Electroexcitation of giant monopole and quadrupole resonances in ^{181}Ta

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A new resonance peak has been found at 14.7 ± 0.2 MeV in spectra of inelastic electrons scattered from ^{181}Ta. The peak exhausts a significant part of the $E0$ sum rule and is characterized by a narrow width of about 2.1 MeV. The giant quadrupole resonances splits into two peaks at 9.5 ± 0.2 and 11.3 ± 0.2 MeV which deplete (29 ± 5)% and (63 ± 8)% of the isoscalar $E2$ energy-weighted sum rule, respectively.

[NUCLEAR REACTIONS ^{181}Ta(e, e'), measured $(E_{e'}, \theta_{e'})$, E_x = 0–30 MeV, reduced $B(E0)$, $B(E2)$ for giant resonances.]

Theoretical and experimental studies of giant resonances have recently been focused on the existence of the giant monopole resonance (GMR).[1,2] Particularly interested is the excitation energy of the monopole resonance since it can be related to the incompressibility of the nuclear matter. Possible existence of the GMR has been suggested at the energy of 80 MeV/$A^{1/3}$ (Refs. 3–5). A characteristic feature of the GMR observed in ^{208}Pb is its very narrow width of about 1.8 MeV. The monopole resonances, however, have been obtained by an indirect way since their resonance energies coincide with the giant dipole resonance (GDR) energy. Here we aim to observe directly a peak of the GMR in ^{181}Ta. The GDR of this nucleus[6] splits into two peaks at 12.35 and 15.3 MeV, which make up a broad resonance structure with a width of about 6 MeV. The overlapping resonances could be resolved if really a narrow peak exists.

Another interest of giant resonances is the observation of the splitting of the giant quadrupole resonance (GQR) in deformed nuclei. Kishimoto *et al.*,[7] Zamischa and Speth,[8] and Suzuki and Rowe[9] have predicted the splitting of the $K = 0$, $K = 1$, and $K = 2$ modes of the isoscalar GQR. A matter of concern is whether or not we can observe the splitting of the GQR due to the nuclear deformation responsible for the splitting of the GDR. Experimental attempts[2] to produce such a phenomenon revealed a broadening of the resonance line but failed to observe the splitting of the GQR.

The experiment involving inelastic electron scattering was performed using beams of the Tohoku 300-MeV electron linear accelerator. Electrons from the ^{181}Ta target were analyzed by a double-focusing magnetic spectrometer. Electrons were measured by a 33 channel ladder detector system with a total momentum acceptance of 3.3%. The setting of the magnetic field of the spectrometer was shifted at a step of the 1.1% interval in order to overlap the momentum range. In this way, nonlinearities and fluctuations of the detector system were made unimportant. Spectra up to excitation energies of 40 MeV were measured at the incident energy and angle of (150 MeV, 25°), (150 MeV, 30°), (150 MeV, 35°), (183 MeV, 35°), (215 MeV, 35°), and (250 MeV, 35°) which covers a momentum transfer range from 0.38 to 0.81 fm^{-1}. Measured cross sections were normalized to the cross section of ^{12}C measured in the same run. Data were accumulated with an overall resolution of 0.15%.

The radiation tail was calculated for internal bremsstrahlung by the formula of Mo and Tsai.[10] For target bremsstrahlung and ionization loss we used the formulas suggested by Friedrich.[11] The tail function for the single-photon emission was corrected for multiple soft-photon radiation.[3,11] Depending upon the size of the radiation tail, in order to minimize the contribution from the target thickness part, we used targets of different thickness of 4.58, 14.2, and 95 mg/cm^2.

Unfolded spectra are shown in Fig. 1 where the spectrum at 150 MeV, 35° corresponds to the momentum transfer near the maximum for $L = 2$. Error bars indicated arise not from the statistics but from the unfolding procedure and they are proportional to the size of the radiation tail subtracted. A narrow peak at 14.7 MeV and broad bumps centered at 11 and 24 MeV, which indicate an $E2$-like q dependence, are seen in measured spectra. A peak rising at low energy side (~4 MeV) is a complex which contains excitations of $E2$, $E3$, etc. The 11-MeV peak seems to correspond to the isoscalar $E2$ resonance known around this energy.[2] This bump rises up at 9 MeV and falls off at 11 MeV. The broad peak observed around 24 MeV may be attributed to the isovector $E2$ resonance. In order to divide the resonance part and underlying background, a polynominal $y = a_0\sqrt{\omega} + a_1\omega + a_2\omega^2$ and the distorted wave Born approximation

