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[1]B. Borderie *et al.*, Z. Phys. A 299, 263 (1981).

[2]B. B. Back *et al.*, Phys. Rev. Lett. 46, 1068 (1981).

[3]W. J. Swiatecki, Phys. Scr. 24, 113 (1981).

[4]C. Gregiore *et al.*, Nucl. Phys. A 387, 37C (1982).

[5]W. Nörenberg, Z. Phys. 290, 335 (1979).

[6]S. Bjørnholm and W. J. Swiatecki, Lawrence Berkeley Laboratory Report No. LBL-14074, 1982 (to be published).

[7]S. Cohen, F. Plasil, and W. J. Swiatecki, Ann. Phys. (N.Y.) 82, 557 (1975).

[8]A. Bohr, in *Proceedings of the United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Vol. 2, p. 151.

[9]I. Halpern and V. M. Strutinski, in *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy* (United Nations, Geneva, 1958), p. 408.

[10]F. Videbaek *et al.*, Phys. Rev. C 15, 954 (1977).

[11]S. A. Karamyan *et al.*, Yad. Fiz. 6, 494 (1967) [Sov. J. Nucl. Phys. 6, 360 (1968)].

[12]R. F. Reising *et al.*, Phys. Rev. 141, 1161 (1966).

[13]V. E. Viola, Jr., Phys. Rev. 129, 2710 (1963).

[14]R. Bock *et al.*, Nucl. Phys. A388, 334 (1982).

[15]Yu. Ts. Oganessian *et al.*, Nucl. Phys. A239, 353 (1975).

[16]G. Münzenberg *et al.*, Z. Phys. A 302, 7 (1981).

[17]G. Münzenberg *et al.*, Z. Phys. A 300, 107 (1981).

[18]G. Münzenberg *et al.*, to be published.

[19]C. Y. Wong, Phys. Rev. Lett. 31, 766 (1973).

[20]H. Esbensen, Nucl. Phys. A352, 147 (1981).

Identification of $E2$ Strength Distribution in ^{65}Cu by the (e,p_0) Reaction

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Double-differential cross sections for the reaction ^{65}Cu$(e,p_0)^{64}$Ni$_{\mathrm{g.s.}}$ were measured at eleven laboratory angles ranging from 42° to 138° with incident electron energies from 13 to 28 MeV. These have been decomposed into $E1$ and $E2$ components by use of a resonance model. Besides the large $E1$ cross section, the $E2$ strength is clearly separated at $E_x = 14.9$ MeV with the width of 5.1 MeV corresponding to the isoscalar giant quadrupole resonance.

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Giant multipole resonances (GMR) other than $E1$ have been studied by various projectiles. Up to now most of the experiments have been carried out only for inclusive reactions. With such reactions, it is difficult to determine in a model-independent way the multipolarities of the GMR. Successful completion of $(e,e'p)$ experiments concerning the determination of the multipolarities of the GMR is expected.[1] Yet at this stage no results have been reported. Concerning exclusive reactions, several authors have already reported on the angular distributions of the emitted particles through electrodisintegration. The ^{16}O(e,p_0) angular distribution has been measured by Schoch *et al.*,[2] which showed that the contributions due to the spin current are important in the angular distribution analysis. Their interest, however, concerns excitation energy region much higher than that of the GMR. Skopik, Asai, and Murphy[3] have measured ^{56}Fe(e,α) angular distribution in the GMR region, and have found the isoscalar giant quadrupole resonance (GQR) to lie at 17.6 MeV with a width of 3.1 MeV, and with the α-decay channel exhausting a sizable percentage of the isoscalar $E2$ energy weighted sum rule (EWSR). Phillips and Johnson[4] have measured $\sigma(E_x, \theta)$ of the $^{16}O(\gamma, n_0)$ reactions in the energy region of $E_x = 25-45$ MeV, and deduced $E2$ strength which exhausts 68% of the isoscalar $E2$ EWSR. Arruda *et al.*[5] measured $\sigma(e,f)$ for ^{234}U and ^{236}U, and deduced $\sigma_{E2}(\gamma,f)$ in the GQR region which exhaust 70% and 87% of the isoscalar $E2$ EWSR, respectively.

