Giant Multipole Resonances in ^{90}Zr Observed by Inelastic Electron Scattering

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Inelastic electron scattering from the giant dipole resonance region in ^{90}Zr was measured. In addition to the usual dipole resonance we have found new resonances at 14.0 MeV and around 28 MeV. The spins and parities and transition strengths of these states are discussed.

Recently studies of the giant-dipole resonance region using inelastic electron scattering have been extended to medium and heavy nuclei. For example, at Darmstadt, such an experiment was performed on La, Ce, and Pr by using primary electrons of relatively low energies (50–65 MeV).[1] In this Letter we report the results of inelastic electron scattering from the giant resonance of ^{90}Zr, obtained by using the beam of the Tohoku 300-MeV linear accelerator. Spectra were measured up to about 40 MeV in excitation energy at momentum transfers of 0.5, 0.58, 0.78, and 1.0 F^{-1}. These momentum transfers were chosen to be favorable for the excitation of the quadrupole or monopole resonances. In addition to the usual dipole resonance we have observed a large resonance peak at 14 MeV and a broad bump around 28 MeV. By comparing the experimental form factors with the prediction of the hydrodynamical model these resonances were found to be of $E2$- or $E0$-like character.

The experiments were performed at energies of 150, 183, and 250 MeV. Scattering angles were chosen to be rather forward angles so that the longitudinal terms dominated the excitation function. An enriched ^{90}Zr target (97.5% enrichment, 49.9 mg/cm^2 thickness) obtained from Oak Ridge National Laboratory was used. The spectrometer and detection apparatus have been described elsewhere.[2] The data were taken at the overall energy resolution of 0.15%. The excitation energies are accurate to ± 200 keV in the region of the giant dipole resonance. The cross sections were normalized against elastic and inelastic electron-carbon cross sections measured in the same experiment. The cross sections as a function of the excitation energy are displayed in Fig. 1. These spectra were corrected for radiative effects as described elsewhere.[3] In the upper part of Fig. 1 the giant dipole resonance in ^{90}Zr observed by using monochromatic photons is shown for comparison.[4] The photon cross section is approximated by a Lorentz line with $E_1 = 16.65$ MeV and $\Gamma_1 = 4.0$ MeV. The corresponding resonance observed by electron scattering appears to be considerably broader than expected from the Lorentz line mentioned above. It seems to suggest the excitation of another resonance as indicated by the arrow at 14.0 MeV. The relative magnitude of these peaks changes with increasing momentum transfer and the 14.0-MeV peak contributes mainly to the cross section at high momentum transfers. Another broad resonance is also seen in the vicinity of 28 MeV. The cross sections of these peaks depend strongly on the estimation of the continuum background, which has been considered to be due to the electrons

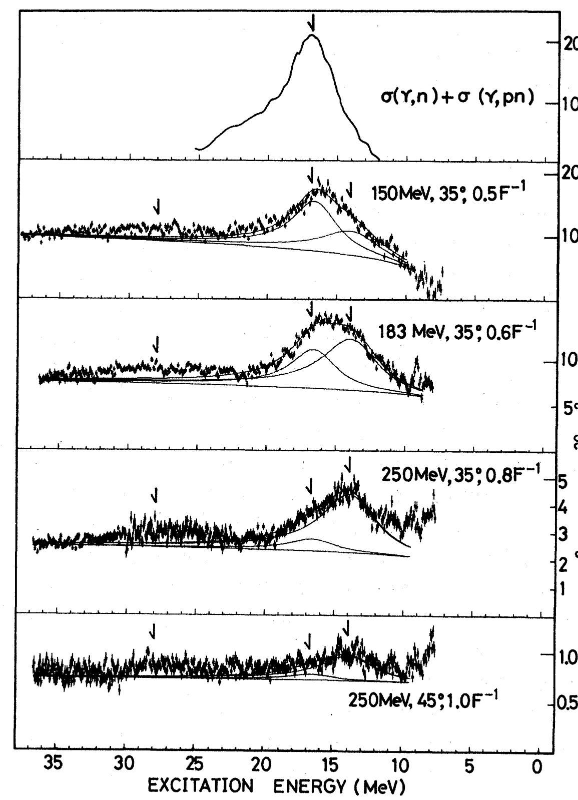

FIG 1. Spectra of photoreaction and electron scattering in ^{90}Zr. The arrows indicate the positions of the 14.0–, 16.65–, and 28-MeV peaks.

