New Giant Resonances in 172-MeV α Scattering from ^{208}Pb

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Spectra of 172-MeV α scattering from ^{208}Pb indicate in addition to giant monopole and quadrupole excitation new giant resonance structures in hadron scattering at $E_x = 17.5 \pm 0.8$ and 21.3 ± 0.8 MeV with corresponding widths of 4.8 ± 0.8 and 5.9 ± 0.8 MeV. The angular distributions indicate $L = 3$ and 1 giving rise to an interpretation as isoscalar giant octupole resonance (17.5 MeV, 60% energy-weighted sum-rule strength), and isoscalar giant dipole resonance (21.3 MeV, 90% energy-weighted sum-rule strength).

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During the last few years a large amount of information on giant resonances has been obtained from the scattering of different projectiles. The richest structure of excitation has been observed in electron scattering[1,2] with evidence for isovector dipole, isoscalar and isovector quadrupole, and isoscalar octupole resonances. Whereas in electron-scattering isoscalar and isovector excitations are excited about equally strong, in hadron scattering isoscalar giant resonances are dominant. In particular the isoscalar character of a scattering provides an excellent tool for the study of isoscalar giant resonances. So far, in hadron scattering the isoscalar giant quadrupole resonance (GQR) and a low-lying octupole resonance has been studied for light and heavy nuclei.[3] Recently, evidence for the isoscalar giant monopole resonance (GMR) has been obtained for heavy nuclei.[4,5] In the present Letter we present evidence for two other giant resonances excited in α scattering at higher excitation energy.

The experiments were performed with a 172-MeV α beam from the Jülich isochronous cyclotron JULIC. The details of the experimental setup are described by Morsch and co-workers.[5,6] Spectra are shown in Fig. 1 which indicate strong excitation of giant resonances. Clearly we observe the GQR at 10.9 MeV and the GMR at 13.8 MeV with widths of 2.6 MeV. Above these resonances, which have been studied recently,[5,6] the spectra exhibit still another structure which is much broader and extends up to 28 MeV of excitation. However, spectra at different angles indicate a different shape of this structure, e.g., at angles of about 8° and 15° the part at $E_x \simeq 17.5$ MeV is enhanced with respect to the higher-excitation part. This is reversed at an angle of 10° (see Fig. 1). This indicates more than one resonance of different multipolarity. The spectra have been analyzed by fitting the giant-resonance region with four Gaussian peaks (GQR, GMR, and two new resonances) superimposed on a continuous background as illustrated in Fig. 1. A good fit to all spectra is obtained by assuming for the new resonances excitation energies of 17.5 ± 0.8 and 21.3 ± 0.8 MeV. The corresponding

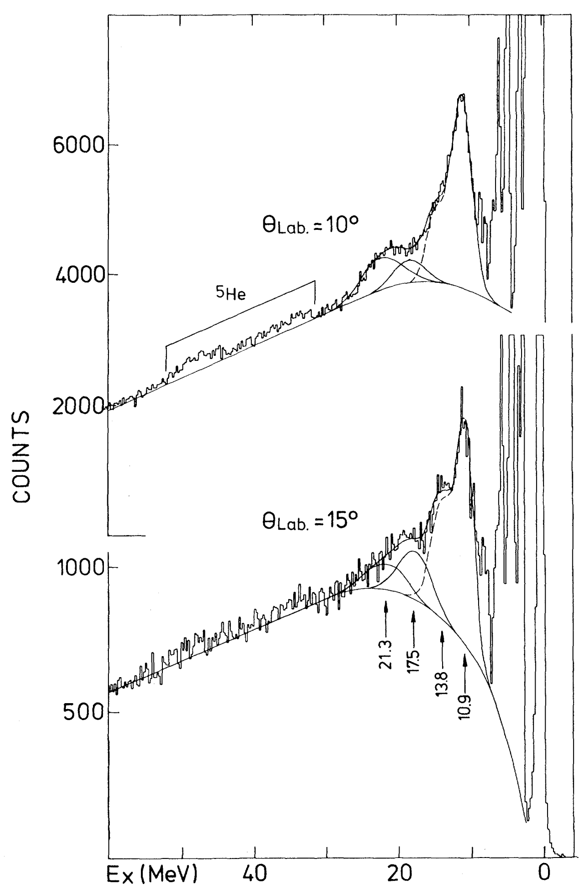

FIG. 1. Spectra of 172-MeV α scattering from ^{208}Pb. The background lines and fits to the giant resonances are indicated as well as the separate peaks for resonances at 17.5 and 21.3 MeV and the sum of GQR and GMR (dashed lines).

