# Excitation of the Isovector Giant Dipole Resonance by Inelastic alpha Scattering: An Experimental Approach

Harakeh, M.N.; Hesmondhalgh, S.K.B.; Hofmann, H.J.; Poelhekken, T.D.; van der Woude, A.; Wilschut, H.W.

***published in***
Physical Review Letters
1989

***document version***
Publisher's PDF, also known as Version of record

***citation for published version (APA)***
Harakeh, M. N., Hesmondhalgh, S. K. B., Hofmann, H. J., Poelhekken, T. D., van der Woude, A., & Wilschut, H. W. (1989). Excitation of the Isovector Giant Dipole Resonance by Inelastic alpha Scattering: An Experimental Approach. *Physical Review Letters*, *62*(1), 16-19.

# Excitation of the Isovector Giant Dipole Resonance by Inelastic $\alpha$ Scattering: An Experimental Approach

T. D. Poelhekken, S. K. B. Hesmondhalgh,[(a)] H. J. Hofmann, H. W. Wilschut, and A. van der Woude
*Kernfysisch Versneller Instituut, 9747 AA Groningen, The Netherlands*

M. N. Harakeh
*Natuurkundig Laboratorium, Vrije Universiteit, 1007 MC Amsterdam, The Netherlands*

(Received 29 June 1988)

The excitation of the isovector giant dipole resonance by inelastic scattering of 120-MeV $\alpha$ particles has been studied with the $^{208}\mathrm{Pb}(\alpha,\alpha',\gamma)^{208}\mathrm{Pb}$ reaction for $0° \leq \theta_{\alpha'} \leq 3°$. The $\gamma$-decay branching ratio to the ground state, extracted from the coincidence data, indicates that not more than $(12 \pm 4)\%$ of the observed singles resonance cross section around 13.6 MeV in $^{208}\mathrm{Pb}$ can be due to isovector dipole excitation.

PACS numbers: 24.30.Cz, 25.55.Ci

Recently a theoretical discussion has arisen concerning the question as to what extent the isovector giant dipole resonance (IVGDR) is excited by inelastic $\alpha$-particle scattering at very forward-scattering angles.[1-5] This is an important question because in heavy nuclei the IVGDR occurs at the same excitation energy as the isoscalar giant monopole resonance (ISGMR), the systematics of which have been used to extract, for instance, the compressibility of nuclear matter.[6-8] Peterson reported[1] distorted-wave Born-approximation (DWBA) calculations which predicted an IVGDR cross section with a strength and an angular dependence comparable to what one would expect for an ISGMR excitation. If true this would mean that all experiments in which the ISGMR was assumed to be excited dominantly[7-10] by inelastic scattering of $\alpha$ particles at small angles were interpreted incorrectly. Although the calculations of Peterson have been contradicted,[2-4] there does not seem to be unanimous agreement that the IVGDR excitation can be safely neglected.[5]

Given this situation plus the fact that the discussion so far has been purely theoretical, we decided upon a direct measurement of the amount of IVGDR excitation in $(\alpha,\alpha')$ scattering at very forward angles, including 0°, by observing the $\gamma$-decay branch to a $0^+$ ground state. Selection rules forbid this decay mode for the ISGMR.

A momentum-analyzed 120-MeV $\alpha$-particle beam provided by the Kernfysisch Versneller Instituut azimuthally varying field cyclotron was used to bombard a 5.0-mg/cm$^2$ $^{208}\mathrm{Pb}$ target enriched to 98%. The beam was stopped in the focal plane of the QMG/2 magnetic spectrograph[11] which was set at 0°. The inelastically scattered $\alpha$ particles, with scattering angles between $-3°$ and $+3°$ in horizontal and vertical directions, were detected in the 52-cm focal-plane detection system.[12] This system provides us with position, angle, and energy information. The coincident $\gamma$ rays were detected in a large $10'' \times 13''$ NaI(Tl) crystal with an anticoincidence shield,[13] placed at 90° and 135° with respect to the beam axis. The $\gamma$ rays were separated from neutrons by means of difference in time of flight with respect to the rf signal. A distance of 75 cm and a time resolution of 3 ns provided a good separation. The resolution of the NaI(Tl) detector, typically 3.0% at 6.13 MeV, is more than sufficient to select the decay to the ground state. A 16-mm-diam Ge x-ray detector was placed at a backward angle of 115° at a distance of 35 cm from the target. The yield of $K$ x rays produced in the target was used to normalize the singles absolute cross section within an accuracy of 10%.[14] The singles data were recorded with a constant downscale factor of 256 parallel to coincidence data processing.

