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EXPERIMENTAL STUDY OF THE E2 STRENGTH DISTRIBUTION IN THE ^{12}C AND ^{16}O NUCLEI

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Résumé. — La distribution des transitions quadrupolaires dans les noyaux ^{12}C et ^{16}O est étudiée par diffusion inélastique de ^{3}He. La résonance quadrupolaire géante présente une structure fine distribuée sur plusieurs niveaux individuels dans les deux noyaux, elle épuise 31 % et 37 % de la règle de somme E2 (EWSR) dans ^{12}C et ^{16}O respectivement.

Abstract. — The distribution of the E2 strength in ^{12}C and ^{16}O nuclei is investigated by inelastic scattering of ^{3}He. The giant quadrupole resonance is found to be splitted into several states in both nuclei and exhausts 31 % and 37 % of the quadrupole energy weighted sum rule (EWSR) in ^{12}C and ^{16}O respectively.

The giant quadrupole resonance (GQR) in nuclei with mass $A > 28$ lies around $63\,A^{-1/3}$ (MeV) excitation energy and exhausts most ($\gtrsim 60$ %) of the energy weighted sum rule (EWSR). In lighter systems, the ^{16}O nucleus has been investigated via the reaction ^{15}N(**p**, γ) (ref. [1]) and more recently by inelastic hadron scattering experiments [2, 3]. All these measurements concur as to the existence of a noticeable E2 strength between 15 and 30 MeV excitation energy. It is clearly shown in ref. [2] that the GQR does not appear as a single broad (4-5 MeV) bump, as in medium mass and heavy nuclei, but is spread over several individual states. This trend is quite analogous to that of the isovector giant dipole resonance (GDR) (ref. [4]) which also appears as a single broad state in nuclei with $A > 40$ and show spreading over several fine structure states in lighter systems. It is of interest to pursue the study of the GQR in lighter nuclei tracking the E2 strength and its spreading into the continuum. In this letter, we report measurements of the distribution of E2 states in ^{12}C and ^{16}O nuclei by inelastic scattering of 130 MeV ^{3}He particles. The ^{16}O data have been used for comparison with the results from the ^{16}O(α, α') study [2] in order to check that the weak ^{3}He-nucleus isovector effective interaction [5] does not produce a noticeable excitation of the isovector states (especially the GDR) in the 20-30 MeV excitation energy region.

The experiments have been performed at the 88″ cyclotron of the Lawrence Berkeley Laboratory. The scattered particles were identified with two $\Delta E - E$ (2.5 mm-5 mm) silicon detector telescopes. The ^{12}C target had a thickness of 650 μg/cm^2. The gas cell for the ^{16}O experiment consisted of a cylinder of 60 mm diameter with a 3 mg/cm^2 Havar window; the pressure in the cell was between 8 and 13 PSI. Spectra were recorded between 12.5 and 40°, with an overall resolution of about 300 to 400 keV for both targets.

The measured spectra have been separated into background and peaks. The background was approximated by fitting by computer, a set of five points of the spectrum with a polynomial. The points were chosen so that the background joined the high-lying continuum smoothly down to the α-particle threshold region, passing by the minima between the peaks in the 10 to 20 MeV excitation energy region. The results obtained are illustrated on figure 1. After subtraction of the background, the difference spectra have been unfolded into single peaks using a computer code performing a χ^2 search in each region of the spectrum and fitting at most 4 three-parameters gaussian-shaped peaks.

The ^{16}O spectra (Fig. 1) are identical to those obtained from the (α, α') reaction [2]. Furthermore no E1 contribution was detected in the analysis of the

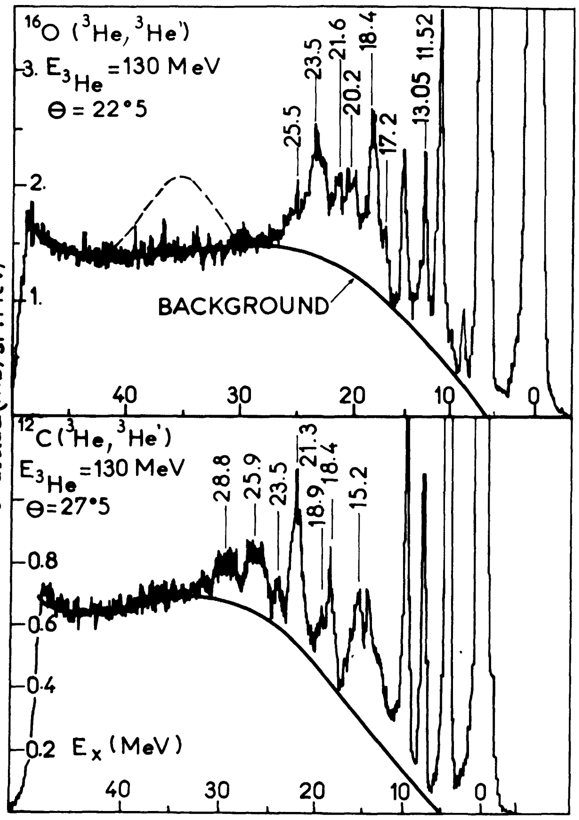

FIG. 1. — Examples of measured spectra. Excitation energies of the E2 states above 10 MeV are indicated. The dashed bump is the expected cross-section for giant octupole resonance (see text).

