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Inelastic alpha scattering to the giant quadrupole and monopole resonances of ^{58}Ni, ^{92}Mo, and ^{120}Sn at 152 MeV

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The isoscalar giant resonance region has been investigated in ^{58}Ni, ^{92}Mo, and ^{120}Sn nuclei by inelastic scattering of ^{4}He particles at small angles where the quadrupole and monopole states can be distinguished through their angular distributions. A monopole resonance is observed in the three nuclei, exhausting, respectively, 23%, 85%, and 110% of the $E0$ energy weighted sum rule.

I. INTRODUCTION

If the giant monopole resonance (GMR) is now well established for nuclei with mass $A > 60$, the existence of concentrated $E0$ strength in lighter nuclei is still more questionable and contradictory results have been reported (Refs. 1–5). These discrepancies most likely arise from experimental difficulties: in inelastic scattering of strongly absorbed projectiles, the unambiguous identification of the GMR requires very small-angle measurements, where $L = 2$ and 0, angular distributions may clearly be distinguished. Moreover, in light nuclei, the giant quadrupole (GQR) and monopole (GMR) resonances are strongly entangled with each other, widely overlap in the experimental spectra, and their respective contributions are difficult to extract. Inelastic scattering experiments using 110 MeV ^{3}He particles[1] have investigated the monopole strength in light nuclei with mass $A \leq 60$ at very small angles, and some monopole strength has been found close to the GQR exhausting only $\sim 10\%$ of the energy weighted sum rule (EWSR). Another systematic study of the GMR by inelastic alpha scattering[2] reported no evidence for a monopole resonance in nuclei with $A \leq 58$. More recently, 120 MeV inelastic alpha scattering and charged-particle decay experiments at very small angles[4] provided evidence for about 30% of the $E0$ strength in the interval 10.5–20 MeV in ^{40}Ca, and a small-angle investigation of inelastic alpha scattering on ^{28}Si (Ref. 5) identified $\sim 66\%$ of the $E0$ EWSR centered at $E_x = 18$ MeV close to the GQR.

A good determination of the location of the monopole strength in light nuclei is very important for it critically constrains the surface term of the nuclear compression modulus. This has been stressed in Ref. 6 where it has been suggested, on the grounds of the Grenoble systematics, that the monopole and quadrupole modes are crossing in the region of mass $A \sim 40-50$, the monopole mode being pushed down by the surface term of the compression modulus.

In the present work, we report 152 MeV inelastic alpha scattering at small angles on ^{58}Ni, ^{92}Mo, and ^{120}Sn. The motivations for this experiment were twofold. One part was aimed at clearing up the controversial question of the monopole strength in ^{58}Ni, and the other at studying the small-angle cross section of the GQR which was found anomalous in ^{3}He scattering. These latter results are reported and discussed in a companion paper (see Ref. 7).

II. EXPERIMENTAL SETUP

The experiment was performed at Institut des Sciences Nucléaires (ISN) Grenoble, with an analyzed beam of 152 MeV alpha particles. Self-supporting ^{58}Ni, ^{92}Mo, and ^{120}Sn targets containing $>98\%$ of the desired isotopes were used, the thicknesses being 6, 4.18, and 4.5 mg/cm^2, respectively. An overall energy resolution of 300 keV was obtained mainly due to the energy straggling in the targets. Inelastically scattered particles were detected and localized by means of a position-sensitive multiwire proportional chamber placed in the focal plane of the magnetic spectrometer covering a solid angle of 0.96 msr. They were identified by a time-of-flight measurement between the radio frequency of the cyclotron and a plastic scintillator plus photomultiplier placed after the localization chamber. The active slit system used in previous experiments[1,8] was operated, providing a drastic reduction of the contamination of the inelastic spectra by slit scattering on the edges of the spectrometer entrance collimator. The collimator aperture is defined by a thin frame of plastic scintillator stuck to the back of a metal support, and coupled to one or two photomultipliers. Each event scattered on the scintillator is then detected and put in anticoincidence with the focal plane detector. This device allows very small scattering angle measurements with a minimized instrumental background (see Refs. 8 and 9 for more details).