The singles data for the full horizontal opening angle of the spectrograph are shown in Fig. 1(a). A continuum background is drawn similar to the one chosen by Brandenburg *et al.*[10] which makes use of more extensive data taken at similar experimental conditions. The horizontal angular range can be subdivided into two parts: $0.0° \leq \theta_{\alpha'} \leq 1.5°$ and $1.5° \leq \theta_{\alpha'} \leq 3.0°$, with the respective singles spectra shown in Figs. 1(b) and 1(c). By subtracting the spectrum of Fig. 1(c) from 1(b) the isoscalar giant quadrupole resonance (ISGQR) is seen in the resulting spectrum 1(d) to vanish nearly completely. On the high excitation side, however, a clear bump on top of a background remains. This bump is usually interpreted as the ISGMR because it follows the $L=0$ angular distribution behavior as predicted by the DWBA calculations (see, e.g., Fig. 1 of Ref. 10). Proper averaging of the DWBA calculations over the opening angle intervals suggests that for the ISGQR about 10% of the cross section would remain after subtraction, consistent with our data. Assuming that IVGDR excitation is negligible, the fractions of the energy-weighted sum rule exhausted by the ISGMR and ISGQR bumps are $(84 \pm 20)\%$ and $(125 \pm 30)\%$, respectively, in good agreement with the literature values.[7,10,15]

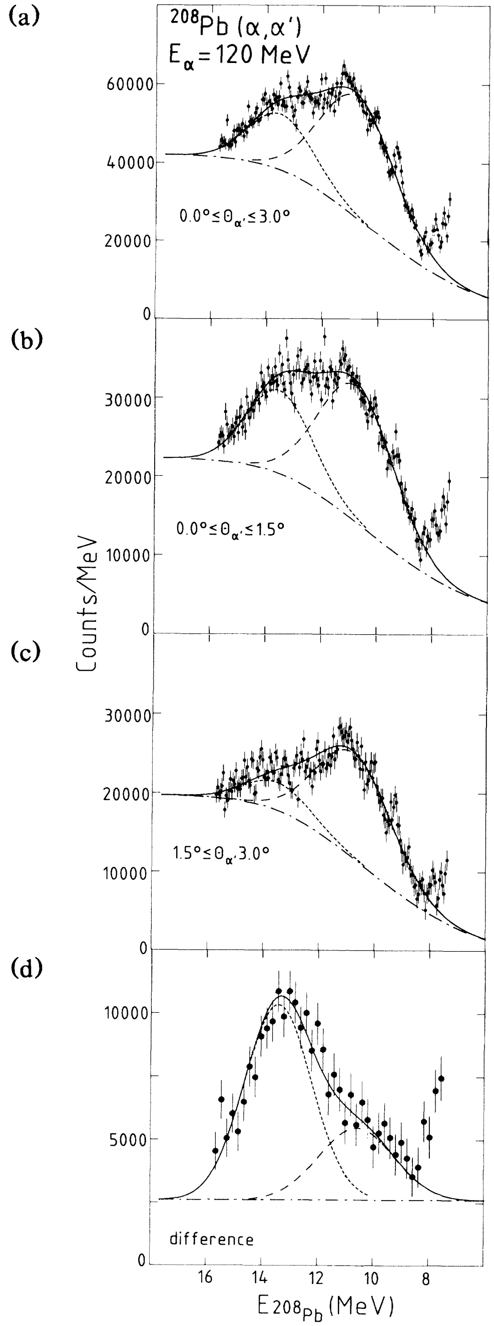

FIG. 1. Singles spectra, downscaled by a factor of 256, at $E_\alpha = 120$ MeV. (a) $0.0° \leq \theta_{\alpha'} \leq 3.0°$, (b) $0.0° \leq \theta_{\alpha'} \leq 1.5°$, (c) $1.5° \leq \theta_{\alpha'} \leq 3.0°$, and (d) the difference between (b) and (c). The curves show the contributions of continuum background (—·), ISGMR-IVGDR plus background (---), and ISGQR plus background (— —), to the spectra. The solid curve is the sum of all contributions.