As far as we know, no attempts have yet been made to determine definitely the $E2$ strength in the GMR region by measuring the angular distribution of the emitted protons from the (e, p_0) reaction. This reaction seems to be very promising for the study of the GMR for several reasons. (1) It is very easily compared to the $(e,e'p)$ reaction and results are available now. (2) Only simple nuclear excitations are expected, and the background is very small compared to hadron-scattering experiments. (3) The complementary data from the (e, e') reaction can be obtained. (4) Definite decomposition of the multipole components may be possible with less model dependence than in the case of (e, e'). In this Letter we report on the results of measurements of $^{65}Cu(e, p_0)$, followed by a discussion.

The $^{65}Cu(e, p_0)$ cross section is expected to be dominated by the simple $2p_{3/2}$ proton knockout reaction,[6] and the angular distribution patterns are expected to be very simple for each multipole transition.[7] A thin foil (9.6 mg/cm^2) of more than 98% enriched ^{65}Cu was bombarded by electrons from the Tohoku University electron linear accelerator. The experiments were carried out at incident electron energies from 13 to 28 MeV in 1-MeV steps. The details of the experimental apparatus and detection method were previously reported.[8] The differential cross sections for the p_0 were measured at eleven angles relative to the incident electron beam from 42° to 138° in steps of about 10°. Since the first excited state in the daughter nucleus ^{64}Ni is at 1.34 MeV, we have integrated the yield from the end-point energy down to this energy of the emitted proton to obtain the pure p_0 differential cross section. The energy loss of the proton in the target is about 140 keV for $E_p = 10$ MeV.

The experimental results are shown in Fig. 1. The error bars represent the statistical uncertainties only. Every distribution is characterized

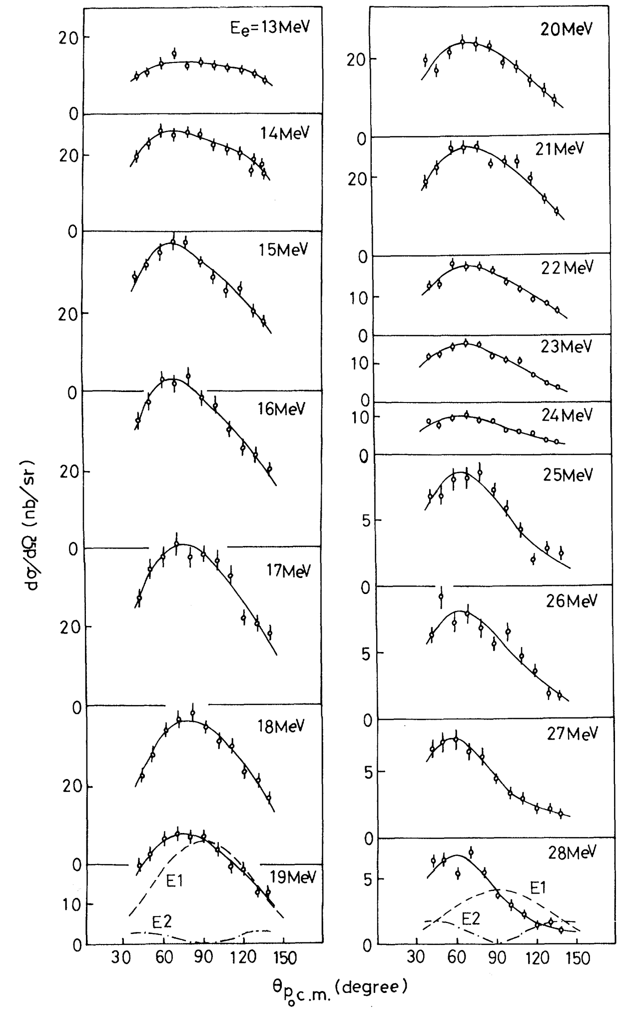

FIG. 1. Measured proton angular distributions of the reaction. The solid lines are the results of least-squares fitting to the experimental data with the resonance model of Ref. 7. $E1$ and $E2$ components are separately shown for the two cases of $E_e = 19$ and 28 MeV.

by a broad peak around 90°. If only $E1$ excitation takes place, the peak should appear at $\theta_{c.m.} = 90°$ and should have symmetrical shape. A large asymmetry with respect to 90° suggests the existence of other multipole transitions, mainly $E2$ transitions in the present energy region.

Expressions for the angular distribution of emitted particles in the (e, x) reaction have been given by several authors.[7,9] We have applied the simple resonance model of Ref. 7 to analyze the present data. We take the resonance velocity potential as the Tassie type, and the initial state of the emitted proton to be the pure $2p$ state with the harmonic-oscillator length parameter b as 2 fm.

