Excitation of the Isovector Giant Dipole Resonance by Inelastic α Scattering and the Neutron Skin of Nuclei

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(Received 2 November 1990)

The cross section of the isovector giant dipole resonance (GDR) excited by inelastic scattering of 120-MeV α particles for $0° \leq \Theta_{\alpha'} \leq 3°$ has been measured using the ^{116,124}Sn$(\alpha,\alpha'\gamma_0)$ and ^{208}Pb$(\alpha,\alpha'\gamma_0)$ reactions. The results are compared with distorted-wave Born-approximation calculations with a GDR form factor depending on the relative difference of proton and neutron radii ($\Delta R_{pn}/R_0$). Within the model used, the $\Delta R_{pn}/R_0$ values for ^{116}Sn, ^{124}Sn, and ^{208}Pb deduced from the comparison of measured and calculated cross sections are $(0.7^{+2.3}_{-0.7})$%, $(4.1^{+2.1}_{-2.5})$%, and (3.0 ± 1.3)%, respectively.

PACS numbers: 25.55.Ci, 21.10.Gv, 24.30.Cz

Determining the shape of the nuclear matter density distribution has received continued interest throughout the history of nuclear physics.[1] Experiments with electrons and muons have provided reliable data for the charge density of stable nuclei. Unambiguous neutron density distributions are much harder to obtain as this necessarily involves the hadron-nucleus interaction, and a model-independent description of this interaction and reaction mechanism is still lacking. According to Batty *et al.*[2] the analysis of $\approx$800-MeV polarized-proton scattering data has the promise of being able to yield absolute results on the neutron density distribution. Recent analyses[3,4] of such data, using a nonrelativistic impulse approximation (NRIA) with various corrections included or a relativistic impulse approximation (RIA), give a good description of spin observables. However, with respect to the determination of nuclear densities there are still some problems.[4,5]

Recently, the excitation of the isovector giant dipole resonance (GDR) by isoscalar probes, especially by α particles, has been studied in detail. The reason for this interest is that the GDR is nearly degenerate with the isoscalar giant monopole resonance (GMR) in heavy nuclei, which gave rise to the concern that its excitation would complicate the interpretation of the GMR data.[6] Theoretically it has been shown that the cross section for GDR excitation depends strongly on the neutron-proton relative radius difference.[7-10] The calculations also show that the effect should be small, which was experimentally confirmed by Poelhekken *et al.*[11] In this Letter we use the fact that the GDR excitation cross section by inelastic α scattering depends strongly on $\Delta R_{pn}/R_0$, the relative neutron-proton radius difference, to determine in a model-dependent but novel way this fundamental quantity. In order to separate effectively the GDR from the GMR, from the giant quadrupole resonance (GQR), and from the nuclear continuum excited in inelastic α scattering, α'-γ coincidence measurements were performed. Since photon decay occurs mainly by $E1$ transitions, a strong enhancement of the GDR in γ_0 decay is expected in comparison to the strength of other multipolarities.[12]

The experimental setup was nearly identical to the one used in Ref. 11. A momentum-analyzed 120-MeV α-particle beam provided by the Kernfysisch Versneller Instituut (KVI) cyclotron was used to bombard a 20.2-mg/cm^2 ^{116}Sn, a 21.9-mg/cm^2 ^{124}Sn, and a 29.9-mg/cm^2 ^{208}Pb target enriched to 90.0%, 96.6%, and 99.0%, respectively. The beam was stopped in the focal plane of the QMG/2 magnetic spectrograph[13] which was set at 0° with respect to the beam direction. The inelastically scattered α particles, with scattering angles between $-3°$ and $+3°$ in the horizontal and vertical directions, were detected in the 47.5-cm multiwire detection system.[14] This system provides position, angle, and energy information. Standard techniques as described in detail in Ref. 15 were used to prepare the beam and to set up the spectrograph for the 0° measurements. The coincident γ rays were detected in a large 10-in.$\times$13-in. NaI(Tl) crystal with a plastic anticoincidence shield,[16] placed at 125° with respect to the beam axis. The angular distribution of $E1$ radiation following the (α,α') reaction can be written in a simple form, when the solid angle of the α' detector is axially symmetric around $\Theta_{\alpha'}=0°$:[17]