The true coincidence data are presented in the two-dimensional scatter plot of the $^{208}$Pb excitation energy versus the $\gamma$-decay energy shown in Fig. 2. Despite the low statistics one can see the kinematical locus corresponding to the decay of the $0^+$ ground state of the residual nucleus.

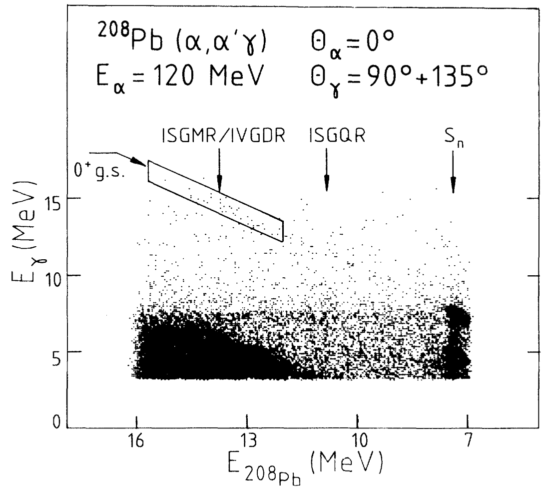

FIG. 2. Two-dimensional scatter plot of the $^{208}$Pb excitation energy vs the $\gamma$-decay energy. Positions of the ISGMR-IVGDR, ISGQR, and the neutron threshold $S_n$ are indicated. The parallelogram represents the final-state gate used to arrive at the value of ground-state coincident $\gamma$ rays $N_c$. Negative counts resulting from subtraction of random coincidences have been suppressed.

In order to give an *upper limit* on the IVGDR cross section we will make the following *worst case* assumptions:

(1) The giant resonance bump on the high excitation energy side [Fig. 1(a)], previously claimed to be the ISGMR, is *completely* due to IVGDR excitation.

(2) All ground-state coincident $\gamma$ rays in the excitation energy range from 12.3 to 15.8 MeV result from the IVGDR $\gamma$ decay.

From the number of ground-state coincident $\gamma$ rays $N_c$ and the area of the singles resonance bump $N_s$ we can deduce directly the experimental ground-state branching ratio of the IVGDR:

$$P_{\gamma_0}^{\mathrm{expt}} = \frac{4\pi N_c}{N_s \epsilon_{\mathrm{NaI}} \, d\Omega_{\mathrm{NaI}} f_{\mathrm{cor}}}, \qquad (1)$$

where $\epsilon_{\mathrm{NaI}}$ is the photopeak plus single escape efficiency and $d\Omega_{\mathrm{NaI}}$ is the solid angle (in sr) of the NaI(Tl) detector. The angular-correlation factor $f_{\mathrm{cor}}$ can be calculated with DWBA. However, since the aim of this Letter is to give an experimental upper limit on IVGDR excitation in $(\alpha,\alpha')$ scattering, the data taken at $\theta_\gamma = 90°$ and 135° (taken with equal statistics) will be added in order to wash out the angular-correlation information. This procedure is justified, first, because our $\alpha$-detection opening angle is axially symmetric around 0° ensuring an axially symmetric angular-correlation pattern around the beam axis, and second, because the in-plane $\alpha$-$\gamma$

angular-correlation pattern will be smeared out as a result of the large spread in the recoil direction for a finite detector opening angle near 0°. The recoil direction changes by about 45° for a change of the scattering angle from 0° to 3°. Therefore we can safely assume $f_{\mathrm{cor}} \approx 1$. The efficiency of the NaI(Tl) detector was calculated with the Monte Carlo code EGS[16] for a number of $\gamma$-ray energies and has been checked against experimental measurements at $E_\gamma = 6.13$ MeV. For this particular experimental setup with a final-state gate as indicated in Fig. 2 and for $E_\gamma = 13.6$ MeV the ESG code predicts $\epsilon_{\mathrm{NaI}} = 29.8\%$. The front end of the detector subtended a solid angle of 88.5 msr. Taking the excitation energy interval ranging from 12.3 to 15.8 MeV, containing 90% of the experimentally measured ISGMR-IVGDR bump, we finally find an experimental branching ratio of the assumed "IVGDR":

$$P_{\gamma_0}^{\mathrm{expt}} = (2.1 \pm 0.6) \times 10^{-3}.$$

Theoretically[15] the total width $\Gamma$ of a giant resonance can be written as a sum of the direct decay width $\Gamma^{\uparrow}$ and the spreading width $\Gamma^{\downarrow}$. Neglecting the intermediate (preequilibrium) decay we can write the branching ratio to the ground state as being the sum of a direct and a compound term[17,18]:

