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SYSTEMATICS OF THE ISOSCALAR GIANT MONOPOLE RESONANCE FROM 60 MeV INELASTIC PROTON SCATTERING ☆

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Evidence for an isoscalar giant monopole resonance is provided for seven nuclei with $A \geqslant 58$. The resonance excitation energy is $\approx 80 \times A^{-1/3}$ MeV. For nuclei with $A \geqslant 90$, nearly 100% of the $L = 0$, $T = 0$ energy-weighted sum rule is depleted in the resonance, in agreement with earlier work on ^{208}Pb and ^{144}Sm. Only $\approx 30\%$ is found in ^{58}Ni, and no clear evidence is found for localized monopole strength in ^{40}Ca.

Recently, a puzzle in the comparison of (p, p′) spectra from ^{144}Sm and ^{154}Sm was resolved [1] by including the excitation of a giant $T = 0$ monopole resonance (GMR), as well as the known giant $T = 1$ dipole (GDR) and $T = 0$ quadrupole (GQR) resonances. The GMR had previously [2,3] been directly observed in $A \geqslant 144$ nuclei by inelastic α-particle scattering. Still earlier reports [4,5] based on more indirect methods indicated that the GMR was to be found at $\approx 80 \times A^{-1/3}$ MeV.

Although protons can excite the GDR which is located at nearly the same energy as the GMR, we recently showed [1] that at forward angles (<20°), the GMR (p, p′) cross section is several times larger than the GDR cross section. Using the same technique, we have analyzed (p, p′) data for a number of other nuclei in order to investigate the GMR excitation as a function of mass number. Here we present results which show the existence of a GMR for nuclei with $A \geqslant 58$. Results which cover a wide nuclear mass range are necessary for an understanding of the systematics of the GMR and for extraction of information on the compressibility of nuclear matter.

Most of the data reported here have been previously published [6]. Measurements were made on ^{40}Ca, ^{58}Ni, ^{90}Zr, ^{120}Sn, ^{144}Sm, ^{154}Sm, ^{197}Au, and ^{208}Pb using ≈ 60 MeV protons from the Oak Ridge Isochronous Cyclotron. Except for the ^{120}Sn target, inelastic protons were detected in the focal plane of a broad-range magnetic spectrograph. The ^{120}Sn measurements were made using a solid-state detector telescope. Complete details of the data analysis will be published elsewhere.

Typical spectra of the giant resonance region for ^{208}Pb, ^{90}Zr, and ^{58}Ni are shown in fig. 1 at forward angles where the GMR peak should dominate the GDR. In all cases, the resonance peak is asymmetrical, being wider on the high-excitation side. For ^{90}Zr and heavier nuclei, we assumed that the resonance structure was composed of two peaks, as indicated in fig. 1. The peak located at $\approx 63 \times A^{-1/3}$ MeV is due to excitation of the GQR [7], which was assumed to be symmetrically shaped in all the nuclei studied. The higher-lying peak located at $\approx 80 \times A^{-1/3}$ MeV is assumed to be due to excitation of the GMR and GDR. The spectra for ^{58}Ni and ^{40}Ca are somewhat more complex due

