Isotopic dependence of the giant quadrupole resonance in the stable even-mass molybdenum nuclei

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Inelastic scattering of 110 MeV ^{3}He particles is used to probe the quadrupole strength in the even Mo isotopes. The peak position of the giant quadrupole resonance is found to decrease more rapidly than predicted by the $A^{-1/3}$ law, a behavior very similar to that exhibited by the photonuclear giant dipole resonance. The width and strength of the giant quadrupole resonance are practically constant in ^{92}Mo through ^{100}Mo.

[NUCLEAR REACTIONS ^{100,98,96,94,92}Mo(^{3}He, ^{3}He′), $E=110$ MeV: Measured $\sigma(E,\theta)$. Position, width, and strength of the giant quadrupole resonance deduced.]

An essential feature of multipole giant resonance in nuclei is the smooth dependence of their excitation energy and strength on the mass number A. Various collective models[1] predict an excitation energy $E_x \sim 80\times A^{-1/3}$ MeV for the isovector electric dipole resonance (GDR) and $E_x \sim 60\times A^{-1/3}$ MeV for the isoscalar giant quadrupole resonance (GQR). The strength of these two modes of excitation are usually assessed via the following energy weighted sum rules[2]:

$$S_{EW}^{T=1,L=1}(E1)=\int \sigma(E)dE \cong 6\times\frac{NZ}{A}(\text{MeV}-\text{fm}^2), \tag{1}$$

$$S_{EW}^{T=0,L=2}(E2)=\sum_n (E_n-E_0)\beta^2{}_n \cong 525\times\frac{1}{A\langle r^2\rangle}(\text{MeV}-\text{fm}^2), \tag{2}$$

where N and Z are the neutron and atomic numbers, (E_n-E_0) and β_n are the excitation energy and deformation parameter of the nth 2^+ state, and $\langle r^2\rangle$ is the mean square radius of the ground state mass distribution.

Data accumulated in recent years indicate[3,4] that these laws can reproduce the gross behavior of E_x and S_{EW}^{TL} for $A \geq 40$ nuclei where one expects the hydrodynamical model to be valid. Deviations from these simple laws for the GDR are rather dramatic in Mo and are probably the largest measured so far (see for example Ref. 5). Our interest in the present work is to investigate the evolution of the form, position, and strength of the GQR in the Mo isotopes. Previous (α,α') work[6] was limited to three isotopes only and hence the trends as regards energy and strength were not fully illuminated. The peak broadening of the GQR in the transition from spherical to deformed nuclei near the isotone number $N=88$ was a subject for several measurements.[6-9] However, in contrast to pronounced broadening observed in the GDR case, the available experimental data indicate small effects for the GQR. Simple models predict that the peak broadening of the GQR is indeed a factor of ~2 smaller than that observed for the GDR,[10] i.e., of the order of 1 MeV.

A beam of 110 MeV ^{3}He particles from the Grenoble variable-energy cyclotron was used to bombard self-supporting foils of ^{92}Mo (4.0 mg/cm^2), ^{94}Mo (0.80 mg/cm^2), ^{96}Mo (4.4 mg/cm^2), ^{98}Mo (0.48 mg/cm^2), and ^{100}Mo (4.0 mg/cm^2). All targets were enriched to ~98% in the appropriate isotope and their thicknesses were carefully determined using an α source. Energy spectra of the scattered ^{3}He particles were detected at forward angles (5°–40° in lab system). The spectra shown in Fig. 1 were taken with a delay-line multiwire proportional counter[11] mounted in the focal plane of a QSD spectrometer. Two plastic scintillators mounted behind the wire counter gave time of flight information. This setup gave clean spectra. The energy resolution was typically less than 100 keV.

The spectra of Fig. 1 show the familiar peak of the GQR superimposed on top of a background whose shape is not known. In order to extract the resonance position, width, and cross section we subtract a linear background as indicated in Fig. 1. The lower-energy edge of the background is taken

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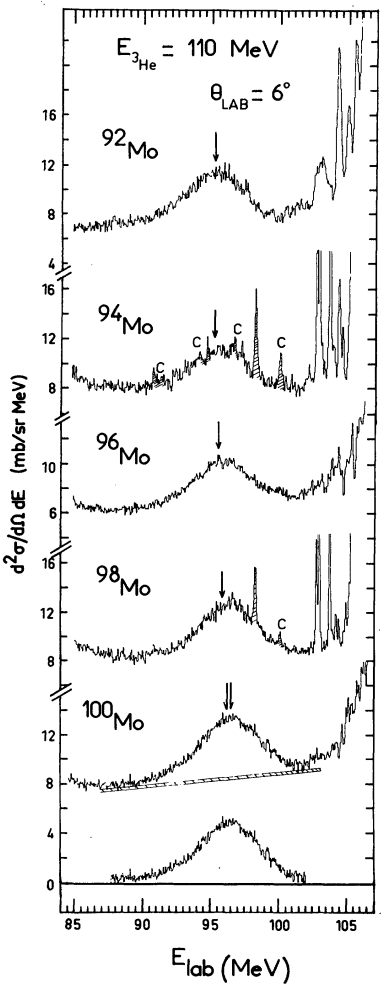