$$I_\gamma(\Theta)=I_\gamma^0[1+a_2P_2(\cos\Theta)]\,.$$

Since at $\Theta\simeq125°$, $P_2(\cos\Theta)=0$, the measurement at that angle provides a good sample for the angle-integrated cross-section determination.

A 12-cm-thick ^{6}LiH absorber was inserted in front of the NaI(Tl) crystal which reduced the background due to capture of slow neutrons by an order of magnitude. The remaining neutrons were effectively separated from the γ rays by time-of-flight discrimination. The distance of 84 cm and a time resolution of ≈ 3 ns allowed a good separation. The resolution of the NaI(Tl) detector, typically 3.5% at 6.13 MeV improving to 2% at 20 MeV, is sufficient to select the decay to the ground state. The efficiency of the NaI(Tl) detector was calculated with the Monte Carlo code[18] EGS for a number of γ-ray energies and has been checked against experimental measurements at $E_\gamma=6.13$, 7.12, and 22.6 MeV. From the comparison between the data and calculations, a 10% relative error was associated with the calculated values. For this particular setup, resolution, and line shape, the EGS code predicts an efficiency $\epsilon=43.6\%$ for $E_\gamma=14$ MeV. The solid angle of the detector was 70 msr.

In order to obtain absolute cross sections, the beam charge was collected during the measurements by a Faraday cup, and the K x-ray yield from the target was measured with a $2\text{-cm}^2\times10\text{-mm}$ Ge detector placed at 125° with respect to the beam direction. The accuracy of the x-ray normalization ($\approx 10\%$) is mainly determined by the uncertainties in the K x-ray production cross sections.[19–21] The two types of normalization were found to be consistent within 10%.

Final-state spectra of the residual nuclei after γ decay were constructed by combining for each event the energy of the inelastically scattered α particle with the energy of the coincident γ radiation. Random coincidences were subtracted. The resulting final-state spectra are shown in Fig. 1. The spectra were fitted with "Gaussian + exponential tail" line shapes. The peak positions and FWHM were free parameters, but the line-shape parameter (tail) was obtained from the EGS Monte Carlo calculation.

For ^{124}Sn, the first excited 2^+ state is nearly as strongly populated as the ground state. This is more then twice as much as one would expect for GDR decay on the basis of the phonon-coupling model (for a recent discussion see Ref. 22 and references therein) using the known $B(E2)$ value of the 2^+ state. Taking into account the dominance of $E1$ radiation in the photon decay process and of excitation of natural-parity states in the (α,α') reaction, this discrepancy may suggest that 3^- strength, which is known to be present in this excitation energy region, has also been excited.

From the final-state spectra, the ground-state transition coincidence cross sections were determined to be 25 ± 6, 37 ± 8, and 36 ± 7 μb/sr for ^{116}Sn, ^{124}Sn, and ^{208}Pb, respectively. These cross sections are obtained for the solid angle of the α' particle ($0°\pm3°$), for the excitation-energy range $12\le E^*\le17$ MeV for ^{116,124}Sn and $11\le E^*\le14$ MeV for ^{208}Pb, and for the full (i.e., 4π) γ solid angle. The uncertainties are mainly due to statistics, x-ray normalization, and the uncertainties in the detection efficiencies of the NaI(Tl) detector and the focal-plane detection system. These cross sections include a small contribution from the γ_0 decay of the isoscalar GQR which can be estimated as 1.4 and 2.3 μb/sr for ^{116,124}Sn and ^{208}Pb, respectively.

