Monopole Excitation in the Giant-Resonance Region of ^{208}Pb†

H. P. Morsch, P. Decowski,* and W. Benenson
Cyclotron Laboratory and Physics Department, Michigan State University, East Lansing, Michigan 48824
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Inelastic scattering of 45-MeV protons and 70-MeV ^{3}He particles has been used to study the giant-resonance region of ^{208}Pb. The giant resonance is found to be highly structured with states of different multipolarities, such as dipole, quadrupole, and octupole. A monopole state is found at 9.11 MeV which exhausts about 2% of the monopole-sum-rule strength.

Among the important open questions in studies of giant resonances is the location of the monopole state. This breathing mode of the nucleus is particularly important because it gives information on the compressibility of nuclear matter, a property which has not experimentally been determined up to present. Theoretical estimates of the excitation energy of the monopole state vary considerably because they depend strongly on the choice of effective interaction.

Recent experimental attempts to observe a giant monopole resonance have centered on ^{208}Pb but have not been conclusive. As a result of inelastic-electron-scattering experiments, Pitthan *et al.*[1] proposed a monopole state at 8.9 MeV which exhausts 50% of the sum-rule strength. However, it was shown by Schwierczinski *et al.*[2] that this state could equally well be quadrupole. Marty *et al.*[3] have compared inelastic deuteron and proton scattering and found that a possible explanation of the differences in the spectra obtained could be a giant monopole resonance at 13 MeV.

In an attempt to clarify the questions raised above we have studied the giant-resonance region in ^{208}Pb using high-resolution, high-statistics, inelastic proton and ^{3}He scattering. To summarize the results, we find that the giant-resonance region is highly structured and that the structure is angle dependent in a way that indicates that some of the peaks are pure dipole, quadrupole, and octupole excitations. One peak has an angular distribution which can be described only by an $L=0$ calculation and hence may comprise part of the long-sought giant monopole resonance. Additional evidence for the monopole character of this state is found from the absence of the peak in the ^{3}He inelastic scattering spectra in agreement with expectations for this type of excitation.

The experiments were performed with 45-MeV protons and 70-MeV ^{3}He particles from the Michigan State University cyclotron. The scattered particles were detected in a delay-line counter[4] on the focal plane of an Enge split-pole spectrograph. The energy resolution (35 keV for protons and 45 keV for ^{3}He particles) was limited by the thick targets (5.4 and 1.8 mg/cm^2, respectively) required to keep impurities to a minimum relative to the ^{208}Pb. A plastic scintillator provided time-of-flight information. This information permitted the elimination of most of the slit-scattered particles, which arrived at the detector 3–10 nsec later than the real inelastic events. Long runs were taken to eliminate statistical fluctuations in the spectra. Nonlinearities in the detector system create a gradual modulation of the spectra at a maximum excursion of about 5%. That the structure discussed in the present paper is not due to these nonlinearities was checked by comparing spectra taken at different field settings.

The raw proton spectra at 12° and 33° are shown in Fig. 1. Gross structures (width of 300 keV or more) similar to these observed in electron and proton scattering[5-7] are seen on top of a continuum which is slowly varying with angle. The scattering from light contaminants shows up mostly as narrow peaks which were identified by comparison to scattering from Mylar ($C_{10}H_8O_4$). In addition to the gross structure, the good energy resolution of our experiment permits the observation of a strong fine structure in the giant-resonance region (width limited by the 35-keV resolution). It is interesting to note that the fine-structure peaks show distinct differences in the angular dependence, which implies the excitation of different multipolarities. There are peaks which show up mainly at forward angles indicated by cross hatching in the 12° spectrum. There are also other peaks which are dominant at larger angles, e.g., at 9.35 and 10.3 MeV. The angular distributions for some of the states with characteristic angle dependence are shown in Fig. 2 along with distorted-wave Born-approximation (DWBA) predictions. To determine the intensities a background was assumed of the type shown in Fig. 1. The assigned $L=3$ excitation at 9.35 MeV