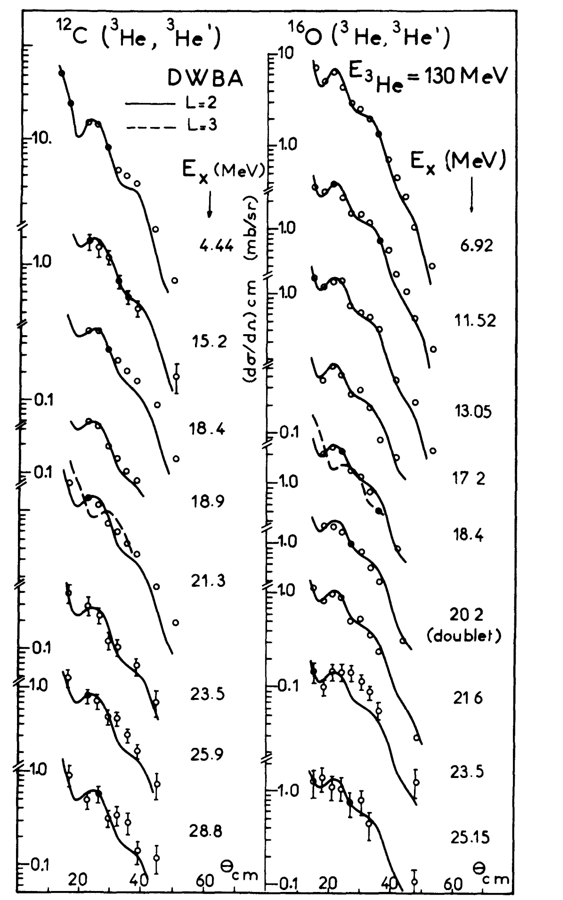

FIG. 2. — Angular distributions of the E2 transitions. The error bars are $\pm 5\,\%$ for the first 2^+ state, $\pm 10\,\%$ for states below $E_x = 15$ MeV and $\pm 15\,\%$ above ; larger error bars are indicated. The points are fitted with DWBA calculations for $L = 2$ transitions (solid line). The dashed line is an example of $L = 3$ calculation.

angular distributions of the individual levels. Moreover, in the ^{12}C spectrum we have found no evidence for the strong E1 state at $E_x \approx 22$-23 MeV (ref. [4]). This confirms that the strength observed in the present experiments is mostly isoscalar, and that the cross-section for the excitation of the GDR can be neglected. For both nuclei, the peak structure of the spectrum between 15 MeV and 30 MeV excitation energy, exhibit the same overall shape across the angular range investigated ; we see this feature as an indication that the continuum is dominated by one excited multipole with negligible inclusion of other L values. Indeed, assuming that two states with different multipolarities and comparable cross-section are excited, the calculations (see below) predict that the extrema of their relative cross-sections would be different by a large factor ($\gtrsim 3$) between 15° and 30° c.m., and this was not observed above $E_x \approx 15$ MeV. The experimental angular distributions displayed on figure 2 exhibit shapes with quite similar structure, slightly changing with the excitation energy.

DWBA calculations have been performed with the code DWUCK (version DWUCK 4). Optical model parameters have been obtained by fitting the inelastic scattering data, they are for ^{12}C : $V = 83.6$ MeV, $r_v = 1.2$, $a_v = 0.77$ mf, $W = 13.45$ MeV, $r_w = 1.83$, $a_w = 0.59$ fm ; and for ^{16}O : $V = 89.7$, $r_v = 1.2$, $a_v = 0.84$ fm, $W = 15.51$ MeV, $r_w = 1.73$, $a_w = 0.58$ fm. The experimental angular distributions have been compared to extended collective model calculations [6]. Multipolarities and deformation parameters β_L have been deduced from this comparison, the latter expressed in terms of percentage of the EWSR limit given by the formula [6] :

$$\sum_n \hbar\omega_L^{(n)} (\beta_L^{(n)} R)^2 = \frac{4\pi}{A} \frac{\hbar^2}{2m} \frac{L(2L+1)^2}{(L+2)^2} \frac{\langle r^{2L-2} \rangle}{\langle r^{L-1} \rangle^2}$$

where R is the radius of the real part of the optical potential, all other notations being the same as in ref. [6]. The multipole-moments of the nuclear matter distribution have been calculated using parameters taken from ref. [7], assuming a Saxon-Wood shape.