III. DATA REDUCTION

Data were taken at 12 laboratory angles between 1.30° and 12° with an angular resolution of ±0.05° for the three targets, with special attention to the 0°–5° region where the first minimum in the $L = 0$ distribution is expected to occur. A sample of spectra obtained is given in Fig. 1. After subtraction of the background, following the usual

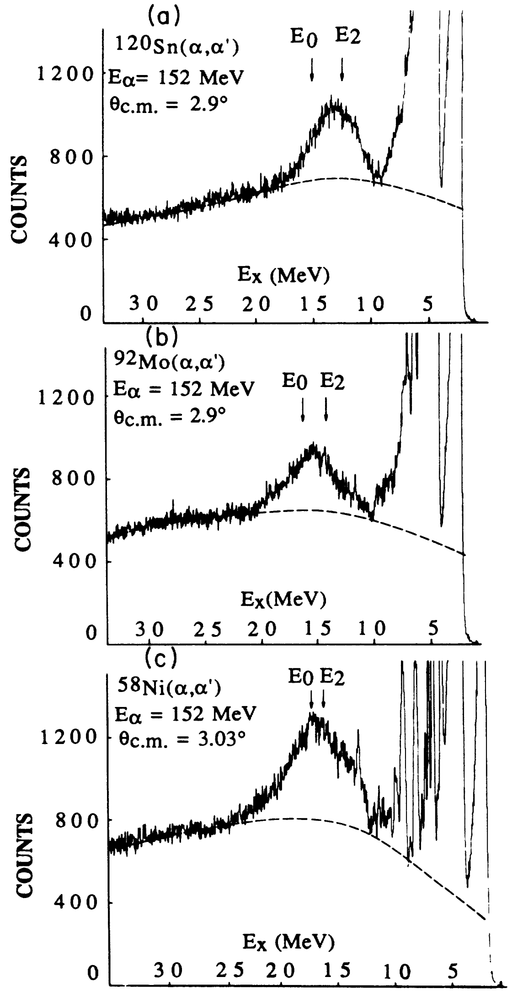

FIG. 1. Inelastic α spectra measured at $\theta_{\mathrm{lab}}=2.5°$. The GQR and GMR peaks are indicated. The dashed lines represent the assumed shape of the subtracted background.

empirical procedure, i.e., smoothly joining the continuum above and below the resonance, the giant resonance (GR) region was fitted for all angles with Gaussian peaks using a multiple-peak fitting routine. The parameters obtained are given in Table I (together with the percentage of the EWSR limit). The uncertainties on the parameters include the contributions due to peak fitting and background subtraction which are both much larger than the statistical errors. For 152 MeV incident alpha particles, the peak from $^5He^*$ breakup should be at least 10 MeV away from the maximum extent of the GMR expected location and cannot give contamination in the region of interest.

Some of the difference spectra are displayed in Fig. 2 showing the behavior of the GR region versus scattering angle. In ^{92}Mo and ^{120}Sn the structure becomes broader when the scattering angle decreases from 6° to 1.3°, and its top shifts to higher excitation energy by about 0.9 MeV, clearly showing the presence of the monopole resonance on the GR high-excitation-energy side. In the two nuclei, the best fit was obtained with two peaks, the parameters of which (excitation energy and width) are very close to the values obtained in Ref. 2 from the inelastic alpha scattering experiment at $E_\alpha = 129$ MeV. On the other hand, the GMR width obtained from our data is about 20% larger than the values deduced from our previous results on inelastic ^3He scattering.[1,9]

Regarding the ^{58}Ni nucleus, a significant concentration (30%) of monopole strength at $E_x = 20$ MeV with $\Gamma = 3.5$ MeV has been reported in Ref. 13 from inelastic proton scattering but the angular distributions published were rather ambiguous (see also, Ref. 11). Evidence for a concentrated $L = 0$ strength was also found from inelastic ^3He scattering[1] but at $E_x = 17$ MeV with $\Gamma = 2.5$ MeV. The authors of Ref. 3, using inelastic alpha scattering, found no evidence for any concentrated monopole strength either at $E_x = 20$ MeV or at $E_x = 17$ MeV, and best fit their small-angle data with a single-peak consistent with an $L = 2$ transfer. In our data, the shape of the GR peak is almost the same at all angles. However, a careful examination of this region indicates that the top of the peak shifts slightly to higher excitation energy by about 0.400 MeV when the scattering angle moves from 5° to 1.32°, allowing the identification of another component sitting very close to the GQR bump. Moreover, the whole GR structure has a tail extending up to 21 MeV on the high-excitation-energy side, and exhibits some narrow peaks on the low-energy side [Fig. 2(a)]. Several fitting attempts were made in order to clarify the situation, but excluded these narrow peaks from the procedure.