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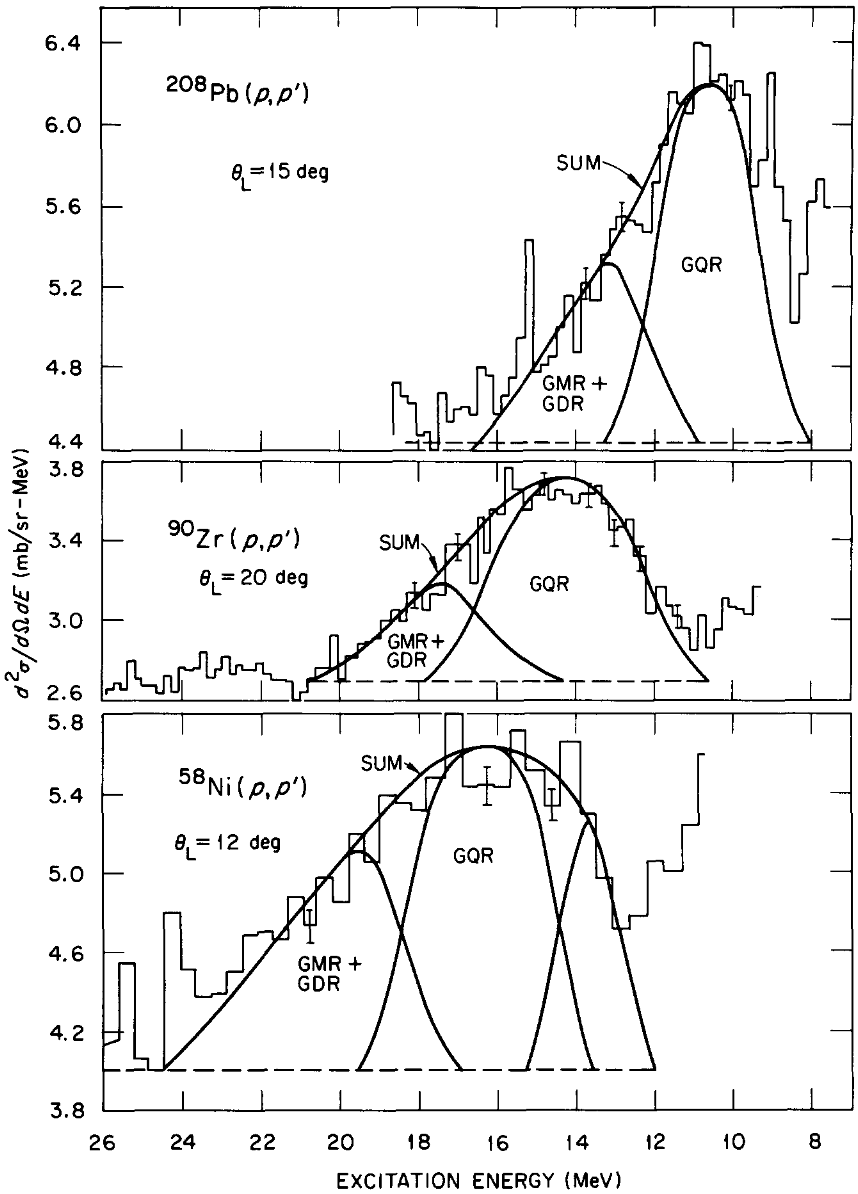

Fig. 1. Giant resonance spectra from the 60 MeV (p, p') reaction on ^{208}Pb, ^{90}Zr, and ^{58}Ni. The measured spectra are shown as a histogram. Error bars on the data represent statistical uncertainty only. The resonance structure is assumed to be composed of two separate peaks, as shown by the solid curves and described in the text. The assumed shape and magnitude of the nuclear continuum underlying the resonances are shown by the dashed line.

to an additional peak located 2 to 3 MeV below the GQR (as indicated for ^{58}Ni in fig. 1). The shape of the $\approx 80 \times A^{-1/3}$ MeV peak was found to be symmetric for nuclei with $A \geqslant 90$, but asymmetric (wider on the high-excitation side) for the lighter nuclei. The extracted peak parameters are listed in table 1. They were determined from the small-angle data, where (except for ^{40}Ca) the GDR contribution to the peak is negligible.

Our analysis is supported by comparison of our results for the GQR with those from ≈ 100 MeV α-

Table 1
Parameters of the GQR and GMR deduced from 60 MeV inelastic proton scattering. For each nucleus, the lower excitation energy peak is the GQR.