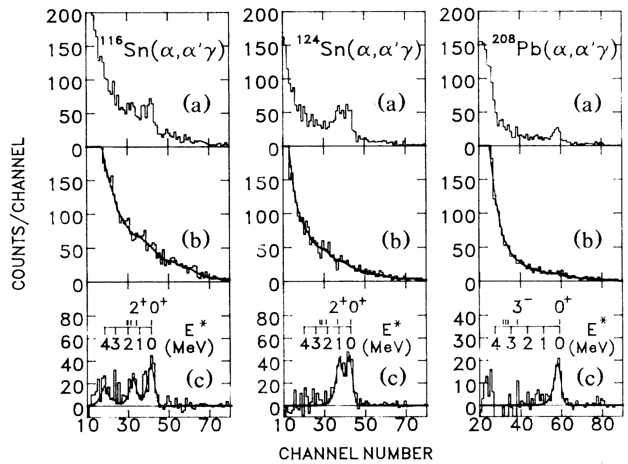

FIG. 1. Final-state spectra of ^{116}Sn, ^{124}Sn, and ^{208}Pb after γ decay of the $12\le E^*\le17$ MeV excitation energy region for ^{116,124}Sn and $11\le E^*\le14$ MeV energy region for ^{208}Pb populated in (α,α') reaction with $E_\alpha=120$ MeV and $\Theta_{\alpha'}=0°\pm3°$. (a) Spectra without random subtraction. (b) Random coincidence spectra obtained from two beam bursts, one preceding and one following the one with the prompt coincidences; the smoothed curves are used for random subtraction. (c) The real spectra obtained by subtracting half of the smoothed random spectrum (b) and (a), with the results of the peak fitting.

Distorted-wave Born-approximation cross sections for the excitation of the GDR in inelastic α scattering were calculated using the code[23] ECIS with the optical-model parameters determined by Brissaud *et al.*[24] for ^{116}Sn and ^{124}Sn, and by Goldberg *et al.*[25] for ^{208}Pb. In the derivation of the coupling potentials, which are the most crucial quantities in the calculations, the prescription of Satchler[8] was followed: The Goldhaber-Teller (GT) model is adopted for the GDR, the same radial shape is assumed for the neutron (ρ_n) and proton (ρ_p) density distributions, and the parameter α is introduced, which is related to the central densities of the proton and neutron distributions by

$$\frac{\rho_p(r=0)}{\rho_n(r=0)}=\frac{Z+\alpha(N-Z)/2}{N-\alpha(N-Z)/2}\,. \tag{1}$$

The parameter α is closely related to the relative neutron-proton radius difference:

$$\frac{\Delta R_{pn}}{R_0}=\frac{R_n-R_p}{(R_n+R_p)/2}=\alpha\frac{2(N-Z)}{3A}\,. \tag{2}$$

The transition potential is given by[8]

$$\Delta U_{\rm tr}=\alpha\beta_1\left[\frac{N-Z}{A}\right]\left[\frac{dU_0}{dr}+\frac{1}{3}R\frac{d^2U_0}{dr^2}\right], \tag{3}$$

which is thus obtained from the real (V) and imaginary

(W) parts of the optical potential (U_0). The β_1 deformation length is given by

$$\beta_1^2 = \frac{\pi\hbar^2}{2m}\frac{A}{NZE_x}, \tag{4}$$

where E_x is the excitation energy of the GDR.[26] Coulomb excitation is included by adding the usual[8] Coulomb transition potential. The calculations were performed as a function of the excitation energy by taking the value β_1 from Eq. (4), thus assuming 100% exhaustion of the energy-weighted sum rule. The results were then folded with the photonuclear strength distribution $[\sigma_\gamma(E)]$ (Ref. 26) as follows:

$$\sigma_{\alpha\alpha'}(E) = \sigma_{\alpha\alpha'}^{100\%}\frac{A}{0.06NZ}\sigma_\gamma(E). \tag{5}$$

This folding was found to be very important due to the strong excitation-energy dependence of the Coulomb excitation.[12,27-30] The result of the folding for ^{208}Pb is shown in Fig. 2.

