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^{89}Y(γ,p$_0$) cross section deduced from the ^{89}Y(e,p$_0$) reaction

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Angular distribution of the ^{89}Y(e,p$_0$) reaction has been measured in the giant resonance energy region at 12 laboratory angles ranging from 30° to 140°. The obtained differential cross sections have been decomposed into $E1$ and $E2$ components using a resonance model. The $E1$ and $E2$ components of the ^{89}Y(γ,p$_0$) cross section were estimated to exhaust 2.9% and 1.7% of the $E1$ and $E2$ sums, respectively. The derived excitation functions for $E1$ and $E2$ are well explained by a direct-semidirect model. The result confirms the isovector giant quadrupole excitation in ^{89}Y.

I. INTRODUCTION

Information about giant resonances other than $E1$ is very important in the field of nuclear physics. Inelastic electron and hadron scattering experiments[1,2] have been performed to study the isoscalar and isovector giant quadrupole resonances (GQR's). Estimates of the $E2$ strength by the electrodisintegration and photodisintegration experiments have also been made for intermediate mass nuclei utilizing the difference between the $E1$ and $E2$ virtual photon and bremsstrahlung spectra.[3-5]

The angular distribution of the emitted nucleons following photonuclear reactions shows a characteristic feature of interference between $E1$ and $E2$ transitions. A number of experiments designed to study this feature have tried to estimate the $E2$ strength in the giant dipole resonance (GDR) region; however, in general it is very difficult to determine the multipolarities from the angular distributions of the emitted particles alone. In part, the reason for this is that in the existing theories[6] there are a number of parameters to be evaluated in order to ascertain the multipolarities. In addition, the experimental data have large uncertainties.

In order to determine the multipolarity of a particular excitation, it is convenient to select particles decaying to specific residual levels. Ryan *et al.*[7] and Kerkhove *et al.*[8] have measured the proton angular distributions from the ^{27}Al(γ,p$_0$) and ^{31}P(γ,p$_0$) reactions, respectively, and have deduced the $E2$ strength in the GDR region. Employing a simple resonance model,[9] the $E2$ strength distributions of the ^{63,65}Cu(e,p$_0$) reactions have also been estimated from the proton angular distribution data.[10] Van Camp *et al.*[11] have already measured σ (E_x,θ) of the ^{89}Y(γ,p$_0$) reaction in the energy region of $E_x = 13-23$ MeV, and deduced the upper and lower limits of $E2$ strength in their region. Their results indicate no prominent $E2$ structure.

The present paper presents the angular distribution of the ^{89}Y(e,p$_0$) reaction cross section in the giant resonance energy region. In particular, we extend the excitation energy up to 30 MeV and find clear evidence for the isovector giant quadrupole resonance.

II. EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

Since ^{89}Y has a closed neutron shell ($N = 50$), and one proton in the $2p_{1/2}$ subshell,[12] the angular distribution patterns of emitted protons in the (e,p$_0$) reaction are expected to be very simple for different multipole transitions.[10]

A thin foil (9.9 mg/cm^2) of natural ^{89}Y was bombarded by the electrons from the Tohoku University 300 MeV linear accelerator. The beam was momentum analyzed to within 1.5% and focused onto the target by the 90° deflection achromatic transportation system.

The bombarding electron beam current was measured using a ferrite loop current transfer system placed upstream from the target. Emitted particles were analyzed using a Browne-Buechner type of broad-range magnetic spectrometer, and detected by a ladder of 100 Si(Li) solid state detectors set along the focal plane. Output pulses from each detector were pulse-height analyzed into 128 channels using a multiplexing system, and stored by an on-line computer. By setting a thin Al foil just in front of the detectors, the pulse heights of protons were separated from those of other particles. The experimental arrangement has been described elsewhere in detail.[13]

The experiments were carried out at incident electron energies from 13 to 31 MeV in 1 MeV steps. The differential cross sections for the (γ,p$_0$) reaction were measured at 12 angles relative to the incident electron beam, from 30° to 140° in steps of 10°. Since the first excited state in the residual nucleus ^{88}Sr is at 1.84 MeV, we have integrated the measured proton yield from the end-point energy down to 1.84 MeV to obtain the pure p$_0$ differential cross section. The energy loss of protons in the target was about 130 keV for $E_p = 10$ MeV, which is small enough for the present study.

In order to analyze the spectra, the data measured in the laboratory system were transformed to the center of mass system;[4] these results are shown in Fig. 1. The error bars represent the statistical uncertainties only. Each distribution of Fig. 1 is characterized by a broad peak near 90°. If only $E1$ excitation was present, the peak should appear at $\theta_{\text{c.m.}} = 90°$ and should be symmetric. A large asymmetry about 90° suggests the presence of other multipole transitions. $E2$ excitation is the most likely candidate in the present energy region (the $M1$ strength is expected to be located in the lower energy region[11]).

