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EXCITATION OF GIANT RESONANCES IN ^{208}Pb BY INELASTIC SCATTERING OF ^{16}O

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ABSTRACT

Inelastic scattering of ^{16}O ions on ^{208}Pb has been studied at a bombarding energy of 140 MeV. A broad peak is observed at an excitation energy of about 11 MeV and two narrower peaks at 9.2 and 14.3 MeV. DWBA calculations indicate that the observed cross section in this region exhausts all of the expected E2 strength based on the energy-weighted sum rule. The strength of the 14.3 MeV resonance makes it unlikely to be a monopole excitation.

Giant resonances in general, and in particular those in ^{208}Pb, have been extensively investigated in recent years [1]. Various projectiles ranging from electrons to ^{6}Li particles have been used for exciting giant resonances. A variety of different projectiles is helpful for understanding the details of the observed states such as their structure, multipolarity, and strength distribution. The excitation of giant resonances by inelastic scattering of heavy ions was first reported [2] for 104 and 140 MeV ^{16}O and for 130 MeV ^{20}Ne on ^{197}Au and ^{208}Pb. Recently, giant resonances in ^{27}Al were excited with ^{12}C ions [3], and in Zr and Pb with ^{12}C and ^{14}N ions [4]. The interest in using heavy ions for the excitation of giant resonances in two-fold. First, these experiments provide additional information on the structure of the giant resonances -- for instance, the stronger excitation of components populated through large angular momentum transfer. In addition, it has been proposed [5] that the giant resonances could play an important role as doorway states for heavy-ion deeply-inelastic collisions. It has also been suggested that in heavy systems, the dominance of multiple excitation of the giant resonances implies that it is extremely unlikely that either fragment will actually emerge excited in a single identifiable giant resonance [6]. Both predictions can be tested in heavy-ion inelastic scattering. In the present work we report the excitation of giant resonances in ^{208}Pb by the inelastic scattering of ^{16}O ions at 140 MeV.

A ^{208}Pb target of thickness 1.4 mg/cm^2 was bombarded with a 140 MeV ^{16}O beam from the Lawrence Berkeley Laboratory 88-Inch Cyclotron. The target was a self-supporting foil covered on both sides with 150 μg/cm^2 carbon layers to prevent the evaporation of the lead. The scattered ions were momentum-analyzed with a magnetic spectrometer [7] where their time-of-flight and energy loss were also measured. All these parameters were recorded by a computer and stored event by event on magnetic tape. The presence of light contaminants on the target was not a problem since they gave rise to very low energy particles at the angles covered in the experiment. Data were taken at nine laboratory angles between 31° and 50° in 2°-3° steps. The energy resolution of 450 keV FWHM was mainly due to the target thickness. Energy calibration was done by using elastic scattering and inelastic scattering to low-lying states in ^{208}Pb, and by the transfer reaction ^{208}Pb(^{16}O,^{15}O)^{209}Pb populating the ground state and 1.45 MeV excited states, equivalent to Q-values of -11.72 and -13.17 MeV. During much of the experiment the particles corresponding to elastic and inelastic scattering to most of the low-lying states were removed from the detector by an appropriate mask placed in the focal plane of the spectrometer. This technique greatly reduced the total counting rate and dead time of the system.

The energy spectrum of ^{16}O ions detected at 35° is shown in Fig. 1. This spectrum shows several features common to all spectra. The giant resonances (9 - 15 MeV) sit on top of a background which is not flat and which is probably due to excitation of the continuum in ^{208}Pb and to tails of bound states -- mainly that of the 6.1 MeV state in ^{16}O. The figure also shows the assumed background, the unfolding of the resonance, and the total fit to the data as discussed below.

In order to obtain the angular distribution for the resonances, a systematic subtraction of the background is very important. The background was assumed to be composed of two parts -- a straight line at the high excitation energy region (17 - 22 MeV), a part of which is shown in Fig. 1, and a tail from the bound states at lower excitation energy. Parameters of the straight line were obtained by a least squares fit, and parameters of the Gaussians which describe the bound states were obtained by the minimum χ^2 method. The background defined in this way is shown in Fig. 1. After background subtraction, the most consistent results for all the data were obtained by decomposing the spectra into four Gaussians at excitation energies of 9.2, 11.0, 13.0 and 14.3 MeV with full widths at half maximum of 1.1, 3.0, 1.75 and 1.1 MeV respectively. An example of such a decomposition is shown in Fig. 1. The choice of these energies is not unique, since a variety of different sets of energies and widths may lead to comparable χ^2 values. However, states at similar excitations have been observed in other inelastic scattering experiments [4,8,9].