From the above $\sigma_{\alpha,\alpha'}(E)$ cross sections, the $\sigma_{\alpha,\alpha'\gamma_0}(E)$ coincidence cross sections were deduced following the procedure described in Ref. 12:

$$\sigma_{\alpha,\alpha'\gamma_0}(E) = \sigma_{\alpha,\alpha'}(E)\left[\frac{\Gamma_{\gamma_0}(E)}{\Gamma} + \frac{\Gamma^\downarrow}{\Gamma}B_{\rm CN}(E)\right], \tag{6}$$

where $\Gamma_{\gamma_0}(E)$ is the ground-state photon decay width of the doorway state, Γ is the width of the resonance, $\Gamma^\downarrow$ is the spreading width, and $B_{\rm CN}(E)$ is the γ-decay branching ratio of the compound nucleus. We assumed that $\Gamma^\downarrow/\Gamma \approx 1$.[12] The dominant, direct decay part of the expression was calculated from the experimentally known photoneutron cross sections,

$$\frac{\Gamma_{\gamma_0}(E)}{\Gamma} = \frac{1}{3\pi^2\hbar^2c^2}\frac{E^2}{\Gamma}\int_{\rm resonance} dE\,\sigma_\gamma(E). \tag{7}$$

The $B_{\rm CN}(E)$ γ-decay branching ratios for ^{116,124}Sn were obtained from statistical-model calculations using a modified version of the program[31] CASCADE with level-density parameters of Dilg *et al.*[32] In the case of ^{208}Pb, the experimental $B_{\rm CN}(E)$ values[12] were used.

The calculated $\sigma_{\alpha,\alpha'\gamma_0}$ cross sections averaged over the α' solid angle and integrated over the energy range of the GDR as a function of the relative neutron-proton radius difference are shown in Fig. 3 for ^{116}Sn, ^{124}Sn, and ^{208}Pb, respectively. Using the completely different opti-

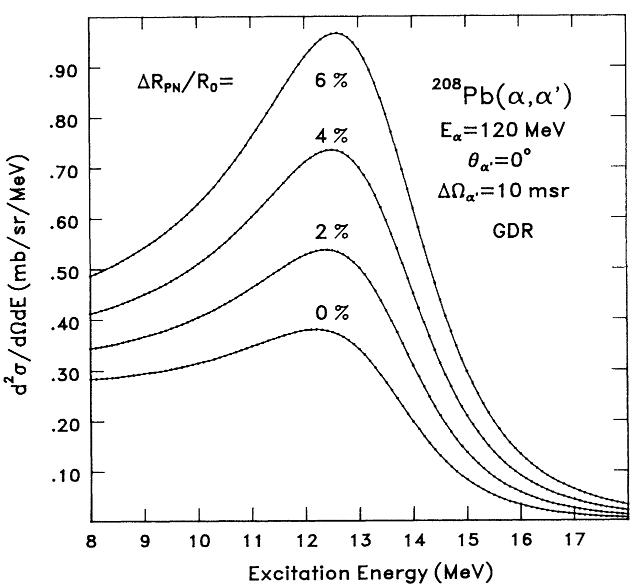

FIG. 2. Differential cross sections of the GDR populated in inelastic α scattering at $E_\alpha = 120$ MeV and $\Theta_{\alpha'} = 0° \pm 3°$ as a function of excitation energy. The curve for $\Delta R_{pn}/R_0 = 0\%$ corresponds to Coulomb excitation only.