$$P_{\gamma_0}^{\mathrm{theor}} = P_{\gamma_0}^{D} + P_{\gamma_0}^{C} \approx \frac{\Gamma_{\gamma_0}^{\uparrow}}{\Gamma} + \frac{\Gamma^{\downarrow}}{\Gamma} \int S(E) \frac{\Gamma_{\gamma_0}^{\downarrow}(E)}{\Gamma^{\downarrow}(E)} dE , \qquad (2)$$

where $\Gamma_{\gamma_0}^{\uparrow}$ is the ground-state photon decay width of the doorway state and $S(E)$ is the Lorentz strength distribution with parameters $E_L = 13.43$ MeV and $\Gamma_L = 4.07$ MeV.[19] Since the photon decay width to the ground state is proportional to the integrated photon absorption cross section for the IVGDR, one can deduce[20] for the direct term

$$\Gamma_{\gamma_0}^{\uparrow}/\Gamma = \sigma_{\mathrm{abs}}(E_L) E_L^2 / 6\pi\hbar^2 c^2 = 1.6 \times 10^{-2}, \qquad (3)$$

where $\sigma_{\mathrm{abs}}(E_L)$ is the photon absorption section at the centroid of the Lorentz strength distribution $E_L$. A more accurate estimate, taking the energy dependence of $P_{\gamma_0}^{D}$ into consideration[20] and integrating over the 12.3-15.8-MeV interval, yields a value very close to the approximate energy independent estimate. The compound term was calculated with an extended version of the code CASCADE[21] based on the Hauser-Feshbach theory.[22] This term will, in comparison with the direct term, have a stronger contribution from the lower-energy part of the IVGDR because of the rapid increase of compound neutron widths with increasing energy. Because of this strong energy dependence the compound $\gamma_0$ branching ratio has been folded with the assumed singles excitation cross-section distribution for the IVGDR in the 12.3-15.8-MeV region. This yields

$$P_{\gamma_0}^{C} = 1.0 \times 10^{-3}.$$

Clearly, $P_{\gamma_0}^{C} \ll P_{\gamma_0}^{D}$ and we stress that this conclusion does not depend strongly on the shape of the singles excitation cross section assumed for the IVGDR in this interval nor on the parameters of the statistical-model calculations such as level density parameters or optical-model potential parameters used to determine neutron transmission coefficients.

By comparing the experimental branching ratio for $\gamma_0$ decay to the sum of the direct and compound theoretical branching ratios in the excitation energy interval ranging from 12.3 to 15.8 MeV, the IVGDR contribution to the resonance cross section can be estimated to be at most

$$\frac{d\sigma}{d\Omega}(\mathrm{IVGDR}) \Big/ \frac{d\sigma}{d\Omega}(\mathrm{resonance}) \leq (12 \pm 4)\% ,$$

which corresponds to an averaged absolute cross section between 0°-3° of 1.5 ± 0.5 mb/sr. This upper limit strongly contradicts the conclusion of Peterson[1] but is in agreement with the conclusions presented by Shlomo *et al.*[3] It especially supports their conclusion that the parameter $\alpha$, which is related to the ratio of the central densities ($r=0$) of the proton $\rho_p$ and neutron $\rho_n$ distributions

$$\frac{\rho_p(r=0)}{\rho_n(r=0)} = \frac{Z + \alpha(N-Z)/2}{N - \alpha(N-Z)/2} , \qquad (4)$$

should be very small. Obviously $N$ is the number of neutrons and $Z$ is the number of protons. Actual computa-