The measured angular distributions were least squares fitted with a Legendre polynomial series of the form

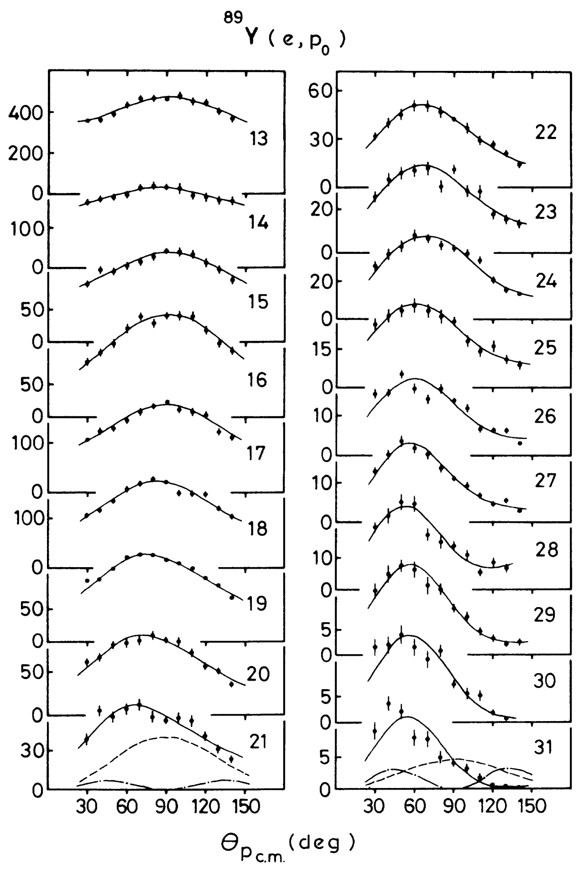

FIG. 1. The measured angular distributions of emitted protons, obtained from the ^{89}Y(e,p$_0$) reaction. The solid curves are the best fits to the data obtained from Eq. (2). $|C_2|^2\sin^2\theta$ and $|C_3|^2\sin^2\theta\cos^2\theta$ are shown separately by the dashed and dot-dashed curves, respectively, for the two cases of $E_e = 21$ and 31 MeV.

$$\frac{d\sigma}{d\Omega_p} = A_0\left[1 + \sum_{l=0}^{4} a_l P_l(\cos\theta_p)\right], \tag{1}$$

where $a_l = A_l/A_0$. In the above equation, A_0 is integrated over angle cross section, and the coefficient a_2 arises from $E1$ and $E2$ strengths, a_4 from $E2$ strength, and a_1 and a_3 from $E1$-$E2$ interference. The measured values of the a_l coefficients are listed in Table I, and shown in Fig. 2. However, from these values alone, it is insufficient to determine the multipolarities, as mentioned in the Introduction.[6]

Assuming that only $E1$ and $E2$ transitions occur, and neglecting the spin of the emitted protons, the differential cross section for the reaction is given by the simple classical expression[9]

$$\frac{d\sigma}{d\Omega_p} = |C_1|^2 + \sin^2\theta_{\text{c.m.}}\,|C_2 + C_3\cos\theta_{\text{c.m.}}|^2, \tag{2}$$

where $|C_2|^2$ and $|C_3|^2$ correspond to the $E1$ and $E2$ transition strengths, respectively. The magnitude of $|C_1|^2$ represents the evaporation cross section, independent of multipolarities.

Using Eq. (2), a fit to the angular distribution data resulted in a value of χ^2 of 0.4–6.3 (normalized χ^2, weighted by the inverse square of the errors).

The best fitted curves are shown in Fig. 1 by the solid curves. The angular distribution patterns for $E1$ and $E2$ transitions are also shown in Fig. 1 for the two cases.