widths [full width at half maximum (FWHM)] are 4.8 ± 0.8 and 5.9 ± 0.8 MeV, respectively. The resonance parameters for the GQR and GMR are used as in Refs. 5 and 6: $E_x = 10.9$ and 13.8 MeV, FWHM = 2.6 MeV. A consistent description of our spectra could be obtained by use of a simple form of the underlying background: At higher excitation energies between 30 and 55 MeV, a linear energy dependence of the background is assumed in all spectra. For lower excitation energies, a smooth polynomial fit of order ≤ 5 was used bending down to the minima of the discrete spectrum (at about 7 and 2 MeV). The angular dependence of the background (shown in Fig. 2) was found and checked to be smooth. As compared to the background choice in Refs. 5 and 6, the present background is much lower in the region above the GMR but matches that in Refs. 5 and 6 in the region of the GQR. This allows the

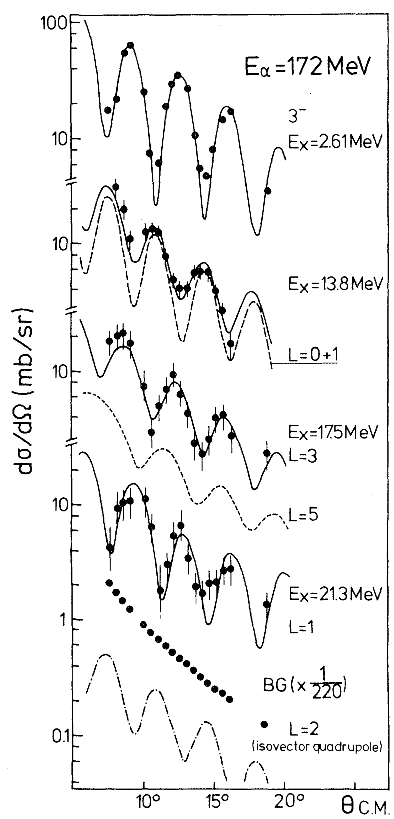

FIG. 2. Differential cross sections in comparison with microscopic DWBA calculations discussed in the text. The points without error bars in the bottom part indicate the cross section of the background under the 17.5- and 21.3-MeV resonances. The background under the 13.8-MeV resonance is similar in shape but smaller by a factor of 3.

evaluation of the new broad structures which could not be recognized before with the background shapes of Refs. 5 and 6. It should be noted that the structure seen between 30 and 55 MeV of excitation above the linear background (Fig. 1) corresponds to the excitation of the ^{5}He breakup channel.[7]

The resulting differential cross sections are presented in Fig. 2. Quite remarkably, a pronounced structure is observed for the two new resonances indicating excitations of rather pure multipolarity. Typical uncertainties in the deduced cross sections for the broad structures at $E_x = 17.5$ and 21.3 MeV were estimated to be ± 30% and about 20% for the narrow resonances at $E_x = 10.9$ and 13.8 MeV using the background form discussed above. In Fig. 2 these errors are shown unless indicated otherwise. As compared to the analysis of the GMR with different background in Refs. 5 and 6 the differential cross section for the 13.8-MeV resonance is now about 20% larger and has less pronounced diffraction minima (Fig. 2). For the 10.9-MeV resonance the cross section is quite similar to that in Ref. 6. For comparison, the differential cross sections are also shown for the excitation of the 3^- state at 2.61 MeV. The diffraction pattern is quite similar to those for the new resonances. This indicates excitation of negative-parity resonances ($L = 1, 3$). It should be mentioned that, in a recent ^{16}O scattering experiment[8] also, a structure has been observed around $E_x \sim 20$ MeV which was interpreted as being due to 3^- and 5^- giant resonances. However, the shape of this structure[8] is different from that in Fig. 1, especially at the low-excitation-energy side, and tends to be more narrow.