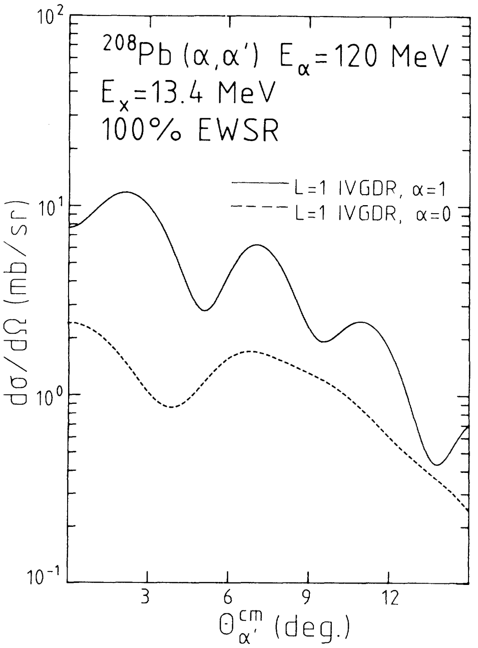

FIG. 3. Differential cross sections for the IVGDR ($L=1$, $\Delta T=1$) calculated with the coupled-channels code ECIS (Ref. 23) for the fully energy-weighted sum rule. Curves for nuclear plus Coumomb excitation with constructive interference ($\alpha=1$) and pure Coulomb excitation ($\alpha=0$) are shown.

tion of the IVGDR excitation with a value of $\alpha=0$ (see Fig. 3), with use of the coupled-channel code ECIS,[23] already gives an averaged cross section (1.46 mb/sr) equal to our upper limit. The optical potential parameters were taken from Ref. 24. The calculation for the full nuclear coupling potential constructively interfering with the Coulomb part ($\alpha=1$) strongly overpredicts the cross section. This means that the excitation of the IVGDR in $(\alpha,\alpha')$ scattering is predominantly due to Coulomb excitation and only for a very small part on account of the nuclear coupling potential. Note that, independent of the value of $\alpha$, the IVGDR calculation can never reproduce the large cross section which remains in the subtraction method presented in the first part of this Letter.

Summarizing, experimental data indicate that IVGDR excitation in inelastic $\alpha$ scattering at very small scattering angles is only a small effect in comparison with ISGMR excitation. This implies that such data are very suitable for the determination of the ISGMR properties.

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 Zuiver Wetenschappelijk Onderzoek (ZWO).

---

[a] Present address: Cavendish Laboratory, Cambridge CB3OHE, England.

[1] R. J. Peterson, Phys. Rev. Lett. **57**, 1550,2771(E) (1986).

[2] K. Nakayama and G. Bertsch, Phys. Rev. Lett. **59**, 1053 (1987).

[3] S. Shlomo *et al.*, Phys. Rev. C **36**, 1317 (1987); S. Shlomo *et al.*, Phys. Rev. Lett. **59**, 1054 (1987).

[4] G. R. Satchler, Nucl. Phys. **A472**, 215 (1987).

[5] R. J. Peterson, Phys. Rev. Lett. **59**, 1055 (1987).

[6] J. P. Blaizot, Phys. Rep. **64**, 171 (1980), and references therein.

[7] M. Buenerd, J. Phys. Paris, Colloq. **45**, C4-115 (1984), and references therein.

[8] A. van der Woude *et al.*, Phys. Rev. Lett. **58**, 2383 (1987), and references therein.

[9] C. M. Rosza *et al.*, Phys. Rev. C **21**, 1252 (1980).

[10] S. Brandenburg *et al.*, Nucl. Phys. **A466**, 29 (1987).

[11] A. G. Drentje *et al.*, Nucl. Instr. Methods **122**, 485 (1974).

[12] J. C. Vermeulen *et al.*, Nucl. Instr. Methods **180**, 46 (1981).

[13] H. J. Hofmann *et al.*, to be published.

[14] G. J. Balster *et al.*, Z. Phys. D **2**, 15 (1986).

[15] J. Speth and A. van der Woude, Rep. Prog. Phys. **44**, 46 (1981); L. S. Cardman, Nucl. Phys. **A354**, 173c (1981); A. van der Woude, Prog. Part. Nucl. Phys. **18**, 217 (1987).

[16] R. L. Ford and W. R. Nelson, SLAC Report No. 210, 1979 (unpublished).

[17] H. Dias *et al.*, Phys. Lett. B **173**, 355 (1986).

[18] J. R. Beene *et al.*, Phys. Lett. **164B**, 19 (1985).

[19] B. L. Berman and S. C. Fultz, Rev. Mod. Phys. **47**, 713 (1975).

[20] R. D. Starr *et al.*, Phys. Rev. C **25**, 780 (1982).

[21] F. Pühlhofer, Nucl. Phys. **A280**, 267 (1977); M. N. Harakeh, computer code CASCADE, extended version.

[22] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).

[23] J. Raynal, coupled-channel computer code ECIS, private communication.

[24] D. A. Goldberg *et al.*, Phys. Rev. C **7**, 1938 (1976).