Electroexcitation of Giant Resonances in ^{208}Pb

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The giant-resonance region in ^{208}Pb was observed by inelastic electron scattering. We present evidence for the existences of a 2^+ (or 0^+) state at ~22 MeV and a 3^- state at ~19 MeV with giant-resonance character. The resonance states between 8.6 and 11.6 MeV are confirmed to be 2^+ (or 0^+) and the sum of their strengths exhausts about 50% of the $E2$ sum rule or 100% of $E0$.

Recent studies of the giant-resonance region in medium and heavy nuclei using various experimental techniques have demonstrated the existence of new resonances besides the usual giant dipole resonance.[1-7] For example, measurements on ^{90}Zr have resolved a resonance at 14.0 MeV and a broad bump at 28 MeV from the usual giant dipole resonance (GDR) at 16.7 MeV.[4] From the analysis of these form factors, evidence for a giant quadrupole (or monopole) resonance has been presented. In the Letter we report the results of inelastic electron scattering on ^{208}Pb, obtained at the Tohoku University 300-MeV electron linear-accelerator facility. The spectra were measured up to 30 MeV in excitation energy in the momentum-transfer range between 0.5 and 0.8 fm^{-1}. Compared with the previous works on this nucleus,[2,8] using primary electrons of relatively low energies (50–65 MeV), magnitudes of peaks relative to the underlying continuum have been increased to some extent in our spectra.

The experiments were performed at incident energies of 124, 150, 183, 215, and 250 MeV. Forward scattering angles (35° and 40°) were chosen so that the Coulomb term would dominate the excitation function. We employed two 99.5%-enriched ^{208}Pb self-supporting targets of 50.5 and 101.1 mg/cm^2. The data were collected with an overall resolution of 0.15%. The excitation energies were accurate to ±200 keV in the region of the giant resonance. The cross sections were normalized by the yields of elastic scattering.[9,10] The raw spectra were corrected for radiative effects as described elsewhere.[11] Figure 1 displays the cross-section spectra as a function of excitation energy. Resonances have been observed at excitation energies of 8.9, 9.4, 10.0, 10.6, 11.2, 13.4, and 14.1 MeV, and a broad bump in the range of energies 16–27 MeV. In photonuclear reactions the GDR has been observed at $E_x = 13.42$ MeV with a width $\Gamma = 4.05$ MeV and integrated cross section 3.48 ± 0.2 MeV b.[12]

In order to extract the cross sections of the resonances the continuum background was approximated by a phenomenological form given by[4] $Y = a(E - E_0)^{1/n}$, where E_0 was assumed to be 7.4

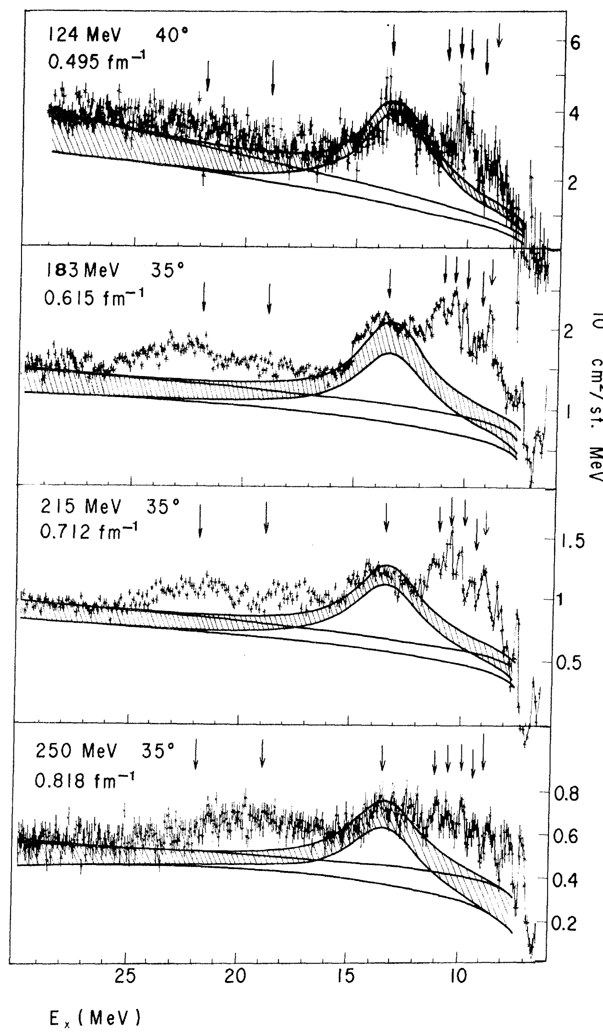

FIG. 1. Inelastic electron scattering spectra in ^{208}Pb at various momentum transfers. Arrows indicate positions of peaks at excitation energies 8.9, 9.4, 10.0, 10.6, 11.2, 13.4, 19, and 22 MeV.

