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Direct Evidence for a New Giant Resonance at $80A^{-1/3}$ MeV in the Lead Region

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Inelastic α scattering experiments at 120 MeV on ^{206,208}Pb, ^{197}Au, and ^{209}Bi reveal the existence of a new isoscalar resonance located at $\sim 80A^{-1/3}$ MeV in addition to the well-known resonance at $\sim 63A^{-1/3}$ MeV. The angular distribution of this new resonance, though not inconsistent with an $E4$ assignment, is better described by $E0$ or $E2$. It would exhaust approximately 100%, 50%, or 17% of the corresponding isoscalar $E0$, $E2$, or $E4$ energy-weighted sum rules, respectively.

The existence of an isoscalar giant resonance at an excitation energy $E_x = 63A^{-1/3}$ MeV has now been well established. The bulk of the experimental data indicate that this resonance is predominantly quadrupole ($E2$) and that it exhausts a substantial fraction of the isoscalar energy-weighted sum rule (EWSR).[1] An important open question is whether nonquadrupole collective strength is present at high excitation energies. Experimental evidence for nonquadrupole strength in the giant resonance region has been found in ^{16}O[2] and ^{28}Si[3] where the detection of such strength is facilitated because the giant quadrupole resonance (GQR) is fragmented. Some indirect evidence for such strength in heavier nuclei comes from an analysis of inelastic electron scattering experiments. Specifically, the existence of a giant monopole in ^{90}Zr and ^{208}Pb was suggested,[4,5] to explain additional strength at $\sim 80A^{-1/3}$ MeV remaining after subtraction of the strongly excited giant dipole resonance (GDR). Furthermore, by comparing spectra obtained from inelastic deuteron and α scattering, Marty *et al.*[6] found evidence for additional isoscalar strength in ^{40}Ca, ^{90}Zr, and ^{208}Pb which they could explain by assuming the existence of an isoscalar monopole (breathing mode) resonance which would be located at the same energy. Recently the presence of $L = 3$ ($\sim 15\%$ of the EWSR) and $L = 0$ ($\sim 2\%$ of the EWSR) isoscalar strength in the continuum region of ^{208}Pb has been deduced from a high-resolution inelastic-proton-scattering experiment.[7]

In this Letter we present data on inelastic α scattering on ^{208}Pb at $E_\alpha = 120$ MeV. The spectra show that in addition to the well-known giant resonance located at $E_x = 10.9 \pm 0.3$ MeV with a width of 3.0 ± 0.3 MeV, there is another smaller peak located at $E_x = 13.9 \pm 0.3$ MeV with a width of 2.5 ± 0.6 MeV. This comprises the most direct evidence for the existence of a new giant resonance (GR) at $80A^{-1/3}$ MeV for which a full angular distribution has been obtained. The angular distribution of the 13.9-MeV structure is well described by an $L = 0$ or 2 transfer but is also not inconsistent with an $L = 4$ transfer. The measured cross section indicates that it exhausts approximately

100%, 50%, or 17% of the corresponding $L=0$, 2, or 4 isoscalar EWSR, respectively. We also present data for ^{197}Au, ^{206}Pb, and ^{209}Bi which clearly show a similar structure in the giant resonance region. This indicates that the occurrence of this new resonance is a general feature in this mass region.

The data for ^{208}Pb were taken using the 120-MeV analyzed α beam from the Kernfysisch Versneller Instituut cyclotron. The scattered particles were detected by means of two counter telescopes yielding an overall energy resolution of about 150 keV (full width at half-maximum, FWHM). Peaks in the spectra arising from a small amount of ^{12}C and ^{16}O impurity were identified by comparison with α spectra from a Mylar target. By using a blank target frame we made sure that scattering from the frame was negligible in the energy region of interest at all angles. Relative cross sections were converted to absolute cross sections by comparing the relative elastic scattering cross sections with the predictions of optical-model calculations. This procedure is believed to be accurate to 10%. Figure 1(a) shows spectra for ^{208}Pb obtained at 14° and 17°. Fine structure[1] is observed but is not the subject of the present investigation.

The data for ^{197}Au, ^{206}Pb, and ^{209}Bi were taken during a different run using a similar setup. In Fig. 1(b) we display the 13° spectra obtained for these nuclei with the one obtained from ^{208}Pb. These spectra are very similar in shape and they all show an additional bump located approximately at $E_x = 80A^{-1/3}$ MeV. This excitation energy coincides with the GDR energy, which is probably the reason that it has not previously been observed directly, although indirect evidence for it has been presented.[5,6] It is noteworthy to remark here that the excitation of the GDR in inelastic α scattering from ^{208}Pb at $E_\alpha = 115$ MeV is expected[8] to be an order of magnitude smaller than the measured cross section for the 13.9-MeV structure.