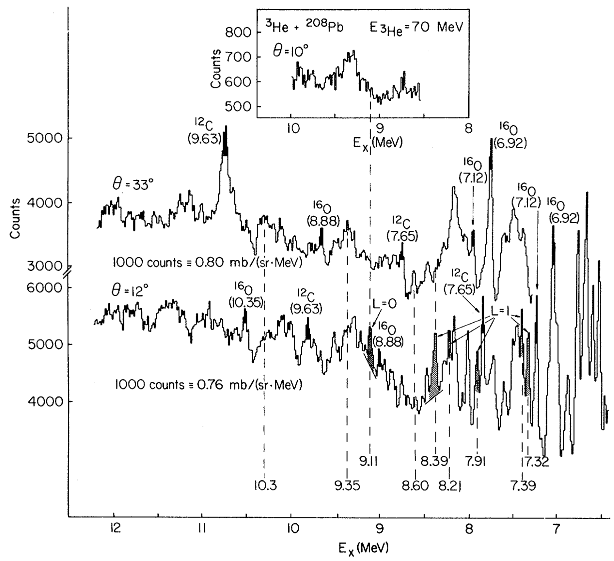

FIG. 1. 12° and 33° spectra from the reaction ^{208}Pb(p, p') at 45 MeV. The contaminant peaks are blackened and the $L=0$ and $L=1$ peaks are cross hatched. A typical background used to determine the intensity is indicated for two of the peaks. The inset shows part of a 10° spectrum from the reaction ^{208}Pb(^{3}He, ^{3}He$'$) at 70 MeV.

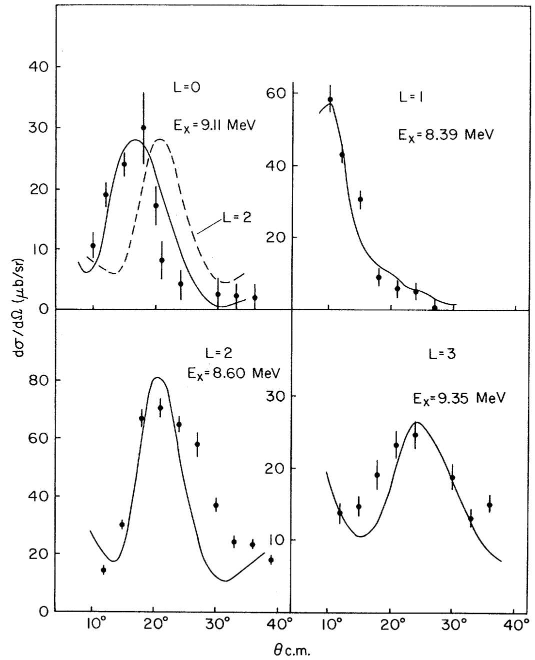

FIG. 2. Angular distributions for several states observed in the ^{208}Pb(p,p') spectra. The curves represent the DWBA calculations described in the text. The error bars are statistical only and do not include the uncertainty of estimating the background.

could not be resolved from other states (mainly $L=2$ states) nearby. Therefore, only the central part of the gross structure with a width of 40 keV is plotted in Fig. 2.

The DWBA calculations were carried out with microscopic and folding-type form factors. For dipole, quadrupole, and octupole transitions, collective-model transition densities were folded with a Serber nucleon-nucleon force. For the radial form a Gaussian with a range of 1.68 fm was used, leading to a volume integral of 446 MeV fm^3. This interaction is consistent with the force used to describe few-nucleon systems[8] and is close to that used for other (p,p') calculations.[9] The results are insensitive to the choice of transition density between the Jensen-Steinwedel[10] or Goldhaber-Teller model[11] for dipole excitations or between simple surface derivative or the Tassie model[12] for higher multipoles. Becchetti-Greenlees optical-model parameters were used.[13] Details of the calculations will be presented elsewhere. For the monopole excitations a microscopic 1p-1h (one-particle, one-hole) calculation was performed in the manner described by Morsch.[14] The calculated transition density is consistent with collective-model transition densities.[15] All of the calculations included Coulomb excitation, which is important for the forward angles studied. The general shape of angular distributions was quite insensitive to various arbitrary choices of models and parameters and is therefore considered to be a reliable indication of the multipolarity.