FIG. 1. Spectra from the (^{3}He, ^{3}He′) reaction on even mass Mo targets at 6°. The arrow indicates the position of the GQR as determined in the present experiment. The subtracted linear background and the resulting resonance peak are shown for ^{100}Mo in the lower part of the figure. Contamination peaks are indicated by *c*.

at a well-defined minimum in the inelastic scattering cross section while the higher-energy edge is fixed at a point well above the resonance peak. Such a procedure yields an asymmetric peak (see Fig. 1) with a full width at half maximum (FWHM) nearly the same as that obtained in α scattering.[6] The properties of this peak, treated as a single resonance, are listed in Table I. It is important to note that the resonance cross section is only ~30% of the total inelastic cross section in the resonance region. Thus even small errors in the assumed shape or cross section of the underlying background can produce large errors in the resonance cross sections. A parabolic shape, which is used in similar studies, reduces the resonance cross section by ~20%. Nonetheless, by treating the data in a consistent manner one can establish on the basis of a comparative analysis whether there is an evolution of the GQR characteristics as the target mass increases.

Angular distributions of the first quadrupole state and the GQR as obtained from the procedure mentioned above are shown for ^{92}Mo and ^{100}Mo in Figs. 2 and 3. Also shown are distorted wave Born approximation (DWBA) calculations for $L = 2$ transfers obtained with the conventional collective model. Good fits to our angular distributions are obtained for both the first 2^+ state and the GQR. The curves of Figs. 2 and 3 were obtained with the optical potential parameters ($V = 160$ MeV, $r_v = 1.203$ fm, $a_v = 0.610$ fm, $W_D = 23.9$ MeV, $r_W = 1.044$ fm, $a_W = 0.968$ fm, $V_{so} = 1.67$ MeV, $r_{so} = 0.915$ fm, $a_{so} = 0.796$ fm) of Sato *et al.*[12] which were found to reproduce the elastic cross sections at forward angles for both ^{92}Mo and ^{100}Mo. Other optical potentials yield almost identical angular distributions and relative cross sections, but the magnitude of the cross section could differ by as much as 40%. The comparison of the measured cross sections to those calculated by DWBA is given in Table I. The prediction for higher L values (not shown in Figs. 2 and 3) are well out of phase at forward angles and can be ruled out. Recently Harakeh *et al.*[13] and Youngblood *et al.*[14] have argued for an $L = 0$ giant reso-

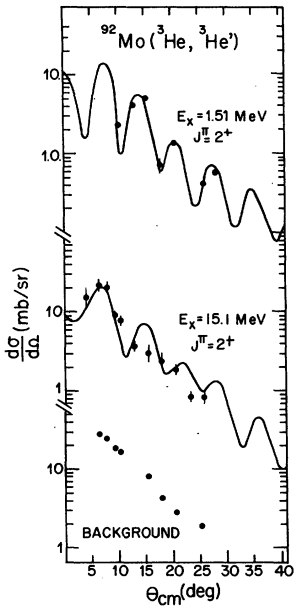

FIG. 2. Angular distributions for the ^{92}Mo(^{3}He, ^{3}He′) ^{92}Mo leading to the first quadrupole state and to the GQR. The solid curves are the predictions of DWBA for $L = 2$ transfers. Background angular distribution is shown on bottom.

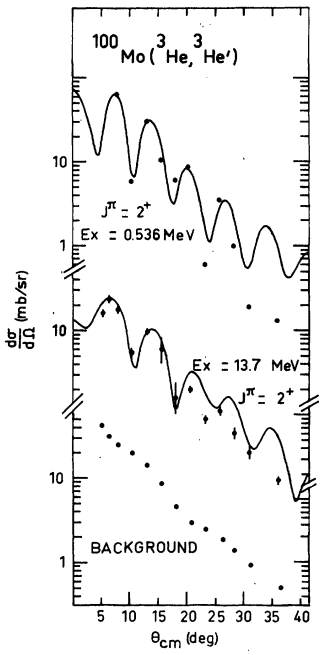

FIG. 3. Angular distributions for the ^{100}Mo(^{3}He,^{3}He′) ^{100}Mo leading to the first quadrupole state and the GQR. The solid curves are the predictions of DWBA for $L=2$ transfers. Background angular distribution is shown on bottom.

nance in the lead region at $E_x \sim 80 \times A^{-1/3}$ MeV. We see no evidence for such a state in our data. Also our DWBA prediction for a breathing mode $L=0$ state[15] is out of phase, and shows a deep minimum at 5° which does not exist in the data. In any case, the calculated cross section of a breathing mode state can explain, at most, some 40% of the observed strength.