MeV and n and a are adjustable parameters determined in the fitting procedure. We have subtracted the contribution of the GDR from the spectra assuming the Breit-Wigner resonance form given by

$$\sigma(E) = C\Gamma[(E - E_x)^2 + \tfrac{1}{4}\Gamma^2]^{-1}, \qquad (1)$$

where C was obtained by multiplying the $B(E1)$ value derived from the (γ, n) cross section by the distorted-wave Born-approximation (DWBA)[13] cross section normalized to the unit value of $B(E1)$. The GDR curve, with a total width $\Gamma = 4.05$ MeV and background given by the above form, were fitted simultaneously as shown in Fig. 1, where the cross-hatched area indicates the errors arising from the fitting together with those

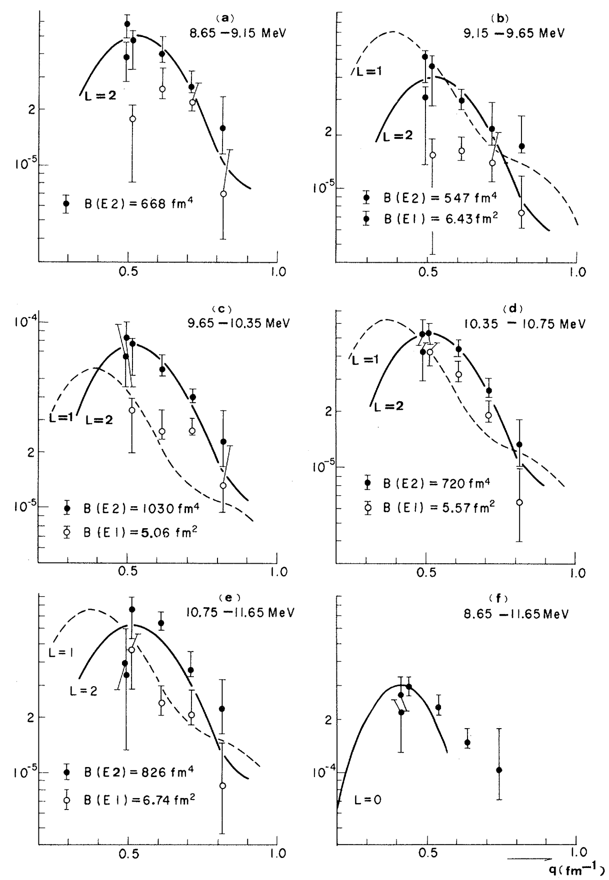

FIG. 2. Form factors for peaks at 8.9, 9.4, 10.0, 10.6, and 11.2 MeV integrated in the range of excitation energies indicated in the upper corner of each graph. Open circles, form factors extracted only from the peak parts which are seen manifestly. (a)–(e) Form factors plotted against q_{eff}. The $B(EL)$ values shown in the lower corner were obtained by comparing these form factors with the theoretical curves of $L = 1$ and 2. (f) Sum of the form factors compared with the monopole form factor described in the text.

of the (γ, n) cross section. In order to compare with theoretical predictions, we have integrated the cross sections in certain ranges of excitation energies. The form factor is defined to be the observed cross section divided by the Mott cross section. Figures 2 and 3 show the experimental form factors for the 8.9-, 9.4-, 10.0-, 10.6-, and 11.2-MeV peaks and the bump above the GDR. In order to identify the multipolarities of the excitations, these form factors were compared with theoretical form factors calculated by the DWBA code.[13] The transition charge density used in the analysis was taken from the hydrodynamical model.[14] In this model the transition charge density is given by $\rho_{\mathrm{tr}} = N r^{L-1}(d/dr)\rho(r)$, where N is a normalizing factor and L is the multipolarity. For $\rho(r)$ a Gaussian shape with $c_{\mathrm{tr}} = 6.25$ fm and $z_{\mathrm{tr}} = 2.93$ fm was employed.[9]