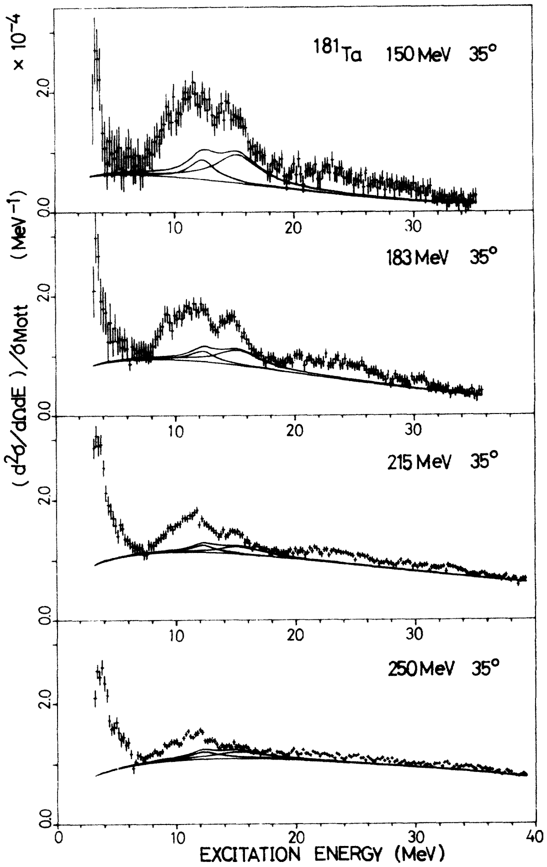

FIG. 1. Spectra of inelastic electrons scattered from ^{181}Ta. The radiation tail was subtracted by the calculation. Solid curves represent the giant dipole resonance and underlying background.

(DWBA)[12] giant dipole resonance were fitted simultaneously as shown in Fig. 1. The difference between the new peak at 14.7 MeV and GDR is evident. In the calculation of the GDR $K=0$ and $K=1$ components we used the Goldhaber-Teller (GT) model extended to deformed nuclei.[9,13] Assuming a Breit-Wigner line shape the DWBA GDR is equivalent to the transition strength and width of the photonuclear reaction.[6]

After the subtraction of the GDR and background, the remaining cross sections are displayed in Fig. 2. The peak centered at 11 MeV differs noticeably from the Lorentz or Breit-Wigner resonance curve as mentioned above. Recently, a vibrating potential model was applied to deformed nuclei by Suzuki and Rowe.[9] Eigenfrequencies of the GQR states are estimated to be $\sqrt{2}\hbar\omega(1-\frac{1}{3}\delta)$, $\sqrt{2}\hbar\omega(1-\frac{1}{6}\delta)$, and $\sqrt{2}\hbar\omega(1+\frac{1}{3}\delta)$ for $K=0$, 1, and 2 modes, respectively, where δ is determined to be 0.206 from the experimental dipole energies $\omega(K=0)=12.35$ MeV and $\omega(K=1)=15.3$ MeV. Then the quadrupole energies in this nucleus are obtained at 9.43, 9.78, and 10.82 MeV for the $K=0$, 1, and 2 states, respectively. The observed bump at 11 MeV was decomposed into three components by a χ^2 fitting procedure. Two prominent peaks which deplete $(29\pm5)\%$ and $(63\pm8)\%$ of the isoscalar $E2$ energy-weighted sum rule (EWSR) was obtained at 9.5 ± 0.2 and 11.3 ± 0.2 MeV, respectively. The results are in good agreement with the above predicted energies indicated by arrows in Fig. 2. A minor peak at 12.6 MeV (Table I) with large uncertainty arises from the fitting procedure. The present result is consistent with the schematic model[7] and with the microscopic calculation.[8] It seems natural to connect the 9.5- and 11.3-MeV peaks to the $K=0$ state and unresolved $K=1$ and 2 state, respectively.

A new resonance has been found at 14.7 ± 0.2 MeV with a width of 2.1 ± 0.3 MeV, which cannot be differentiated between an $E0$ or $E2$ assignment. If we assume, however, that this state is an $E2$, then the GQR splits into components which are inconsistent with the above theoretical predictions. Many theories[1] predict the existence of the monopole resonance near $2\hbar\omega$. This, however, is the case of the spherical nuclei. Recently, the configuration space of the microscopic calculation in deformed nuclei has been enlarged to obtain reliable results for the monopole and other multipole resonances.[14] Then the monopole resonance of the breathing mode is predicted at the excitation energy slightly higher than $2\hbar\omega$, which is consistent with an $E0$ assignment for the resonance at 14.7 MeV. This resonance depletes $(93\pm8)\%$ of the isoscalar $E0$ EWSR (Table I).