Five resonances at 7.32, 7.39, 7.91, 8.21, and 8.39 MeV show the rapidly falling angular dependence which is consistent with an $L=1$ assignment. The possible nature of these states will be discussed elsewhere. As one would expect from previous work on the giant quadrupole resonance,[5-7] we observe many states of quadrupole character, e.g., at 8.47, 8.60, 8.75, 8.88, 9.25, and 9.52 MeV. There is also indication for octupole strength in the gross structures at 9.35 and 10.3 MeV. This is supported by electron-scattering data,[2] in which the structure at 9.35 MeV is essentially missing.

Only one state (9.11± 0.03 MeV) is observed to have an angular distribution consistent with $L=0$ assignment. It shows up as a relatively strong peak at small angles and disappears for larger angles. Further evidence for the $L=0$ nature was obtained by ^{3}He scattering at 70 MeV. A monopole excitation is predicted to be very weak (about an order of magnitude smaller than quadrupole) using the models described above. This is because ^{3}He's at these energies bring in large angular momentum and therefore favor higher angular momentum transfer. In our ^{3}He spectra at different angles between 10° and 25°, no peak around 9.11 MeV has been found. The gross structure located above 9 MeV which shows up clearly in ^{3}He scattering is definitely of quadrupole and, as discussed above, possibly of octupole character.

The question arises as to whether the 9.11-MeV state is one of the states seen in the (γ,n) reaction in this energy region[16] which would rule out a monopole assignment. If the strong peak in (γ,n) at 9.03 MeV is of quadrupole nature, then it would show up as a very strong peak in our inelastic-proton-scattering as well as in our ^{3}He-scattering experiments. Neither in our experiment nor in inelastic electron scattering has such a strong and narrow quadrupole state been observed which indicates an $E1$ or $M1$ character in agreement with conclusions drawn in Ref. 6. Both $E1$ and $M1$ states are observed in (p,p') but show angular distributions very different from that of our monopole state.

The comparison of the microscopic DWBA calculation with the experimental cross sections for the 9.11-MeV state yields a monopole strength of about 2% of the energy-weighted monopole sum rule. Of course, such an estimate contains uncertainties due to the effective monopole interaction and the DWBA approach used. In determining an $E0$ matrix element from our data there are additional uncertainties. The separate proton and neutron components and hence the $E0$ matrix element depend on the models used; e.g., our 1p-1h transition density yields an $E0$ matrix element $\langle r^2\rangle$ of 16 fm^2 whereas a collective-model description using $\rho_n \sim (N/Z)\rho_p$ gives a 13 fm^2. An $E0$ matrix element of this order may not give rise to a pronounced peak in (e,e'). Therefore, the fact that in the electron spectrum of Ref. 2 no such peak is observed at this energy is not inconsistent with the present results.

A strong monopole state at 8.9 MeV proposed in Ref. 1 has not been seen in our experiment. Instead we find in this region many peaks of quadrupole character. Thus we conclude that the structure observed in Refs. 1 and 2 consists mainly of quadrupole states, as suggested in Ref. 2.

At lower excitation energies we find no monopole strength. Also the high-resolution (p,p') experiment of Wagner *et al.*[17] shows no monopole excitation below 7 MeV. (Pairing vibration states at 4.86 and 5.24 MeV are not excited in proton scattering.) The monopole strength found in our experiment corresponds to about one single-particle unit; it is too large to be accounted for by n-particle, n-hole configuration mixing in contrast to $E0$ matrix elements found in light nuclei.[18] This clearly indicates a 1p-1h excitation which contains some fraction of the giant-monopole state. Currently we are investigating higher excitation energies to search for further pieces of the giant-monopole excitation.

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*On leave from Institute of Experimental Physics, University of Warsaw, Warsaw, Poland.

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