The resonance region was also analyzed in energy bins 1 MeV wide. The angular distributions of such energy bins, across the resonance region, all exhibit the shape shown in Figs. 2 and 3. This fact and the observation that the widths obtained in the present work remain constant in the range 4°–40° and are almost the same as those obtained from α scattering indicate, as has been suggested previously,[16] that the $T=1$, $E1$ (or possibly the $T=0, E0$) resonance at $E_x \sim 80 \times A^{-1/3}$ MeV does not contribute significantly to the extracted cross sections. We have verified also that the angular distribution of the assumed background has no oscillating structure.

We note here three aspects of the data given in Table I: (i) The resonance width (FWHM) is the same within the experimental error for all of the Mo isotopes. (ii) The resonance position (the energy centroid of the resonance peak) drops far more rapidly than is predicted by the simple $A^{-1/3}$ law. (iii) The energy weighted quadrupole strength exhausted by the GQR is practically constant. This fact remains valid even if one includes the strength of the first 2^+ level which as usual is a substantial fraction of all of the quadrupole strength localized in the low-lying energy region. It is worth mentioning that a similar dependence has been observed for the position of the GDR,[5] but the photoneutron cross section shows a sudden increase as A increases from 92 to 94 and 96. Unlike the quadrupole sum, the dipole sum [Eq. (1)] does not depend

TABLE I. Properties of the GQR and first excited 2^+ state.

A	E_x [a] (MeV)	FWHM [b] (MeV)	$(d\sigma/d\Omega)$ (mb/sr)$^{6°}$	β_{nucl} [c]	β_{em} [d]	SRF [e] %
92	1.51	···	···	0.07	0.111	2.5
	15.1±0.4 (15.1)	5.0±0.4	21.5±4.5	0.13	···	83.8
94	0.87	···	···	···	0.161	···
	14.8±0.4 (15.0)	5.0±0.4	18.0±4.5	0.12	···	74.7
96	0.78	···	···	0.13	0.166	4.9
	14.7±0.2 (14.9)	5.0±0.3	17.0±4.3	0.12	···	71.7
98	0.79	···	···	···	···	···
	14.2±0.4 (14.7)	4.7±0.4	22.0±5.5	0.13	0.160	86.9
100	0.54	···	···	0.16	0.240	4.8
	13.7±0.2 (14.6)	5.2±0.3	24.5±6.0	0.13	···	88.3

[a] Correspond to energy centroid of the resonance peak, which should be preferred to the position of a Gaussian which fits the resonance. Values in parentheses are the predictions from $A^{-1/3}$ law.

[b] Full width at half maximum (FWHM) of the resonance. The errors reflect the average deviation from the average value calculated at different angles.

[c] From our DWBA analysis: $\beta_{nucl} = [(d\sigma/d\Omega)\exp/(d\sigma/d\Omega)\mathrm{DW}]^{1/2}$.

[d] From electromagnetic transition rates of Ref. 17 with the values of $\langle r^2 \rangle$ taken from Ref. 18.

[e] Sum rule fraction (SRF) exhausted; from our β_{nucl} and Eq. (2).

on the size of the nucleus. Indeed, by taking into account the photoproton yield (which is significant for ^{92}Mo and ^{94}Mo only), the authors of Ref. 5 could reproduce the same dipole sum rule fraction (SRF) for all the Mo isotopes. Dreher[18] has indicated that the charge distribution rms radius increases significantly more when adding two neutrons to the closed shell nuclei of ^{92}Mo and ^{100}Mo rather than to ^{94}Mo or ^{96}Mo. It appears that an increase of 16% in the value of $A\langle r^2\rangle$ between ^{92}Mo and ^{100}Mo is just counterbalanced by a similar decrease in E_x of the GQR so that the quadrupole SRF is also equal for all of the Mo nuclei.

There are two main sources which contribute to the uncertainties in the β and SRF values of Table I. First, as indicated above, the subtraction of the underlying background can produce an error of about 25% in the resonance cross section. Second, there is the dependence of the calculated cross section on the optical potentials for the incoming and outgoing particles and form factor. Particularly the application of the usual deformed optical potential form factors for (α,α'), (p,p'), and (^{3}He, ^{3}He') may yield β_{nucl} values which differ by as much as 40% from β_{em}. One hopes to account for these deficiencies by renormalizing simultaneously all transition strengths. In fact, a normalization constant of ~1.7 would bring our values of β_{nucl} for the first quadrupole states very close to the corresponding β_{em} values. We then emphasize that the deformation parameters and strengths in Table I are reliable when considered as relative values and as such they do reflect a clear evolution in the strength of the GQR.

In summary, a comparative analysis of our data reveals that the GQR position drops far more than predicted by the $A^{-1/3}$ law, but no dramatic shell effect occurs as far as resonance width and strength are concerned.

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