First, the GR was fitted with a single Gaussian peak, according to the conclusions of Ref. 3. The parameters obtained, $E_x = 16.85 \pm 0.3$ MeV and $\Gamma = 5.04 \pm 0.15$ MeV, are different enough from those of Ref. 3 ($E_x = 15.6 \pm 0.3$ MeV and $\Gamma = 4.7 \pm 0.3$ MeV), and well outside the combined experimental errors. Moreover, the experimental

TABLE I. Excitation energy, widths (FWHM), and strengths (% EWSR) obtained for giant resonance peaks in the nuclei studied.

	GQR			GMR		
Nucleus	E_x (MeV)	Γ (MeV)	EWSR (%)	E_x (MeV)	Γ (MeV)	EWSR (%)
^{58}Ni	16.4 ±0.2	4.3 ±0.2	38±8	17.3±0.2	3.1±0.2	23±5
^{92}Mo	14.1 ±0.2	4.55±0.34	23±5	16.2±0.2	4.8±0.3	84±17
^{120}Sn	12.75±0.25	3.7 ±0.3	73±15	15.4±0.4	4.0±0.3	110±22

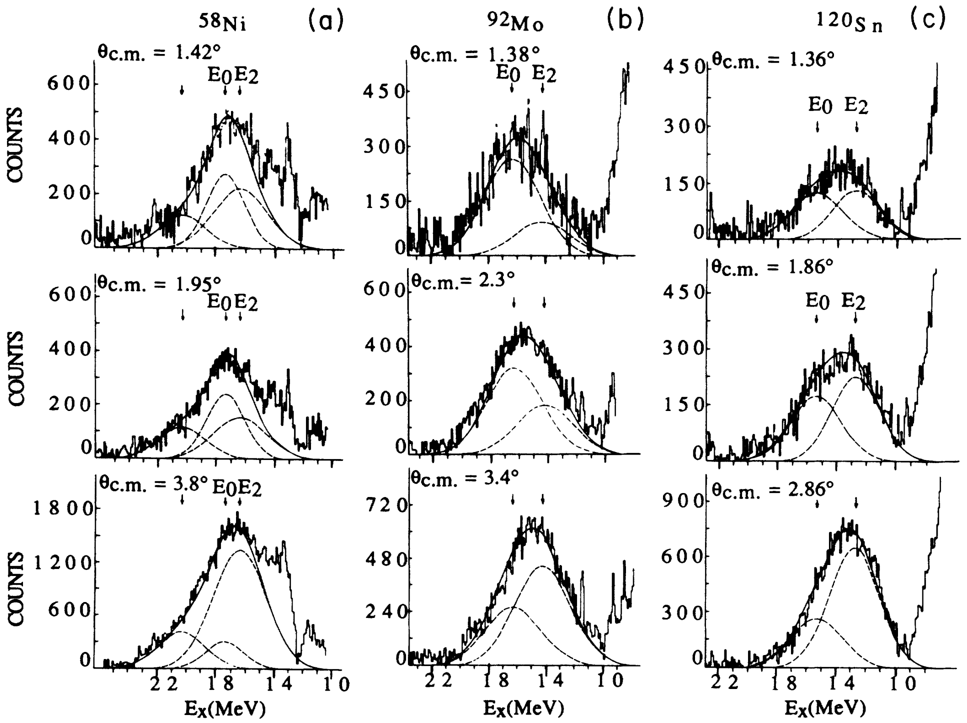

FIG. 2. Difference spectra in the GR region with unfolding into peaks superimposed for (a) ^{58}Ni, (b) ^{92}Mo, and (c) ^{120}Sn, respectively.