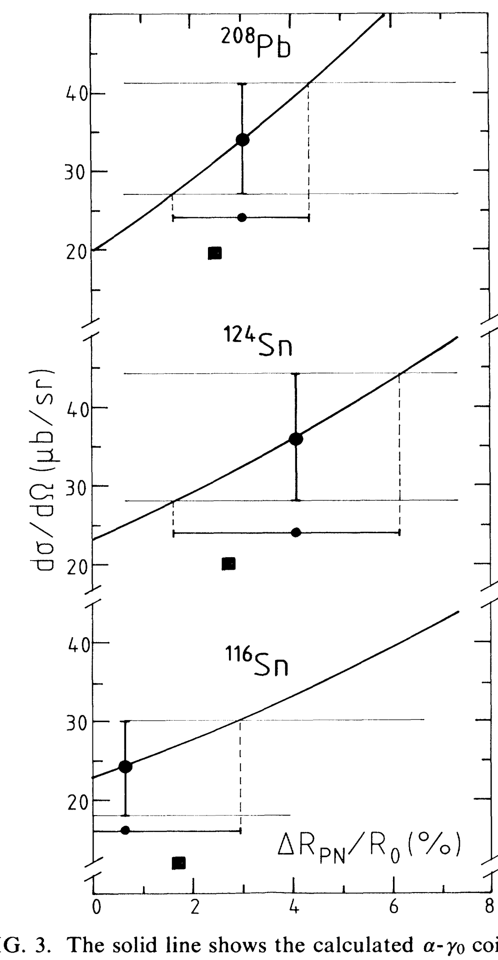

FIG. 3. The solid line shows the calculated α-γ_0 coincidence cross section averaged over solid angle and integrated over energy ($12 \le E^* \le 17$ MeV for ^{116,124}Sn and $11 \le E^* \le 14$ MeV for ^{208}Pb), as a function of $\Delta R_{pn}/R$. The experimental α-γ_0 cross sections for the GDR are shown as large circles with error bars. The deduced value for $\Delta R_{pn}/R$ with the associated uncertainty is also indicated (smaller circles with horizontal bars), together with the theoretical value (squares).

cal-model parameter set of Rozsa *et al.*[33] for ^{116}Sn, the calculated cross section was 6% to 11% less than the one shown in Fig. 3. These differences give an indication of the accuracy of the calculations. In Fig. 3 the experimental cross sections are also shown. From the comparison of the theoretical curves of the cross section as a function of $\Delta R/R_0$ with the experimentally determined cross sections, the $\Delta R/R_0$ values can be deduced. We find that $\Delta R_{pn}/R_0=(0.7^{+2.3}_{-0.7})\%$, $(4.1^{+2.1}_{-2.5})\%$, and $(3.0\pm1.3)\%$ for ^{116}Sn, ^{124}Sn, and ^{208}Pb, respectively. Our results for the $\Delta R_{pn}/R_0$ are somewhat larger than but, within the uncertainties, in agreement with theoretical predictions[34] indicated by squares in Fig. 3. Also, the agreement with an analysis of 800-MeV proton scattering data, as summarized in Ref. 2, which gives $(3.2\pm1.1)\%$, $(5.3\pm2.4)\%$, and $(2.5\pm0.7)\%$ for ^{116}Sn, ^{124}Sn, and ^{208}Pb, respectively, is satisfactory.

Summarizing, we have demonstrated that the determination of the GDR excitation cross section in inelastic α scattering by α'-γ coincidence measurements provides a novel, albeit model-dependent, method to determine the difference of the radii of the proton and neutron distributions in $N\neq Z$ nuclei. The experimental data presented for ^{116}Sn, ^{124}Sn, and ^{208}Pb were analyzed assuming the collective Goldhaber-Teller picture of the GDR. It was found that the extracted $\Delta R_{pn}/R_0$ differences between the proton and neutron distributions are, within the uncertainties, in agreement with theoretical predictions[34] and previous measurements obtained from 800-MeV elastic proton scattering.[2] This method, if applied to deformed nuclei for which it is known that the GDR is split into $K=0$ and $K=1$ vibrational modes, will make it possible to determine the possible differences in the deformation for the neutron and proton distributions.

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).

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