The ^{208}Pb data have been analyzed by fitting the spectra in the giant resonance region with two Gaussian-shaped peaks superposed on an appropriate nuclear continuum. This has been illustrated for the 14° and 17° spectra in Fig. 1(a). The largest peak, GR1, with $E_x = 10.9 \pm 0.3$ MeV and $\Gamma(\mathrm{FWHM}) = 3.0 \pm 0.3$ MeV, corresponds in position and width to the one previously observed in inelastic hadron and electron scattering.[1] The smaller one, GR2, has an excitation energy $E_x = 13.9 \pm 0.3$ MeV and $\Gamma(\mathrm{FWHM}) = 2.5 \pm 0.6$ MeV.

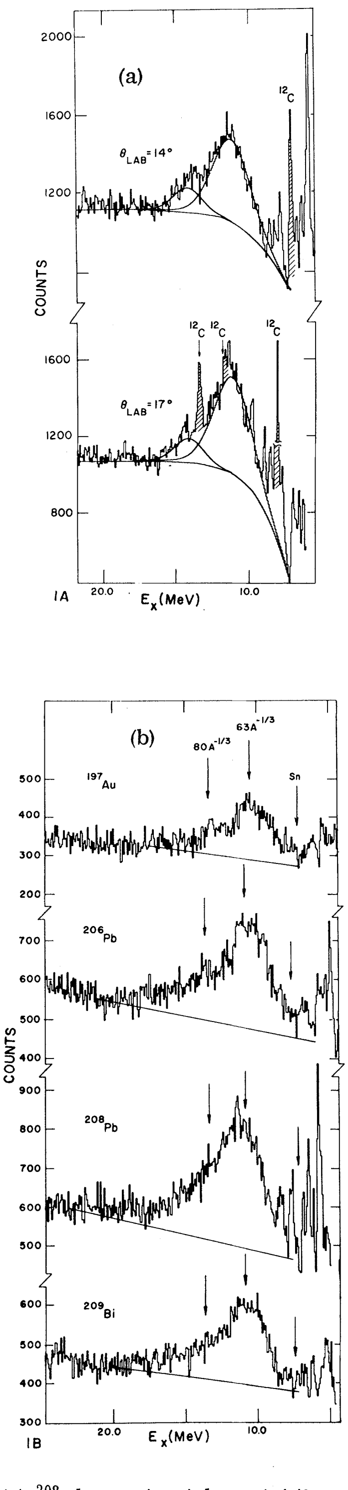

FIG. 1. (a) ^{208}Pb spectra taken at 14° and 17°. The two Gaussian peaks and the background fitted to the data are indicated. (b) Spectra taken at 13° for ^{197}Au, ^{206}Pb, ^{208}Pb, and ^{209}Bi are shown. The neutron separation energies as well as excitation energies corresponding to $63A^{-1/3}$ and $80A^{-1/3}$ MeV are indicated by arrows. The straight lines drawn are only to guide the eye.

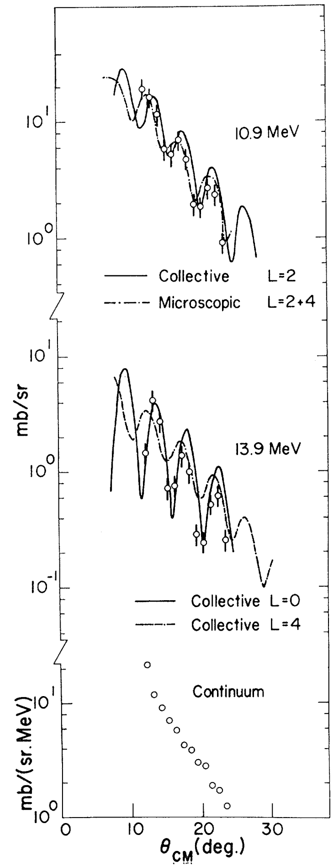

FIG. 2. Angular distributions of GR1 and GR2 and the underlying continuum for ^{208}Pb. 20% errors have been assumed for GR1 and GR2. The solid lines through the data are the results of DWBA calculations with a collective form factor. The dashed-dotted line through GR1 is the result of microscopic calculation with $L = 2+4$. The dashed-dotted line through GR2 is the result of a collective calculation with $L = 4$.

These numbers and the quoted uncertainties are derived from an analysis of the spectra at 12°, 13°, 14°, 17°, and 18°, where a satisfactory fit to the data requires the use of two peaks. For the analysis of spectra at the other angles, which do not show as clearly the occurrence of a second bump, the positions and widths of GR1 and GR2 were fixed at the values given above. The largest uncertainty in such an analysis stems from the uncertainty in the shape and in the magnitude of the nuclear continuum underlying the resonance peaks. We estimate the uncertainty in the cross sections deduced for GR1 and GR2 due to this effect to be ± 20%.