The form factors of the five peaks below the GDR are consistent with the assumption of $L = 2$. The $B(E2)$ values for these 8.9-, 9.4-, 10.0-, 10.6-, and 11.2-MeV peaks have been found to be 668, 547, 1030, 720, and 826 fm^4, respectively. The sum of the last triplet of values is very close to the value 2600 ± 900 fm^4 obtained by Buskirk *et al.*[2] The triplet with the similar excitation energies has also been found in the (γ, n) spectrum by Veyssiere *et al.*[12] However, if the $E2$ assignment is applied to the triplet in the (γ, n) cross

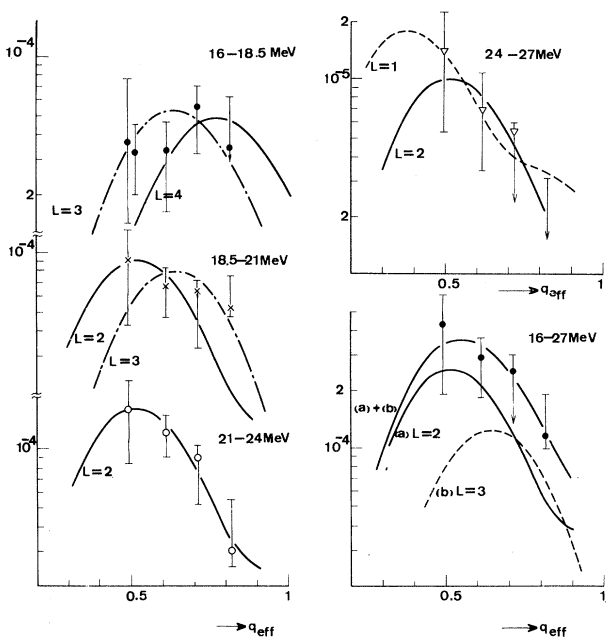

FIG. 3. Form factors integrated over the range of energies indicated in the upper corner. The form factor in the range 16–27 MeV was decomposed to the $E2$ and $E3$ components.

section, then it is found to be several times larger than expected from our data. Thus the triplet observed in the (γ, n) spectrum is mostly of $E1$ nature.

We examined the $E1$ components which may be contained in our inelastic spectra. The form factors extracted only from peak parts which are manifestly seen are plotted (open circles) in Fig. 2. When $E1$ was assumed for these form factors, the values of $B(E1)$ were found to be larger by about an order of magnitude than expected from the (γ, n) spectrum. This leads us to conclude that the form factors in Fig. 2 include little $E1$ components.

The bump above the GDR shifts towards lower excitation energy as the momentum transfer increases. The cross-section peak of quasielastic electron scattering is given by $q^2/2M+$(average nucleon interaction energy). Thus, from the observed q dependence the possibility that this bump is attributed to quasielastic scattering may be eliminated. From careful investigations on ^{12}C under comparable conditions the bump due to the so-called instrumental scattering is very small in our system and can be neglected.

The bump above the GDR has been divided into appropriate ranges, and the form factor of each range is compared with the theoretical curves as seen in Fig. 3. The excitations in the ranges 16–18.5 and 18.5–21 MeV favor the assignment $L=3$ and the excitations in the ranges 21–24 and 24–27 MeV are reproduced with $L=2$. The form factor integrated from 16 to 27 MeV has been decomposed to the $E2$ and $E3$ components as seen in Fig. 3 and the $B(E2)$ and $B(E3)$ values obtained are tabulated in Table I. From these results together with the spectral shapes the energies of the $E2$ and $E3$ resonances may be determined to be at around 22 and 19 MeV, respectively. According to the hydrodynamic picture of density vibration[15] the $E2$, $E3$, and $E4$ resonances are predicted at 21.5, 29, and 36.4 MeV, respectively, if the GDR is assumed to be at 13.4 MeV. The (γ, p) angular distributions for heavy nuclei[16] have suggested the existence of $E2$ resonances in the region of energies 20–30 MeV.

TABLE I. Values of $B(EL)$ and $|M(0)|^2$, and the percentage of the energy-weighted sum rule.

E_X	L	$B(EL)$[a] (fm^{2L})	Type of EWSR	Percentage of sum rule
8.6–11.6	2	$(3.8\pm0.4)\times10^3$	$T=0$	47
	0	$\sim 8\times10^3$ [b]	$T=0$	100
$\simeq 19$[c]	3	$(1.8^{+0.6}_{-1.6})\times10^5$	$T=0$	44
$\simeq 22$[c]	2	$(3.4^{+1}_{-2})\times10^3$	$T=1$	60
	0	$\sim 7.2\times10^3$ [b]	$T=1$	126

[a]Errors from the model dependence of analysis are not included.