In the excitation region of our new resonances structure is seen in electron scattering. Evidence for the giant octupole resonance is obtained at an excitation energy of 16–19 MeV.[1,2] Further, a resonance is seen at $E_x \sim 22$ MeV which was interpreted as the isovector quadrupole excitation.[1,2] This structure has also been observed in the (p,γ) reaction.[9] Our results for the 17.5-MeV resonance are in agreement with the (e,e') results: Energy and width are the same as in Ref. 2, also the structure in the angular distribution is consistent with $L = 3$ (Fig. 2). Our higher-energy resonance at about 21.3 MeV, however, cannot be identified with the isovector quadrupole resonance seen in (e,e') and (p,γ) reactions.[1,2,9] With α particles the excitation of this resonance should be weak, also from our angular distribution we would expect $L=2$. As reported below we made an attempt to interpret our data for the 21.3-MeV resonance assuming an isoscalar dipole excitation.[10] This type of excitation represents a compressional mode with features related to those of the "breathing mode." From microscopic RPA calculations[11] such a mode was predicted close to the energy of our new resonance.

In order to analyze our experimental data in Fig. 2, distorted-wave Born-approximation calculations were performed with use of folding-type form factors. The details of these calculations are the same as in Refs. 5 and 6 as well as the optical potentials. An effective nucleon-nucleon interaction of Gaussian shape was used with 1.68 fm range and a strength of 20.3 MeV. To show the quality of this description calculated cross sections are shown in Fig. 2 for the excitation of the low-lying 3^- state at 2.61 MeV. The transition density used was of the form $\Delta\rho(r) \sim d\rho(r)/dr$ [$\rho(r)$ being the ground state density] with a strength yielding the measured $B(E3)$ value of $7.72\times 10^5\ e^2\cdot\mathrm{fm}^6$ (Nagao and Torizuka[12]). The simple surface derivative transition density $d\rho(r)/dr$ was also used for the description of high-lying excitations except for multipolarity $L=0$ and 1. For these simple macroscopic model transition densities[13,14] have been applied. The GMR cross section is obtained if, in addition to the compressional mode of excitation, a surface component is assumed (the details are discussed in Ref. 6); a small $L=1$ component exciting the $T_<$ component of the isovector giant dipole excitation located at the same excitation energy as the GMR is added (dashed line in Fig. 2 for the 13.8-MeV resonance). For a high-lying isoscalar dipole compressional mode, a transition density was used of the form[14]

$$\Delta\rho(r) = \delta\rho_0 \frac{\partial\rho(r)}{\partial\rho_0} \ln\left(1+\frac{r}{R}\right) + \delta R\, \frac{\partial\rho(r)}{\partial R}\,.$$

The differential cross section for the 13.8-MeV resonance (Fig. 2) is well described by adding to the $L=0$ and 1 excitation (dashed line) a small component of higher multipolarity. The solid line is obtained by assuming $L=4$ and 6 contributions with 3.5 and 6% energy-weighted sum-rule (EWSR) strength, respectively, as suggested by RPA calculations.[15] For the 17.5-MeV resonance a $L=3$ calculation is shown (Fig. 2) with a strength exhausting 60% of the isoscalar EWSR strength. An excellent description of our data is obtained which strongly supports the interpretation of this structure being the giant octupole resonance. Together with the excitation of the 3^- state at 2.61 MeV (23.5% EWSR strength) and higher-lying $L=3$ excitations[16] we can account for the total octupole sum-rule strength.