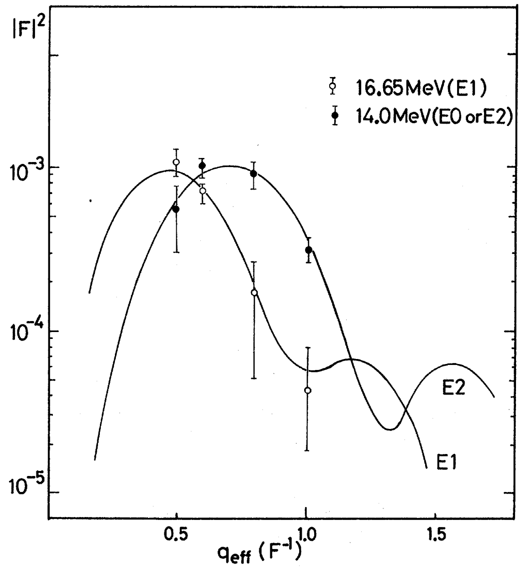

FIG. 2. The experimental form factors for the 14.0- and 16.65-MeV peaks are compared with the $E2$ and $E1$ form factors calculated with the DWBA code written by S. T. Tuan *et al.*, Nucl. Instrum. Methods 60, 70 (1968).

scattered quasielastically from the individual nucleons in the nucleus. This type of background may be complicated, particularly in the giant-resonance region. This continuum contribution was estimated by adopting a phenomenological formula

$$y = a(E_x - E_0)^{1/n},$$

where E_x is the excitation energy, $E_0 = 6.8$ MeV the threshold energy of particle emission, n an adjustable parameter, and a is constrained to fit the point of the spectrum at about 37 MeV. The shape of the background is determined by the least-squares method by taking into account the 16.65- and 14.0-MeV resonances. For the shape of the giant-dipole inelastic electron-scattering resonance, the same Lorentz shape as for photons was employed. A Lorentz line shape of variable width was also assumed for the 14.0-MeV resonance. Reasonable fits for the 14.0- and 16.65-MeV complex were obtained as indicated in Fig. 1. The width of the 14.0-MeV peak was determined to be 4.8 ± 0.6 MeV.

The experimental form factor was obtained by dividing the experimental cross section by the Mott cross section for $Z = 40$. In Fig. 2 the form factors for the 14.0- and 16.65-MeV states are displayed as a function of q_{eff}.[5] In order to identify the multipolarity of these states the results were compared with the hydrodynamical model calculated with the distorted-wave Born-approximation (DWBA) code. The 14.0-MeV form factor follows the theoretical $E2$ curve. However, since an $E2$ inelastic form factor cannot be distinguished from an $E0$ form factor, the 14.0-MeV resonance may be either $E2$ or $E0$.

The resonance around 28 MeV may be seen superimposed on the extended line of the low-lying resonances. The hydrodynamical model predicts the quadrupole giant resonance at a position 1.6 times the peak energy of the usual giant dipole resonance.[6] The (γ, p) angular distribution for heavy nuclei in the γ-ray energy region 23–33 MeV suggests an $E2$ absorption,[7] while Fig. 1 indicates the existence of not only $E2$ excitations, but also other multipole states higher than $E2$.

The reduced radiative transition probabilities $B(EL)$ were extracted using the transition charge density of the Tassie model.[8] In order to achieve a reasonable fit to the $E2$ and $E0$ form factors the parameters of ρ_{tr} were modified from those of the ground state to be $c_{tr} = 0.90c_0$ and $t_{tr} = t_0$, where $c_0 = 4.66$ F and $t_0 = 2.34$ F. The $E1$ form factor was reproduced with the ground-state parameters. The monopole matrix element M_{fi} is obtained by assuming the transition charge density of a breathing mode[9] in the frame of the Born approximation. The result is tabulated in Table I. The 14.0-MeV peak was analyzed by regarding it as either an $E0$ or an $E2$ excitation.

A model-independent evaluation of the transition strength may be achieved by expressing the strength relative to the energy-weighted sum rule (EWSR). A 2^+ or 0^+ state of this kind may be built on transitions between shells N and $N+2$, the energy being $2\hbar\omega \simeq 18$ MeV. The oscillations are shifted to lower frequencies because of the attractive nuclear forces of $T = 0$. For excitation with $T = 0, L > 1$, it is[10]

$$\sum_f (E_f - E_i) B(EL, i \to f) = Z^2 e^2 L(2L+1)^2 \hbar^2 \langle r^{2L-2} \rangle / 8\pi AM$$

and for an isoscalar monopole excitation it is[11]

$$\sum_f (E_f - E_i) |M_{if}|^2 = (h^2/M) Z \langle r^2 \rangle.$$

The sum rules were evaluated by calculating $\langle r^n \rangle$ using the ground-state Fermi distribution. The fractions of the sum rule exhausted by the states observed are entered in Table I.