Projectile excitation cannot contribute to the observed spectrum at these excitation energies, which are well above the threshold for particle emission from ^{16}O. Combined excitation of the target and projectile is expected to be negligible since the cross-sections for excitation of the relevant bound states in ^{208}Pb (4.1 and 5.4 MeV) are about 5 mb/sr at 40°, compared to 8 mb/sr for the resonances. We therefore conclude that the observed spectrum is predominantly due to excitation of resonances in ^{208}Pb. This conclusion is strengthened by the observation of similar structures in ^{197}Au, for which the excitation of discrete states is not observed [2].

The angular distribution of the sum of the four peaks is shwon in Fig. 2, with only statistical errors (including background subtraction) indicated. The absolute errors, including systematic errors in background subtraction, are estimated to be 20%. The results of DWBA calculations for an L=2 transition, normalized to the data at the grazing angle, are also shown in the figure. The optical parameters were obtained by interpolation of the parameters given in Ref. [10]. The question of the multipolarity of the various components of the giant resonances region in ^{208}Pb and in particular the question of the breathing mode (the giant monopole resonance) is still open. In a recent paper [8] the results from previous experiments, in which several different projectiles were used to excite the giant resonances in ^{208}Pb, are discussed in detail. The conclusion drawn is that the (L=0) breathing mode is located mainly at the excitation energy of 8.9 ± 0.2 MeV, exhausting 50% of the energy-weighted sum rule (EWSR). Another recent paper [9], in which a similar analysis is done and RPA calculations are carried out, comes to the conclusion that the breathing mode is located at the excitation energy of 14 MeV, exhausting 80% of the EWSR. The 9 MeV resonance, according to this paper, is proposed to be a component of the split $T = 0$ giant quadrupole resonance. Both papers assign the broad peak centered at 11 MeV as mainly a $T = 0$ giant quadrupole resonance.

In order to help in resolving this problem we have carried out DWBA calculations for the 9.2 and 14.3 MeV states excited in the present work, assuming both L=0 and L=2 transitions. The transition potential was calculated using the procedure suggested by Satchler [11], and the parameters were taken from Ref. [10]. The results are summarized in Table 1, and indicate that the 14.3 MeV resonance is unlikely to be a monopole excitation since this assumption would imply an excitation strength of 250% of the EWSR. The results of these calculations for the

9.2 MeV resonance are consistent with an L = 0 assignment [8], but the possibility of L = 2 is not excluded. Calculations assuming an L = 2 transition for the whole resonance region show that about 150% of the EWSR for E2 excitation is exhausted (see Table 1). The calculations were carried out for 500 partial waves and were tested for convergence. The large percentage observed may be reconciled with the experimental systematic errors and ambiguities in the DWBA calculations. Of course it cannot be ruled out that other multipolarities are excited in the same energy region.

The present work was carried out at a bombarding energy in which deeply-inelastic processes are expected to occur with a large cross section. For the bombardment of ^{197}Au with ^{16}O at 135 MeV, a cross section of about 400 mb for deeply-inelastic processes was measured [12]. Although the cross section measured in the present work for excitation of the giant resonances (≈10 mb) is small compared to this value, it still exhausts a large fraction of the EWSR. Since the giant resonances appear to be excited with the maximum allowed strength for inelastic scattering, it is difficult to conclude that significant flux is removed by multistep excitation into the deeply-inelastic continuum [3-6]. For this sytem of ^{16}O + ^{208}Pb at 140 MeV the giant resonances do not appear to act as doorway states for deeply inelastic scattering, and it will be interesting to see if this conclusion is supported by detailed calculations, which predict that the observed strength of the direct excitation depends on the system [5,6]. Further experimental investigations to compare the relative strengths of excitation of giant resonances and deeply-inelastic scattering as a function of incident energy may help to clarify the role of giant resonances in deeply-inelastic processes.

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TABLE 1.

Values of B(E2) and $|M(0)|^2$ and the percentage of the T=0 sum rule limit.