The angular distributions of GR1 and GR2 for ^{208}Pb ar shown in Fig. 2. Several distorted-wave Born-approximation (DWBA) calculations were performed to fit these distributions. The optical potential used was that obtained[9] from α elastic scattering on ^{208}Pb at $E_\alpha = 139$ MeV. The deformation parameters $\beta_\lambda R$ obtained from the collective-model calculations[2] are shown in Table I. For $L \geqslant 2$ they can be converted to $B(E\lambda)$ values by using the relevant data for an excited state of the same multipolarity for which the $B(E\lambda)$ value is well established from electromagnetic measurements.[2] The result of such a calculation for GR1 and GR2 (assuming pure quadrupole excitations) using the $B(E2)$ value of the 2^+ state at 4.1 MeV for normalization[10] is also shown in Table I. The "new" resonance GR2 has also been fitted (solid line) with an $L = 0$ angular distribution using the version-I form factor of Satchler[11] and an $L = 4$ one obtained using the collective model (dashed-dotted curve). The $L = 4$ distribution does not reproduce the data for GR2 as well as

TABLE I. Summary of results obtained for giant-resonance peaks.

	E_x [a] (MeV)	Γ(FWHM) [a] (MeV)	J[b]	βR[c]	S[d] (% EWSR)	S[e] (% EWSR)
GR1	10.9 ± 0.3	3.0 ± 0.3	2	0.66	145 ± 30	90 ± 20
GR2	13.9 ± 0.3	2.5 ± 0.6	0	0.41	110 ± 22	117 ± 24
			2	0.34	50 ± 10	30 ± 6
			4	0.35	17 ± 4	

[a]As obtained from this experiment.
[b]Assumed J value for the giant resonances.
[c]Obtained from a collective model analysis; uncertainty of ± 20% is assigned on basis of data analysis.
[d]Obtained from a collective model analysis normalizing for the 2^+ and 4^+ cases to the corresponding low-lying states.
[e]From folding model calculations using the Tassie model densities.

the $L = 0$ curve or the $L = 2$ curve (not shown but very similar to $L = 0$).

We also performed microscopic calculations similar to the ones described by Halbert *et al.*[8] We included, in addition to the real interaction, an imaginary term as is used in the collective model with a deformation parameter βR equal to the one calculated for the real part.[8] The low-lying states are well reproduced in shape by these calculations while the magnitude is reproduced within 40%. For GR1 the random-phase-approximation calculations[12] predict considerable $E2$ (53% of the EWSR) and $E4$ (16% of the EWSR) strength in the 9–15-MeV excitation interval. The calculated angular distribution for GR1 taking into account only these predicted 2^+ and 4^+ strengths is shown as a dash-dotted curve in Fig. 2. The agreement is surprisingly good.

In yet another approach, the α-nucleon potential is folded into transition densities obtained from collective models, e.g., surface derivative and Tassie densities. Here the strength and range of the nucleon-nucleon interaction are obtained from a fit to the low-lying states. The calculated angular distributions are very similar to the ones obtained from the collective model.

The different calculations for the strength of GR1, assuming it to be a pure quadrupole resonance, are in reasonable agreement, as is shown in Table I. It exhausts approximately the total $E2$ isoscalar EWSR which agrees with previous analyses.[1] On the other hand, the data for GR1 can also be quite well reproduced with an $E2+E4$ mixture as has been shown above.

For GR2, assuming it to be $E0$ excitation, the different models predict that it exhausts the total EWSR (see Table I). Although none of these models for $E0$ excitation has been tested at high excitation energies, it nevertheless indicates that if GR2 were a giant monopole, it would exhaust a considerable fraction of the EWSR.

On the basis of the angular distribution it is impossible to differentiate between an $E0$ and an $E2$ assignment for GR2. However, if GR2 were a quadrupole resonance exhausting 50% of the EWSR, it would imply that in a spherical nucleus like ^{208}Pb one would have a splitting of the isoscalar $E2$ strength in two components. This is contrary to what one would expect, for instance, from a hydrodynamical model.[13] This argument makes an $E2$ assignment less likely. Also the fact that a small fraction (2% of the EWSR) of the monopole resonance has been located at 9.3 MeV[7] makes it possible that the giant monopole resonance is located indeed around $E_x = 14$ MeV and not pushed to higher excitation energies as some theories predict. While an $E4$ assignment is not as favored as an $E0$ or $E2$ assignment on the basis of the angular distribution, some $E4$ strength is predicted[12] at these excitation energies. Only a small fraction of the EWSR (~17%) is needed to describe the data. Clearly more data obtained with different particles at different bombarding energies are needed to make it possible to distinguish between the different multipolarities.

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