With the assumption of only the pure $E1$ transition, fits to the angular distribution data resulted in very large values of χ^2. By taking both the $E1$ and $E2$ transitions into account, the values of χ^2 reduce to 0.5–2.0 (normalized χ^2, weighted by the inverse square of the errors). Considering the small number of counts and the limited angular range in the present experiment, these fits are judged to be satisfactory. In other words, the inclusion of the $E2$ transition is very important in the analysis of the presently measured cross sections of the reaction $^{65}Cu(e,p_0)$, and the inclusion of higher processes such as $E3$ transitions is not justified. In fact, if we include the $E3$ transition in the calculation, the values of the multipole strength parameters cannot be determined unambiguously. The best-fit curves are shown in Fig. 1 by the solid lines. Note that for the p-state proton knockout process, the angular distribution patterns for $E1$ and $E2$ transitions are expressed roughly as $\sin^2\theta$ and $\sin^2\theta \cos^2\theta$, respectively, which are also illustrated in Fig. 1 for two cases. These angular dependences are almost totally determined kinematically, and do not depend much on the shapes of the velocity potential and the wave functions.

In Fig. 2 we have rearranged the same data shown in Fig. 1 as functions of the incident electron energy. The broken lines connect the best-fit values obtained above for each energy and angle. Since the $E2$ strength is expected to be very weak at 90°, the excitation function at 90° represents the energy dependence of the $E1$ strength. From eleven excitation functions in Fig. 2, it is clear that besides the large $E1$ peak at $E_e \cong 17$ MeV, we have another peak at $E_e \cong 16$ MeV, whose angular dependence is of the $E2$ type.

The cross sections are converted to the $\sigma_L(\gamma, p_0)$ for $E1$ and $E2$. They have been obtained by integrating the best-fit theoretical curves shown in Fig. 1, over $d\Omega$, and dividing them by the $E1$ and $E2$ virtual photon numbers, and are shown in Fig. 3 as functions of the excitation energy E_x ($=E_e - 0.9$ MeV, which is the average of the integrated energy region). The error bars indicated are the quadrutic sum of fitting (67% confidence level) and statistical uncertainties. To these cross sections are least-squares fitted the Lorentzian line shapes of the form

$$\sigma_L = \frac{(E_x\Gamma)^2}{(E_x^2 - E_R^2)^2 + (E_R\Gamma)^2}\sigma_0. \quad (1)$$

The $E1$ cross section is fitted by one resonance shape peak at $E_R = 16.9$ MeV and $\Gamma = 7.3$ MeV with $\chi^2 = 3.1$, corresponding to the giant dipole resonance (GDR). Both Flutz *et al.*[10] and Sund *et al.*[11] have reported a deformation-split GDR in ^{65}Cu. The presently measured $E1$ strength can also be fitted by the sum of two Lorentzian curves: $E_R = 15.5$ and 19.4 MeV with $\Gamma = 4.6$ and 7.0 MeV, respectively ($\chi^2 = 2.9$). These values are consistent with the results of Fultz *et al.* and Sund *et al.* Another parameter set, $E_R = 16.7$ and 20.4 MeV with $\Gamma = 7.1$ and 0.85 MeV, respectively, explains the data equally well ($\chi^2 = 3.0$), which may be explained by the isospin splitting of the GDR.[12] Within the accuracy of the present experiment, it is very difficult to settle the detailed structure in the GDR. The $E2$ cross section is fitted by two resonances. The one at $E_R = 14.9$ MeV with Γ

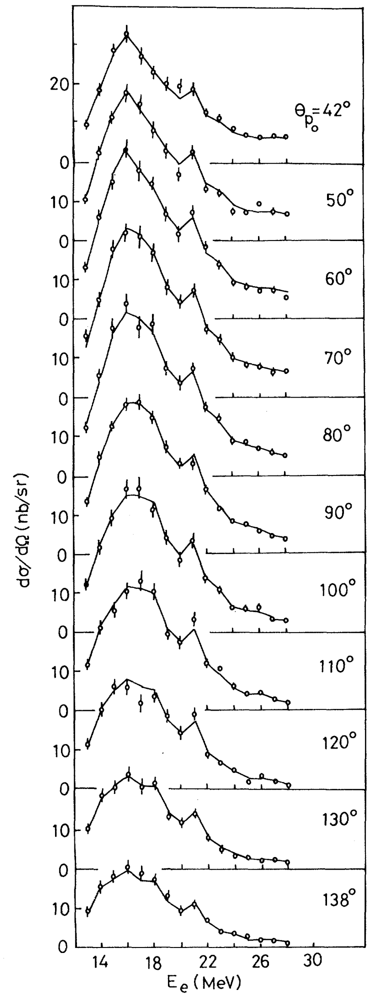

FIG. 2. The same data and the calculated results as in Fig. 1 rearranged as functions of the incident electron energy for eleven laboratory angles.