Nucleus	Excitation energy (MeV)	Width (MeV)	% EWSR (T = 0)
^{208}Pb	10.9 ± 0.3	2.6 ± 0.5	80 ± 20
	13.4 ± 0.5	3.0 ± 0.5	90 ± 25
^{197}Au	11.2 ± 0.3	3.0 ± 0.5	80 ± 20
	13.6 ± 0.5	3.0 ± 0.5	100 ± 25
^{144}Sm	12.8 ± 0.3	2.8 ± 0.5	80 ± 20
	15.5 ± 0.5	2.5 ± 0.5	100 ± 25
^{154}Sm	12.0 ± 0.3	3.7 ± 0.5	80 ± 20
	15.5 ± 0.5	2.5 ± 0.5	100 ± 25
^{120}Sn	13.5 ± 0.3	3.4 ± 0.5	80 ± 20
	16.8 ± 0.5	3.5 ± 0.5	100 ± 25
^{90}Zr	14.2 ± 0.3	4.0 ± 0.5	60 ± 15
	17.5 ± 0.5	3.0 ± 0.5	60 ± 25
^{58}Ni	16.5 ± 0.3	3.8 ± 0.5	50 ± 10
	19.8 ± 0.5	3.5 ± 0.5	30 ± 10
^{40}Ca (GQR only)	17.8 ± 0.3	2.5 ± 0.5	40 ± 10

particle scattering [8]. In that reaction, for angles greater than ≈10°, the GMR is weakly excited, compared to the GQR. Thus, the (α, α') results for the energy, width, and depletion of the energy-weighted sum rule (EWSR) of the GQR are essentially free from influence of the GMR. Our results for the GQR for nuclei with $A \geqslant 90$ are in good agreement with the (α, α') work. As indicated above, the analysis for ^{40}Ca and ^{58}Ni is made more difficult due to the presence of additional resonance structures. For ^{58}Ni we separated from the GQR peak a peak located at 13.5 MeV, having a width of 1.7 MeV as reported from the ^{58}Ni(d,d′) reaction [9]. In ^{40}Ca we observe an ≈700 keV wide peak located at ≈15.7 MeV. We have removed this peak from the GQR peak shape. The widths of the ^{40}Ca and ^{58}Ni GQR peaks, as determined by this procedure, are narrower than the values reported from the (α, α') measurements (3.5 ± 0.3 and 4.9 ± 0.2 MeV, respectively). However, these differences may arise from the manner in which the 13.5 MeV and 15.7 MeV peaks were treated in the respective data. The EWSR depletion for the GQR deduced for these nuclei is in good agreement between the two experiments. For ^{40}Ca our analysis of the GQR is consistent with recent results from small-

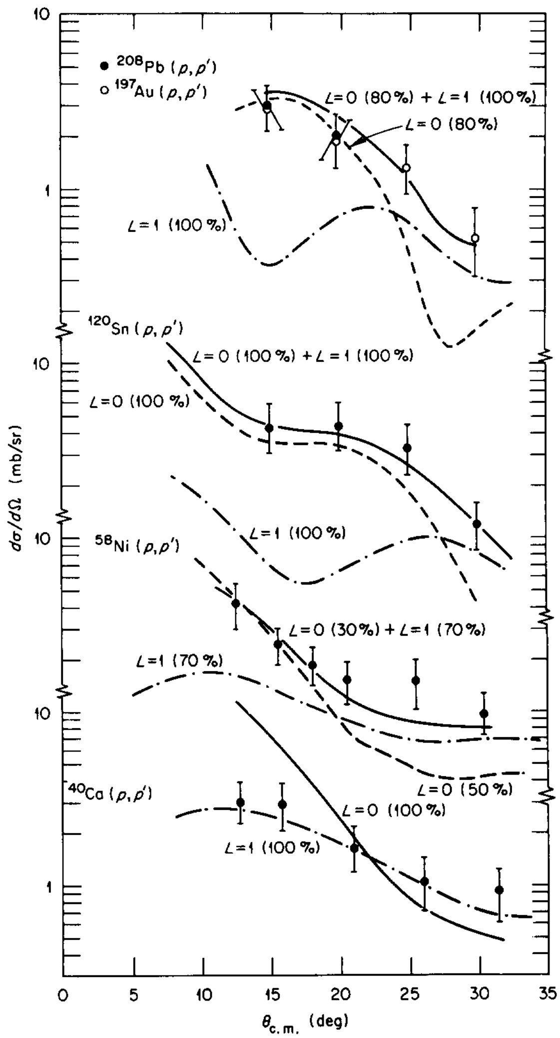

Fig. 2. Cross sections for the GMR–GDR peak in several nuclei compared with DWBA calculations. The fraction of the EWSR strength used for normalization of the calculated cross section is shown on the curves (%).

angle (τ, τ') measurements [10].