angular distribution is more strongly peaked at small angles ($\theta < 3°$) than expected from $L = 2$ transfer and in disagreement with distorted-wave Born approximation (DWBA) calculations. Fixing the peak parameters at the values given in Ref. 3 leads to a poor fit. Two-peak fits were also performed with the parameters of the two components fixed either at the values given in Ref. 11, or at the values of Ref. 9, but the data could not be properly reproduced in this way. Free fits with two peaks never led to consistent solution for all angles. Finally, the best fit was obtained with three Gaussian peaks located at 16.39±0.22 MeV, 17.31±0.20 MeV, and 20.18±0.23 MeV, with $\Gamma = 4.3 \pm 0.2$ MeV, 3.08±0.2 MeV, and 3.8±0.75 MeV, respectively. The parameters of the first two peaks (see Table I) are very similar to those obtained from (^{3}He, ^{3}He′) data, respectively, for the GQR and the

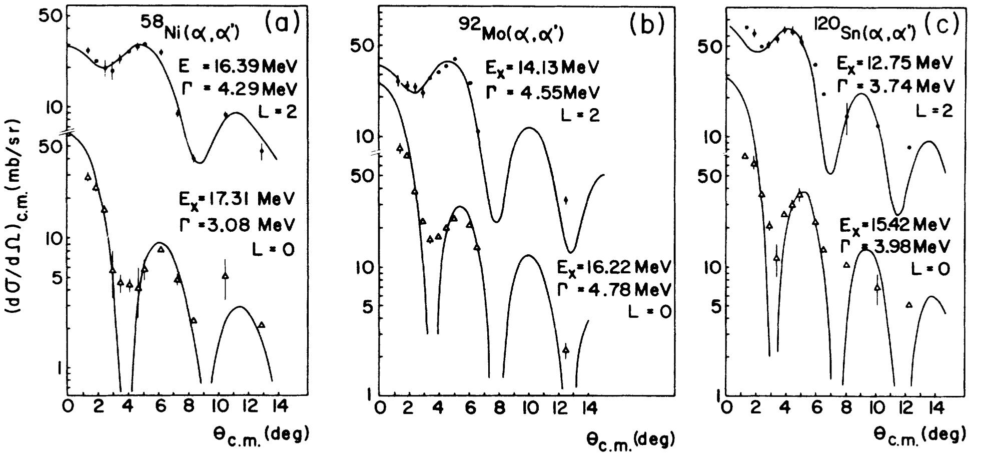

FIG. 3. Angular distributions obtained for the GR peaks. The curves are DWBA calculations for the L transfers indicated. The error bars correspond to statistical and background errors.

TABLE II. Optical-model parameters used in the DWBA analysis. The potentials are of the Woods-Saxon type 11: r_R and r_I are reduced values.

Nucleus	V_R (MeV)	r_R (fm)	a_R (fm)	W_I (MeV)	r_I (fm)	a_I (fm)	r_c (fm)
^{58}Ni	−118.2	1.24	0.79	−20.47	1.59	0.57	1.30
^{90}Zr	−117.5	1.27	0.78	−21.02	1.56	0.57	1.30
^{120}Sn	−119.4	1.26	0.76	−30.7	1.43	0.70	1.30

GMR, apart from the GMR width which is again ~20% larger.

IV. DATA ANALYSIS AND DISCUSSION

The angular distributions are displayed in Fig. 3. The error bars on the data points account only for the variation of the GR parameters. The experimental points are compared to DWBA predictions computed with the code DWUCK4 (Ref. 10). The distorted waves were generated using the 152 MeV alpha optical-model parameters of Ref. 11 given in Table II. To the contrary of the ^{3}He scattering experiment,[1] the small-angle cross sections of the ^{92}Mo and ^{120}Sn GQR are very well reproduced by DWBA curves. For the GMR, the calculated angular distributions were obtained using the form factor defined in Ref. 12 (version 1), assuming the monopole resonance to be a compressional mode. It was recently suggested[5] that this breathing mode form factor could be inappropriate for light nuclei like ^{58}Ni. However, the two form factors given in Ref. 12 differ essentially by the volume and diffuseness oscillation contributions to the radial dependence of the mode, the diffuseness part being 0 in version 1. This point has already been discussed by several authors;[14,15] there is no rigorous argument in favor of either prescription, and the better defendable validity of version 2 over version 1 in light nuclei has still to be established.