Excitation energy (MeV)	L^π	B(E2) or $|M(0)|^2$ (fm^4)	Percentage of T = 0 sum rule [a)]
9.2	0^+	4.4×10^4	66%
	2^+	0.13×10^4	10%
10 - 14	2^+	1.54×10^4	140%
14.3	0^+	10.5×10^4	250%
	2^+	0.45×10^4	54%

[a)] The sum rule limits are defined as follows:

$$S_L = E_x B(EL) = \frac{3A\hbar^2 LR^{2L-2}}{8\pi m} \qquad L \geqslant 2 \qquad \text{[Ref. 1]}$$

$$S_0 = E_x |M(0)|^2 = \frac{6A\hbar^2 R^2}{5m} \qquad \text{[Ref. 11]}$$

where A is the mass number of the nucleus, and m is the nucleon mass.

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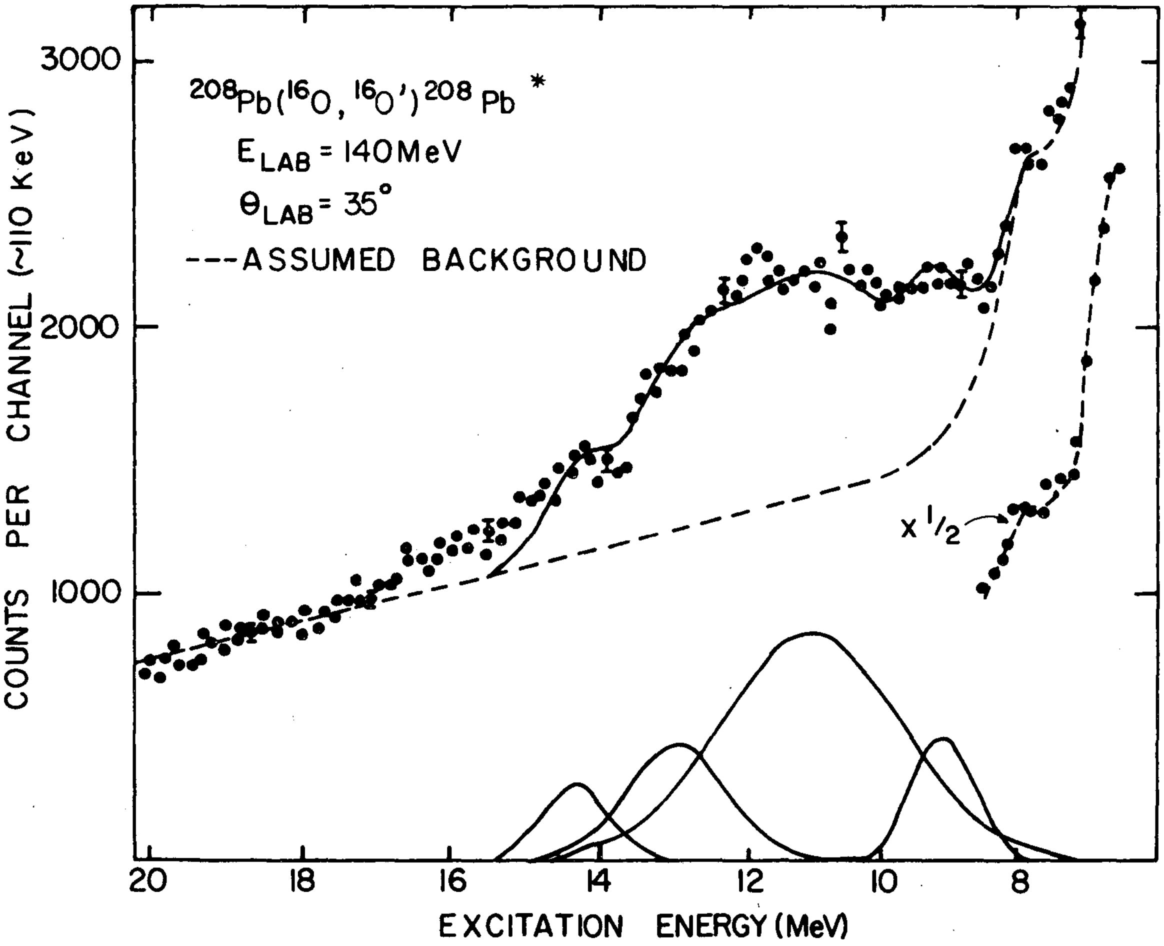

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Fig. 1. Energy spectrum for $^{208}Pb(^{16}O, ^{16}O)^{208}Pb$. The unfolding of the resonance portion of the spectrum into four Gaussian peaks and a background is indicated.

