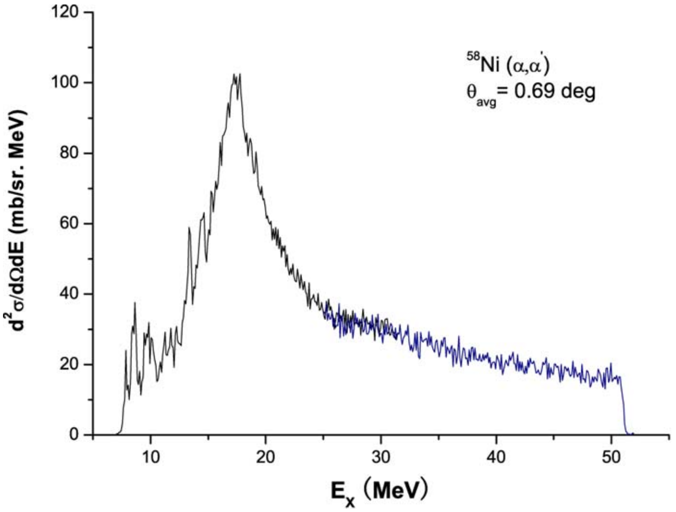

Fig. 1. Excitation energy spectrum for the $^{58}\mathrm{Ni}(\alpha, \alpha')$ reaction at $E_\alpha = 386$ MeV. Inelastically-scattered α particles were measured with the magnetic spectrometer at $\theta = 0°$ with two different settings of the magnetic field to cover the excitation-energy ranges of $E_x = 5.0$–35.0 MeV and $E_x = 22.0$–52.0 MeV.

$$\sigma^{\mathrm{exp}}(\theta_{\mathrm{c.m.}}, E_x) = \sum_{L=0}^{L=7} a_L(E_x) \times \sigma_L^{\mathrm{cal}}(\theta_{\mathrm{c.m.}}, E_x), \qquad (1)$$

where $\sigma_L^{\mathrm{cal}}(\theta_{\mathrm{c.m.}}, E_x)$ is the calculated distorted-wave Born approximation (DWBA) cross section corresponding to 100% energy-weighted sum rule (EWSR) for the Lth multipole.

The DWBA calculations were performed following the method of Satchler and Khoa [16] using density-dependent single folding, with a Gaussian α-nucleon potential (range $t = 1.88$ fm) for the real part, and a Woods–Saxon imaginary term; the calculations were carried out with the computer code PTOLEMY [17]. Input parameters for PTOLEMY were modified [18] to take into account the correct relativistic kinematics. The shape of the real part of the potential and the form factors for PTOLEMY were obtained using the codes SDOLFIN and DOLFIN [19]. We used the transition densities and sum rules for various multipolarities described in Refs. [1,20]. The radial moments for ^{58}Ni were obtained by numerical integration of the Fermi mass distribution with $c = 4.08$ fm and $a = 0.515$ fm [20]. The folding-model parameters with the computer code PTOLEMY were obtained from analysis of $^{58}\mathrm{Ni} + \alpha$ elastic- and $J^\pi = 2^+$ inelastic-scattering data at $E_\alpha = 386$ MeV taken in a separate experiment. The folding model parameter extracted for the real part of the potential is $V = 37.02$ MeV, and the parameters for the Woods–Saxon type imaginary part were: $W = 36.86$ MeV, r_I(reduced radius) $= 0.95$ fm, and a_I(diffuseness) $= 0.67$ fm. Using these parameters, the DWBA calculation for the first $J^\pi = 2^+$ state in ^{58}Ni was carried out with PTOLEMY using a collective form factor with the previously-known $B(\mathrm{E2}) = 0.070\ e^2\,\mathrm{b}^2$ [21,22]. Fig. 2 compares the results of the calculations and the experimental data; the calculations reproduce elastic scattering cross sections as