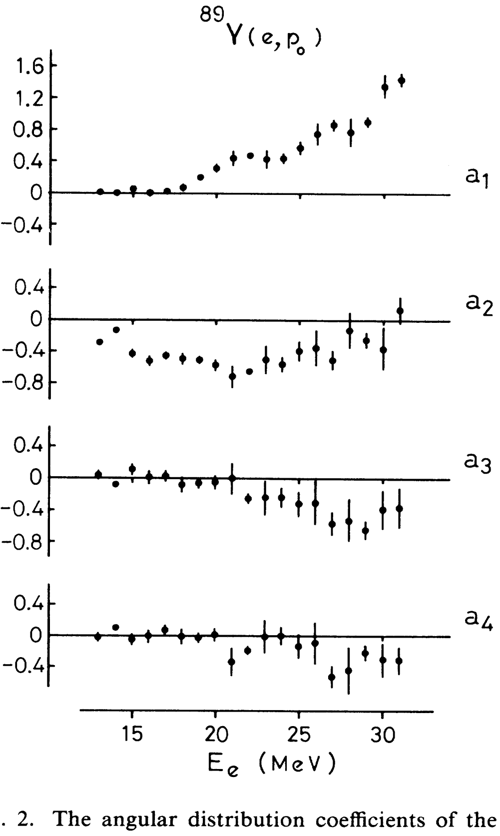

FIG. 2. The angular distribution coefficients of the Legendre decomposition as a function of electron energy.

TABLE I. The Legendre coefficients for the decomposition of the angular distributions from the ^{89}Y(e,p$_0$) reaction.

E_e (MeV)	A_0 (nb/sr)	a_1	a_2	a_3	a_4
13.0	410.57±6.77	0.02±0.03	−0.28±0.04	0.05±0.06	−0.02±0.06
14.0	180.77±1.59	0.01±0.02	−0.12±0.02	−0.08±0.03	−0.11±0.03
15.0	113.76±2.58	0.05±0.04	−0.42±0.06	0.12±0.08	−0.04±0.08
16.0	122.18±3.14	0.00±0.04	−0.52±0.07	0.01±0.09	−0.00±0.09
17.0	142.17±2.93	0.03±0.04	−0.45±0.05	0.04±0.07	0.08±0.07
18.0	136.29±3.99	0.07±0.05	−0.48±0.08	−0.08±0.10	0.00±0.10
19.0	103.46±2.08	0.20±0.04	−0.50±0.05	−0.05±0.07	−0.02±0.07
20.0	68.76±1.75	0.31±0.04	−0.57±0.07	−0.05±0.09	0.02±0.08
21.0	45.21±2.57	0.44±0.10	−0.71±0.15	0.01±0.20	−0.32±0.19
22.0	33.83±0.60	0.48±0.03	−0.64±0.04	−0.25±0.06	−0.18±0.06
23.0	27.09±1.84	0.43±0.12	−0.48±0.19	−0.23±0.23	0.01±0.22
24.0	29.51±1.08	0.45±0.07	−0.55±0.10	−0.23±0.13	0.01±0.12
25.0	20.67±0.96	0.58±0.08	−0.38±0.13	−0.31±0.16	−0.11±0.15
26.0	15.40±1.28	0.76±0.15	−0.35±0.23	−0.29±0.29	−0.08±0.27
27.0	13.97±0.61	0.87±0.08	−0.50±0.12	−0.55±0.15	−0.50±0.14
28.0	13.59±1.18	0.78±0.18	−0.11±0.23	−0.52±0.27	−0.42±0.30
29.0	9.18±0.32	0.91±0.06	−0.24±0.10	−0.64±0.12	−0.20±0.11
30.0	7.81±0.61	1.37±0.15	−0.35±0.27	−0.37±0.25	−0.29±0.22
31.0	5.03±0.28	1.45±0.09	0.15±0.07	−0.36±0.25	−0.30±0.17

III. RESULTS AND DISCUSSION

The $E1$ and $E2$ cross sections of the ^{89}Y(γ,p$_0$) reaction have been obtained by integrating the best-fit theoretical curves shown in Fig. 1 over angle, and dividing them by the $E1$ and $E2$ virtual photon spectra obtained from the distorted wave Born approximation.[14] These are shown in Fig. 3(a) as functions of the excitation energy E_x ($=E_e-1.05$ MeV). The value of E_x is the centroid of the integrated energy region of the virtual photon spectra. The error bars are the quadratic sum of the fitting and statistical uncertainties. The $E1$ component of the (γ,p$_0$) cross section obtained by Van Camp *et al.*[11] is shown in Fig. 3(b) for comparison. Agreement between them is complete within the experimental errors, over the common energy range; we have extended the measurement up to $E_x=30$ MeV.

The $E1$ excitation function peaks at 16.8 MeV, i.e., the energy at which the $T_<$ GDR is found in (γ,n) experiments.[15,16] We have integrated the deduced $\sigma_{E1}(\gamma,\mathrm{p}_0)$ over the present experimental energy range, and obtain a value of 38.64±0.56 MeV mb, which is 2.9% of the classical $E1$ sum of $60NZ/A$.