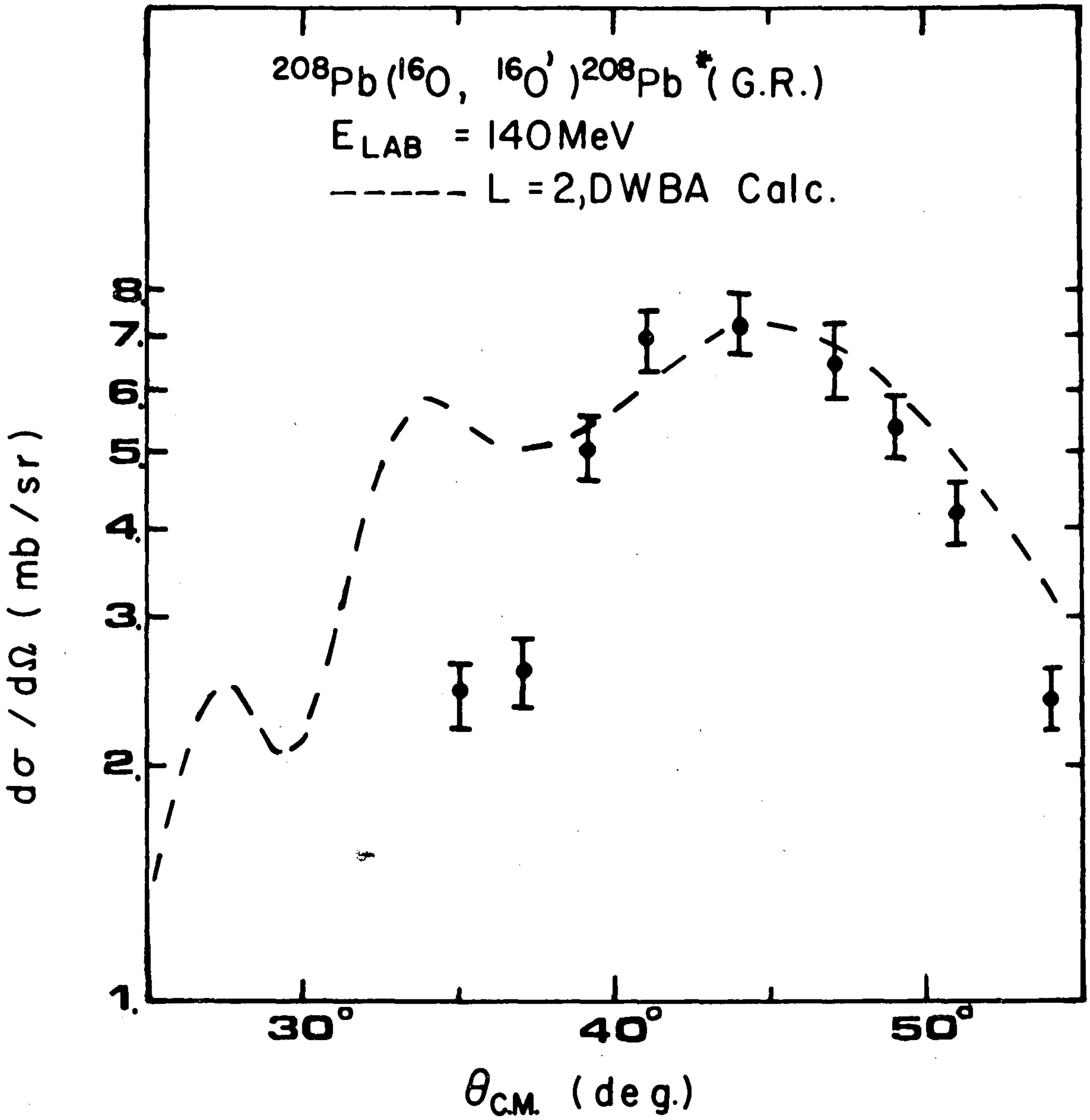

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Fig. 2. Angular distribution of the sum of all peaks in the giant resonance region in ^{208}Pb. The errors do not include systematic ambiguities in background subtraction. The dashed line is the result of a DWBA calculation for a L = 2 transition.

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