For the two nuclei, the DWBA calculations using complex form factor fit very well the first 2^+ (Fig. 2) and 3^- levels, providing a sound basis for L-assignments to high excitation energy states. However the deduced $(\beta_L R)$ values are much smaller than those obtained from other reactions due to very different real and imaginary radii of the ^3He optical potential. Hence, the deformation lengths have been extracted using real form factor calculations as they fit correctly the forward angles cross-sections and provide ($\beta_L R$) values in agreement with other experimental values for the first 2^+ and 3^- states of both ^{12}C (ref. [8]) and ^{16}O (ref. [9]). The angular distributions of the assigned E2 transitions are shown on figure 2, fitted with $L = 2$ DWBA calculations, one $L = 3$ calculated shape is also indicated for comparison. For the ^{16}O nucleus they confirm the results of ref. [2]. However the angular distribution of the 23.5 MeV state exhibits a slight bump in the 25°-30° region, rather than a rapid fall off observed for the other angular distributions. This may be due either to a contamination by another multipolarity or to the microscopic wave function of this state [16]. In ref. [10] evidence has been obtained for a large E3 strength ($\approx 70\,\%$ EWSR) centered around $E_x \approx 35$ MeV. We have calculated the expected cross-section in our data and found that for 50 % EWSR and assuming a 5 MeV FWHM this giant octupole resonance should appear as shown on figure 1. Its non observation raises some questions about the assumptions made in ref. [10]. For the ^{12}C nucleus (1) E2 assignments have previously been made for the 15.2 MeV (ref. [11]) and the 18.4 MeV (ref. [12]) states. However E2 strength at higher energy has not been observed hitherto. A state found at 21.3 MeV from inelastic scattering of 155 MeV protons was assigned E3 on a solid basis [12] and some other E3 strength has been located around 21.6 MeV (ref. [13]). The present results suggest that the latter could be isovector, but there is some uncleared ambiguity about the presence of E2 and E3 strength in the 21-22 MeV excitation energy region of ^{12}C. The present results also suggest that the E1 strength reported in ref. [14] could have been overestimated because of some undetected E2 cross-section in the spectra.

For the two nuclei studied, the percentages of the EWSR limit exhausted in the observed E2 transitions are listed in table I together with the excitation energies, widths and deformation lengths. The total E2 strength exhausted up to 30 MeV excitation energy is around 46 % in ^{12}C and 55 % in ^{16}O, the latter value in reasonable agreement with previous measurement [2]. In both nuclei, the giant quadrupole resonance is splitted into several states and its strength is spread over a larger excitation energy range ($\sim$ 13 MeV) for ^{12}C than for ^{16}O ($\sim$ 8 MeV). The centroid of the GQR (assumed to include states at $E_x > 15$ MeV) lies around 21.5 MeV in both nuclei and the strength corresponds to 31 % and 37 % of the EWSR for ^{12}C and ^{16}O respectively. Thus, in conclusion, it is clear that in light nuclei the GQR exhausts a markedly smaller part of the sum rule limit and lies at a smaller excitation energy ($\sim$ 50 to 53 $A^{-1/3}$ MeV) than in heavier nuclei, exhibiting trends similar to those observed for the isovector giant dipole resonance.

(1) In a just published paper [15], similar results are reported on ^{12}C but the deduced values for the E2 strengths are markedly smaller.

TABLE I

Excitation energies E_x, full width at half maximum (FWHM) *corrected from experimental resolution Γ, deformation length ($\beta_2 R$) and percentage of the* EWSR *for the measured quadrupole transitions. Associated uncertainties are indicated for the first two quantities.* (a) *doublet* (19.95 MeV - 20.6 MeV) resolved at $\theta_{lab} = 17°\,5$.

$E_x \pm \Delta E_x$ (MeV)	$\Gamma \pm \Delta\Gamma$ (MeV)	$\beta_2 R$	% S_2
—	—	—	—
4.4		1.60	15.7
15.2 ± 0.3	1.8 ± 0.3	0.55	6.4
18.4 ± 0.1	0.4 ± 0.1	0.35	3.1
18.9 ± 0.15	0.7 ± 0.15	0.27	2.0
21.3 ± 0.15	1.4 ± 0.2	0.51	7.6
23.5 ± 0.2	0.6 ± 0.2	0.23	1.7
25.9 ± 0.3	2.2 ± 0.3	0.39	5.5
28.8 ± 0.4	2.7 ± 0.4	0.34	4.5
^{12}C	Total ^{12}C		46 %
6.92		0.83	7.9
11.52		0.57	6.2
13.05 ± 0.1		0.42	3.7
17.20 ± 0.15	< 0.2	0.25	1.8
18.40 ± 0.1	1.0 ± 0.2	0.56	9.4
20.2 ± 0.2 (a)	doublet	0.46	7.0
21.6 ± 0.2	1.0 ± 0.3	0.36	4.7
23.50 ± 0.15	1.5 ± 0.2	0.43	7.1
25.15 ± 0.3	2.8 ± 0.6	0.40	6.8
^{16}O	Total ^{16}O		55 %

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