The peak observed at about 27 MeV in the $E2$ cross section corresponds to the isovector GQR, which has already been observed in an (e,e′) experiment, but with a fairly large uncertainty.[17] By integrating the deduced $\sigma_{E2}(\gamma,\mathrm{p}_0)/E^2$ over the present experimental energy range, a value $\sigma_{-2}(E2)=1.71\pm0.30$ μb/MeV is obtained, which is 1.7% of the $E2$ sum of $0.255(A/4)\langle r^2\rangle$.[18]

Although several studies by electron and hadron scattering[17,19] have been done which indicate that the isoscalar GQR in ^{89}Y is at $E_x=14$ MeV, no evidence of this is found in the present (e,p$_0$) reaction experiment. It seems that the isoscalar GQR must decay almost ex-

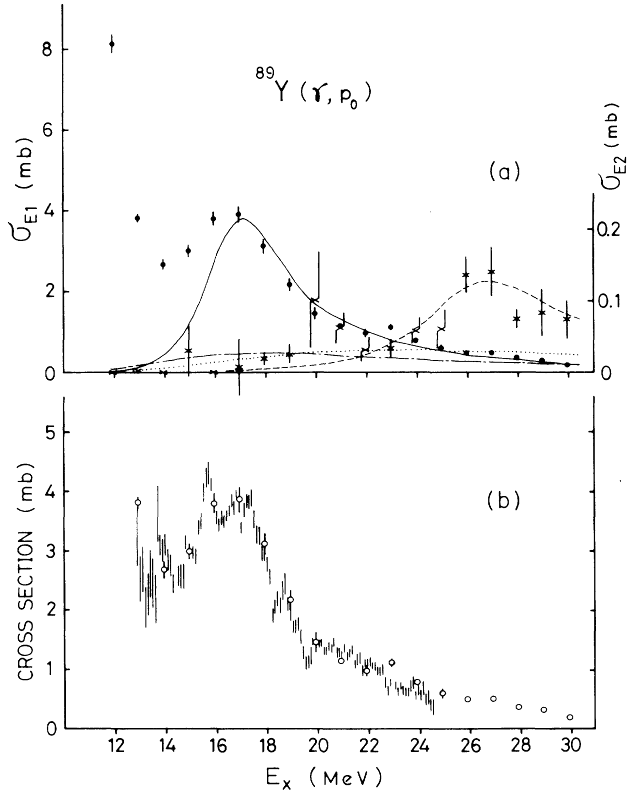

FIG. 3. Cross sections of the ^{89}Y(γ,p$_0$) reaction. (a) Extracted $E1$ (closed circles) and $E2$ (crosses) strengths of the (γ,p$_0$) cross sections. The solid and dashed curves show the results predicted by the DSD model, and the dot-dashed and dotted curves show the results from the direct model for $E1$ and $E2$ strengths, respectively. (b) Comparison of the present results for $E1$ strength (open circles) with those obtained by Van Camp *et al.* (Ref. 11) (vertical bars).

clusively to excited states.

In order to explain the observed $E1$ and $E2$ cross sections we have used the direct and the direct-semidirect (DSD) models.[20] The numerical results are shown for $E1$ and $E2$ components in Fig. 3(a) by the solid and dashed curves (the DSD model), and by the dot-dashed and dotted curves (the direct model). The best fit values for the parameters V_1 (strengths of the symmetry part of the optical potential), E_R (resonance energy), and Γ (resonance width)[20] are, respectively, 155, 16.5, and 4.1 MeV for $E1$, and 190, 26.0, and 7.0 MeV for $E2$ components. The last two parameters correspond to the resonance energy and width of the isovector GQR in ^{89}Y.

Although the simple direct-proton-knockout model cannot explain the $E1$ component of the cross section in this energy region, the DSD model successfully reproduces the high-energy part of the cross section. The remaining part in the low-energy side is attributed to more complex excitations than those considered in the DSD model; a compound process may explain this part.[21]

On the other hand, the $E2$ component can almost be explained by the simple direct-proton-knockout model except for the isovector $E2$ resonance energy region. The DSD model successfully reproduces the cross section in this energy region and confirms the excitation of the isovector giant quadrupole resonance.

IV. CONCLUSION

The $E1$ and $E2$ components of the ^{89}Y(γ,p$_0$) cross section have been deduced from the measured (e,p$_0$) angular distributions by applying a simple resonance model. The data confirm isovector giant quadrupole excitation in ^{89}Y. To obtain the absolute scales of the deduced cross sections, we have integrated the decomposed multipole cross sections and compared them with theoretical sum rule predictions. From the results it is concluded that the ^{89}Y(γ,p$_0$) process in the GDR region is much simpler than the compound process, and can reasonably be interpreted by the DSD model.

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