In the present case, however, there is possibility

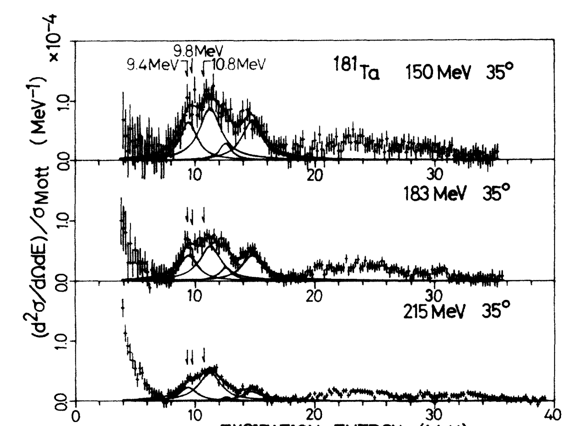

FIG. 2. After the subtraction of the GDR and underlying background the remaining cross section is displayed. The overlapping peaks were decomposed into 9.5-, 11.3-, and 12.6-MeV components and 14.7-MeV peak by a χ^2 fitting procedure. Arrows indicate the quadrupole $K=0$, 1, and 2 states at 9.4, 9.8, and 10.8 MeV, respectively, calculated from the dipole energies.

TABLE I. Line width Γ, $B(EL)$ values, and percentages of the EWSR in ^{181}Ta.

ω (MeV)	J^π	Mode	Γ (MeV)	$B(E2\uparrow)$ (e^2 fm^4)	$B(E0\uparrow)$ (fm^4)	EWSR (%)
9.5 ± 0.2	2^+	$T=0$	1.8 ± 0.6	2147 ± 334		29 ± 5
11.3 ± 0.2	2^+	$T=0$	2.2 ± 0.7	3975 ± 482		63 ± 8
12.6 ± 0.2	2^+	$T=0$	1.3 ± 0.8	634 ± 231		11 ± 5
14.7 ± 0.2	0^+	$T=0$	2.1 ± 0.3		4543 ± 371	94 ± 8
or	2^+	$T=0$		1971 ± 162		41 ± 4
18 ~ 30	2^+	$T=1$		3229 ± 194		74 ± 6

to distinguish between an $E2$ or $E0$ assignment. The quadrupole form factor in deformed nuclei involves an $E4$ term arising from the intrinsic hexadecapole deformation. Hence, the corresponding form factor for the $K=2$ state may differ significantly from the usual $E2$ or $E0$ form factor.[8,9] It seems natural to relate this fact to the observation in Fig. 2 where the peak at 14.7 MeV falls off faster than the peak at 11.3 MeV with increasing momentum transfers.

The experimental form factor of the bump above the GDR is best reproduced by the $E2$ curve of the isovector Goldhaber-Teller (GT) model, but deviates largely from that of the Steinwedel-Jensen model. Accordingly, the choice of the GT model for the isovector GDR mentioned before seems to be not unrealistic. The bump between 18 and 30 MeV exhausts a significant part of the isovector $E2$ EWSR (Table I).

It should be noticed that the resonance shape of the GQR observed in (α, α') reactions[7] differs noticeably from the present observation indicating a large tail extending to the higher excitation energy side. A possible explanation has recently come from the (α, α') reaction on heavy nuclei[15] that a new isoscalar $E0$, $E2$, or $E4$ resonance locates at ~80 MeV/$A^{1/3}$.

The observed width of $E0$ resonance (Table I) is much narrower than the GDR. Possible explanations have been given by Bertsch[16] and Ui.[17] According to their schematic calculations the spreading width due to decaying into the 2p-2h states is cancelled to be zero for isoscalar giant resonances. The escaping width due to particle emission is usually small in heavy nuclei.

In conclusion, a new resonance at 14.7 ± 0.2 MeV in ^{181}Ta is assigned to be an $E2$ or $E0$, but the latter is favorable. The GQR observed at 9.5 and 11.3 MeV are consistent with the values calculated from the splitting of the GDR. There is a possibility to distinguish between $E2$ and $E0$ in deformed nuclei.

After the preparation of this paper we have noticed the paper (Ref. 18) which covers almost the same momentum transfer and same excitation energy. Although the motivation is different, the result of this paper and that of Ref. 18 disagree as to the existence of the 14.7-MeV peak and furthermore disagree as to the magnitude (by a factor of 3) of the $E2$ peaks where there is agreement as to existence. The discrepancy of the $E2$ strength, however, is explained as being due to the difference of the transition density used in the analysis. If the analysis is performed with the same parameter obtained from the ground state density as employed here, their EWSR values for the 9.5-, 11.4-, and 23.2-MeV peaks may be modified to (20 ± 10)%, (55 ± 20)%, and (75 ± 19)%, respectively, in agreement with the present result. They analyzed the 15.3-MeV peak assuming only $E1$ and obtained a strength somewhat larger than that of the photonuclear reaction. Furthermore, the measured form factor corresponding to the 15.3-MeV peak overshoots the theoretical $E1$ curve at the angles near maximum for $L=2$ or 0, which is not inconsistent with existence of other multipolarities around this excitation energy.

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