Cross sections for the GMR–GDR peak are plotted in fig. 2 for some of the nuclei studied. The uncertainties shown are dominated by the uncertainty in extraction of the peak shape and in the magnitude and shape of the nuclear continuum assumed to underly the giant resonance structure. The curves are from DWBA calculations. The $T = 0$ excitations were calculated with the usual deformed optical-potential model [11,12];

version 1 of the monopole model [12] was used. The sum rule limits were evaluated with radii suggested by electron scattering data. Two new features were introduced into the isovector giant dipole excitation. We took the mixture of Steinwedel–Jensen (SJ) and Goldhaber–Teller (GT) models suggested by curve (c) of fig. 3 in Myers et al. [13]. More importantly, the isovector interaction $U_1(r)$ was taken from a recent unified analysis [14] of (p, p), (n, n) and (p, n) analog transition data. This analysis gave energy-dependent global potentials from which we chose set B; this was also used to generate the distorted waves. The $U_1(r)$ term, especially the imaginary part, is weaker than that used previously [12] and results in considerably smaller GDR cross sections. The consistency of the results obtained in the present studies and in the previous comparison of ^{144}Sm and ^{154}Sm(p, p′) is evidence of the validity of this interaction for exciting the GDR. The percentage of the classical dipole sum rule used was taken from photonuclear measurements [15]. This was accomplished by determining the fraction of the total photonuclear cross section that lays within the limits of our experimentally extracted GMR–GDR peak.

Except for ^{40}Ca, the trend of the angular distributions shown on fig. 2 is the same for all the nuclei studied. The measured cross sections cannot be accounted for by the GDR alone at any angle, and the GMR alone cannot account for them at all angles. However, the sum of the calculated GMR and GDR cross sections provides excellent agreement with the data.

Comparisons between the measured and calculated cross sections yield a depletion of $\approx 100\%$ of the EWSR for the GMR for nuclei with $A > 90$. (The ^{90}Zr results were available at only two angles and are therefore less certain.) For ^{58}Ni, 100% would considerably overestimate the measured cross sections. These data are best described by a depletion of $(30 \pm 15)\%$.

The ^{40}Ca cross sections on fig. 2 are clearly different from those for the other nuclei shown. They do not show the strong rise at forward angles, characteristic of the $L = 0$ calculation, and they are consistent with the cross sections calculated for $L = 1$ alone. Thus, assuming the model used for $L = 0$ and $L = 1$ is valid for light nuclei, we find the ^{40}Ca results to be consistent with only excitation of a GDR (plus the GQR). (A small mixture of $L = 0$ ($\lesssim 15\%$) could be consistent within the uncertainty on the data.) This result agrees with recent ^{40}Ca(τ, τ') measurements [10].

In summary, we find the reanalysis of available 60 MeV proton inelastic scattering data to be consistent with the existence of a GMR in all nuclei studied with $A > 58$. For $A > 90$ the GMR exhausts $\approx 100\%$ of the $L = 0$, $T = 0$ EWSR. However, for ^{58}Ni the data indicate that only $\approx 30\%$ of the EWSR may be depleted. The peak energy is close to $80 \times A^{-1/3}$ MeV. No evidence for a GMR is found in ^{40}Ca. In order to extract values of K_∞, the incompressibility of infinite nuclear matter, from our monopole excitation energies, allowance must be made for Coulomb, surface, and neutron-excess effects. Theoretical estimates of these effects are very uncertain. The RPA calculations of Blaizot et al. [16] which can reproduce the excitation energy in ^{208}Pb, imply $K_\infty \approx 200$ MeV, while the approach of Wong [17] tends to give somewhat smaller values, perhaps as small as 150 MeV.

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