It is of interest to note that if either an $E0$ or an $E2$ assignment is made for the 14.0-MeV state, most of the EWSR is exhausted, thus constituting another indication of its giant resonance charac-

TABLE 1. $B(E1)$, $B(E2)$, and M_{fi}, and energy-weighted sum-rule (EWSR) limits.

E_x (MeV)	J^π	P^a	$E_x P^b$	(EWSR)^b	$\frac{E_x P}{\text{EWSR}}$
16.65	1^-	17.0 ± 5.0	283 ± 86	264	1.07 ± 0.32
14.0	2^+	990 ± 300	13900 ± 4200	24900	0.56 ± 0.17
14.0	0^+	2050 ± 610	28700 ± 8500	28000	1.03 ± 0.3

$^a P$ is $B(E1)$ in units e^2 F^2 for $J^\pi = 1^-$, $B(E2)$ in e^2 F^4 for $J^\pi = 2^+$, and $|M_{fi}|^2$ in F^4 for $J^\pi = 0^+$.

^{b}Units are MeV times units of P.

ter. The resonance around 28 MeV also shows a collective nature. We have found the same kind of resonances for the relatively spherical nuclei ^{54}Fe, ^{116}Sn, and ^{208}Pb as well as for deformed ^{152}Sm. In contrast to the general relation $80A^{1/3}$ MeV for the peak energies of the giant dipole resonances, the newly discovered giant resonances are described by $65A^{1/3}$ MeV and $\sim 120A^{1/3}$ MeV, respectively.

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[1]R. Pitthan and Th. Walcher, Phys. Lett. 36B, 563 (1971).

[2]M. Kimura *et al*., Nucl. Instrum. Methods 95, 403 (1971).

[3]A. Yamaguchi, T. Terasawa, K. Nakahara, and Y. Torizuka, Phys. Rev. C 3, 1750 (1971).

[4]B. L. Berman *et al*., Phys. Rev. 162, 1098 (1967); A. Lepretre *et al*., Nucl. Phys. A175, 609 (1971).

[5]D. G. Ravenhall, quoted in R. Hofstadter, Rev. Mod. Phys. 28, 214 (1956).

[6]M. Danos and H. Steinwedel, Z. Naturforsch. 69, 217 (1951).

[7]V. G. Shevchenko and B. A. Yuryev, Nucl. Phys. 37, 495 (1962).

[8]L. J. Tassie, Aust. J. Phys. 9, 407 (1956).

[9]H. Uberall, *Electron Scattering From Complex Nuclei* (Academic, New York, 1971), Part B, Chap. 6.

[10]O. Nathan and S. G. Nilsson, in *Alpha, Beta, and Gamma-ray Spectroscopy,* edited by K. Siegbahn (North-Holland, Amsterdam, 1965), Chap. X.

[11]R. A. Ferrell, Phys. Rev. 107, 1631 (1957).

Limits on the Magnetic Moments of Doubly Odd $4N+2$ Nuclei with $T=0$, $J^\pi = 1^+$

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Assuming that the low-lying states of doubly odd nuclei contain only the two lowest SU(4) supermultiplets, I have derived the following lower and upper limits on the magnetic moments of ^{6}Li, ^{10}B*, and ^{18}F, using only experimental data on superallowed Gamow-Teller transitions: $(0.800 \pm 0.016)\mu_N \leq \mu(^6\text{Li}) \leq 0.88\mu_N$, $0.65\mu_N \leq \mu(^{10}\text{B}^*) \leq 0.88\mu_N$, $0.66\mu_N \leq \mu(^{18}\text{F}) \leq 0.88\mu_N$. This shows that relativistic corrections to the magnetic moment of ^{6}Li cannot exceed 7.3%.

In a previous paper[1] I showed that the ground state of ^{6}Li is an almost pure ($T=0$, $S=1$) state of the lowest (100) SU(4) supermultiplet,[2] consistent with good SU(4) symmetry.

The purpose of this note is to present rigorous lower and upper limits on the magnetic moments of doubly odd nuclei under the assumption that SU(4) is a good symmetry and that the ground states do not contain higher supermultiplets other than the (111) supermultiplet. Thus, the ground states of ^{6}Li and