For the higher-energy resonance at 21.3 MeV the structure in the angular distribution also indicates negative parity. However, $L=5$ excitation can be excluded, because the corresponding diffraction pattern is out of phase with the data at small angles (see the dashed line in Fig. 2). Assignment of an $L=1$ excitation yields a good description of the experimental data. The differences in the yield of the two resonances in Fig. 1 are nicely reproduced: At 10° the higher-energy resonance is stronger whereas at 15° a larger cross section is obtained for the 17.5-MeV resonance. With use of the energy-weighted sum rule for isoscalar dipole excitations by Decowski, Morsch, and Benenson,[17] the cross section for the 21.3-MeV resonance corresponds to 90% sum-rule strength. Adding the low-lying excitations (Ref. 17) and the isoscalar component of the giant dipole excitation, we obtain about 100% of the sum-rule strength.

Finally, the cross section for isovector quadrupole excitation is estimated which in α scattering is only due to isospin mixing of the target excited. In the assumption $\Delta\rho^n = (N/Z)\Delta\rho^p$ the $T=0$ part of the isovector excitation is reduced by a factor of $[(N-Z)/A]^2$ as compared to isoscalar excitation. The differential cross section given by the dot-dashed line in Fig. 2 is one order of magnitude smaller than the cross sections measured. We conclude that in α scattering we observe only the isoscalar dipole mode. On the other hand, in (e,e') the dominant contribution in this energy region is due to isovector quadrupole excitation.[1,2] This shows nicely the complementary character of hadron and electron scattering in studying nuclear structure.

In summary, our spectra indicate new giant resonance structure in α scattering at $E_x = 17.5$ and 21.3 MeV. The data for the 17.5-MeV resonance are well described if one assumes giant octupole excitation. The $L=3$ character deduced from the shape of the angular distribution nicely confirms the assignment from electron scattering. The data for the higher-energy resonance at 21.3 MeV can be well understood in terms of the isoscalar giant dipole resonance. This provides first experimental evidence for this compressional mode of excitation, the "squeezing mode" of the nucleus.

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Theoretical Scheme for Axial Compression of a Relativistic Electron Beam

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Bunching the density of a relativistic electron beam via the ∇B drift is analyzed for a beam propagating in a $1/r$ azimuthal magnetic field produced by a current driven in a wire. Substantial enhancement of the beam current is predicted.

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In the past few years great interest in relativistic electron beams (REB) had been kindled because of their use in producing radiation and their possible application to inertial confinement fusion (ICF).[1] Recently, the emphasis in the field of particle-beam drivers for ICF has been diverted to ion beams[2] because of their strong coupling to targets and the possibility of axially compressing them by means of time-of-flight bunching. However, the use of properly constructed external magnetic fields in conducting plasmas in order to achieve both bunching[3] and enhanced coupling to targets[4] of REB has been investigated and found to be possible as well. In the present paper we describe the details of a proposed scheme to bunch REB.

In a $1/r$ azimuthal magnetic field, electrons propagate mainly by ∇B drift so that a REB will axially compress during flight for appropriately ramped diode voltage waveforms. Significant current multiplication can be obtained if a pinched beam is allowed to expand in a plasma-filled gap before entering the magnetic-field drift region. A high-density plasma provides charge and current neutralization of the beam in both the gap and the drift region. The inertia of this high-density plasma minimizes magnetohydrodynamics effects so that very small magnetic field variations will occur during the passage of the beam.

A schematic representation of a proposed experimental set up is shown in Fig. 1. The current

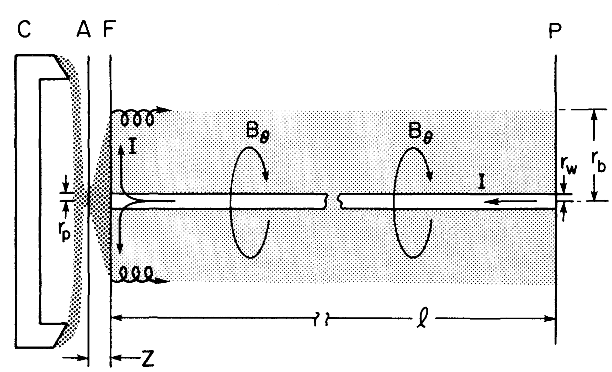

FIG. 1. Schematic representation of the proposed experimental setup showing some typical electron orbits in the magnetic-field–filled drift region; C = cathode. A = anode foil; F = second foil; P = target position.