For ^{58}Ni, the first angular distribution is well reproduced with an $L=2$ DWBA calculation corresponding to about 38% EWSR and the second is consistent with $L=0$ transfer exhausting around 23% of the EWSR limit. Using the version 2 form factor of Ref. 12 leads to an equally good fit to the data and to a sum rule fraction of 54%. The third peak ($E_x=20.2$ MeV, $\Gamma=3.8$ MeV) has an angular distribution which could be reproduced with a combination of $L=2$ and 0 transfers. The contribution from the giant dipole resonance (GDR), which is almost located at the same energy as the GMR, is small compared to the excitation of the GMR in the energy region considered, and can be safely neglected.[16,17]

TABLE III. Comparison of the experimental parameters of the GMR.

Nucleus	E_x (MeV)	Γ (MeV)	EWSR (%)	Reference
^{58}Ni	17.1 ±0.3	2.5 ±0.3	10 ±2	1
	20.0 ±0.5	3.0 ±0.5	40 ±10	1
	17.3 ±0.2	3.1 ±0.2	23 ±5	This work
^{92}Mo	16.35±0.3	4.0 ±0.3	24 ±5	1
	16.2 ±0.2	4.8 ±0.3	84.5±17	This work
^{90}Zr	16.4 ±0.25	3.6 ±0.25	39 ±8	1
	16.2 ±0.5	3.5 ±0.3	90 ±20	2
^{120}Sn	15.45±0.25	3.25±0.3	50 ±10	1
	15.2 ±0.5	4.1 ±0.6	~180	2
	15.4 ±0.4	4.0 ±0.3	110 ±22	This work

The isoscalar monopole strengths deduced from the present work are compared to the values from other small-angle experiments (Refs. 1, 2, and 13) in Table III together with excitation energies and widths. All the present values, except for ^{58}Ni, are in good agreement with those reported in Ref. 2. On the contrary, the present $E0$ widths are about 20% larger than those of Ref. 1, and the $E0$ strength values are also greater. This discrepancy may be due in part to the difference observed between the spectra obtained in (α,α') experiments (present work and Ref. 2), and those from the (^{3}He, ^{3}He′) experiment (Ref. 1): in inelastic alpha scattering data the GR structure seems to extend further up the high-excitation-energy side. We have no explanation for this difference which can be due in part to the choice of the subtracted background.

For ^{58}Ni, the present work confirms the existence of the GMR observed previously at $E_x \sim 17$ MeV in ^{3}He inelastic scattering (Ref. 1) with a yield at a very small angle approximately equal to the GQR, according to the DWBA predictions. However, some other strength seems to be present at higher excitation energy which was not observed in (^{3}He, ^{3}He′) experiment. In light nuclei, it is known that the GQR is strongly fragmented and spread over a large energy interval. It is reasonable to assume that the same happens to the monopole strength: in ^{28}Si and ^{40}Ca, for example, recent works[4,5] show that the $E0$ strength is strongly split and intermingled with $E2$ strength. In ^{58}Ni, the present work shows that only a minor part (~23%) of the total $E0$ strength is observed at $E_x \sim 17$ MeV. As for the missing part of this strength, it may be located at higher excitation energies. Another possibility is that the procedure of analysis is not correct in this nuclear mass range.

V. CONCLUSIONS

We have presented the results of measurements of the giant monopole and quadrupole resonance excitation in ^{58}Ni, ^{92}Mo, and ^{120}Sn with 152 MeV alpha particles. The present work confirms the results of previous (^{3}He, ^{3}He$'$) experiments,[1,8] except for the $E0$ widths which are found to be significantly larger ($\sim 20\%$). Particularly, the existence of the GMR is confirmed in ^{58}Ni, with 23% of the total $E0$ strength located at $E_x \sim 17$ MeV. No anomaly of the GQR cross sections at small angles has been observed for ^{92}Mo and ^{120}Sn in this experiment, which is at variance with ^{3}He inelastic scattering results.

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