[b]$|M(0)|^2=|\langle\sum_i \frac{1}{2}(1+\tau_3)r_i^2\rangle|^2$ in fm^4.

[c]Derived from a broad bump at 16–27 MeV [see Fig. 3(c)].

An inelastic $E2$ form factor cannot be distinguished from an $E0$ form factor. The form factor of a monopole breathing mode is given by[17]

$$F(q)_{BA}=\frac{Z}{R}\frac{1}{(2mA\omega)^{1/2}}q\frac{dF_0(q)}{dq}, \qquad (2)$$

$F_0(q)$ being the form factor of elastic scattering. When the distortion of the electron waves is taken into account,[18] this becomes

$$|F(E_0,\theta)_{DWBA}|^2=|F(q)|_{BA}{}^2[1+Z\alpha\beta(q,E_0)]. \qquad (3)$$

The form factors calculated from this formula are compared with the sum of the form factors in the range from 8.6 to 11.6 MeV (in Fig. 2) and the 22-MeV bump. The monopole matrix elements obtained are 89.5 fm^2 for the 8.6–11.6-MeV resonance and 85 fm^2 for the 22-MeV bump.

The transition strengths can be expressed as percentages of appropriate sum rules. A 2^+ or 0^+ state may be built on transitions between shells of N and $N+2$, with the transition energy of $2\hbar\omega\simeq14$ MeV. The oscillations are shifted to lower frequencies because of the attractive nuclear force of $T=0$. Hence, the 2^+ or 0^+ states below the GDR were compared with the energy-weighted sum rule[19,20] (EWSR) for an isoscalar excitation. The 2^+ (or 0^+) state at ~22 MeV was compared with the EWSR for isovector excitation since $T=1$ interactions raise the transition energy. The $E3$ resonance around 19 MeV was assumed to be an isoscalar excitation with an unperturbed energy of $3\hbar\omega\simeq21$ MeV. The fractions of the EWSR occupied by these states are given in Table I. The resonance states above the GDR as well as the sum of the states between 8.9 and 11.2 MeV exhaust most of the corresponding sum rules, thus constituting another indication of their giant-resonance character.

We conclude that (1) the resonance states in the range from 8.6 to 11.6 MeV could be assigned to be $E2$ or $E0$ and the sum of the transition strengths occupies a major part of the corresponding sum rule for either assignment. However, from the relation between the (γ, n) spectrum and our results an $E2$ assignment cannot be made definitely; (2) the broad bump in the region from 16 to 27 MeV is contributed to by at least $E2$ (or $E0$) excitation at ~22 MeV and $E3$ excitation at ~19 MeV, the sum rule of which both are nearly exhausted.

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Pion-Nucleus Scattering in an Isobar-Doorway Model*

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Elastic pion-nucleus scattering is treated using a separation in Hilbert space via a projection-operator formalism. The basic assumption is that the elastic scattering and reactions due to the π-N resonance proceed through doorway states consisting of a $\Delta(1236)$ resonance in the nucleus. Nonresonant scattering and absorption processes are included by background terms, which are approximately known. The formalism is applied to π^--^{12}C scattering.

Although there are qualitatively successful calculations of pion-nucleus elastic scattering near the energies of the $\Delta(1236)$ π-nucleon resonance ($T_\pi \approx 150$–250 MeV),[1-4] there are many theoretical difficulties with the present theories and no truly quantitative treatment. We propose a new approach which offers a framework in which one can conveniently study most of these difficulties and express the results in terms of physical quantities. This is the isobar-doorway model, in which one treats the states of the π-N resonance (the isobar) in a nucleus as doorways for entrance into all inelastic nuclear states, plus a background of nonresonant scattering and absorption.

As we shall show, the modification of the binding energy when a nucleon is replaced by a resonance appears in an unambiguous way in the present theory. There has been considerable confusion regarding this quantity, which is only remotely related to the shift in the maximum of the π-nucleus cross section as compared to the π-nucleon cross section, plotted against energy.

As a starting point, the π-nucleon states are separated into the resonant $J=\frac{3}{2}$, $T=\frac{3}{2}$ state [the $\Delta(1236)$] and all other (nonresonant) states. This leads to a separation of the states of the π-nucleus system into subspaces. We accomplish