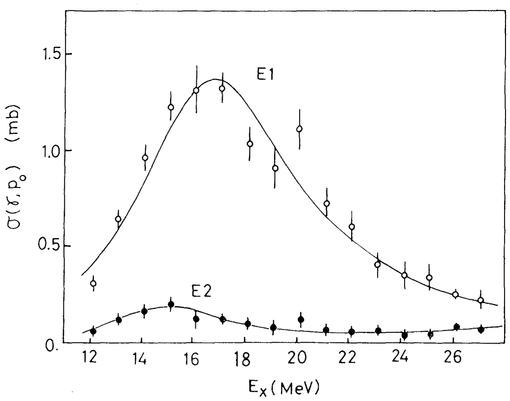

FIG. 3. Extracted $E1$ (open circles) and $E2$ (closed circles) strengths. Solid lines are the least-squares fitted curves with the Lorentzian line shapes.

=5.1 MeV corresponds to the isoscalar GQR, expected at $E_x = 60/A^{1/3}$ MeV = 15 MeV. The other at E_R = 29.2 MeV with Γ = 12.1 MeV may correspond to the isovector GQR, expected at $E_x = 130/A^{1/3}$ MeV = 33 MeV, whose peak, however, is beyond the limit of the present experiment. The χ^2 value for $E2$ is 0.75. The best-fit curves are shown in Fig. 3 by the solid lines. Note that the $E1$ and $E2$ strengths seen in this (e,p_0) channel need not be representative of the whole, since they do not result from a predominantly statistical decay process.

To see what fractions of $E1$ sum and $E2$ isoscalar sum are exhausted, we have integrated the obtained $\sigma_L(\gamma,p_0)$ from E_x = 12.1 to 27.1 MeV and found $\sigma(E1)$ = 10.7 mb·MeV = 1.1% of $60NZ/A$, and $\sigma_{-2}(E2)$ = 6.9 μb/MeV = 14.7% of $0.22Z^2A^{-1/3}$.

Recently Dodge *et al.*[13] have measured the (e,p) and (e,α) cross sections for ^{56}Fe, ^{59}Co, and ^{64}Zn in the electron energy range from 16 to 100 MeV. They have analyzed their data using distorted-wave Born-approximation $E1$ and $E2$ virtual photon spectra. The $E2$ strength has been deduced only in the excitation energy region of the isoscalar GQR. No other $E2$ strength was found. Similar to their results, we have also found the location of the $E2$ peak for the isoscalar GQR. However, the present results show the $E2$ strength even up to the excitation energy of 27 MeV. Theoretically, a similar amount of the $E2$ strength should be found for the isovector part. This problem is yet to be solved.

To conclude, our measurements here have shown that the (e,p_0) angular distributions give us additional information to supplement the existing experimental data concerning the isoscalar GQR. We have also measured and analyzed the (e,p_0) reaction cross sections for ^{63}Cu, ^{54}Fe, and ^{45}Sc. The angular distribution patterns for ^{63}Cu are similar to the present results, and those for ^{54}Fe and ^{45}Sc show shapes characteristic of the f-shell nuclei. Therefore we may say that the angular distribution patterns for the GMR are almost determined by the angular momentum of the initial proton. These data will be published soon.

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[1] Y. Kawazoe and T. Tsukamoto, in *Proceedings of the Conference on Electron and Photoexcitation, Sendai, Japan, 1977,* edited by Y. Kawazoe (Laboratory of Nuclear Science, Tohoku University, Sendai, Japan, 1977), p. 145.

[2] B. Schoch, H. Görniger, P. Jennewein, F. Klein, G. Lührs, and F. Zettl, Phys. Rev. C 22, 2360 (1980).

[3] D. M. Skopik, J. Asai, and J. J. Murphy, II, Phys. Rev. C 21, 1726 (1980).

[4] T. W. Phillips and R. G. Johnson, Phys. Rev. C 20, 1689 (1979).

[5] J. D. T. Arruda-Neto, S. B. Herdade, B. L. Berman, and I. C. Nascimento, Phys. Rev. C 22, 1996 (1980), and 23, 2595 (1981).

[6] C.-O. Wene, Z. Phys. A 272, 77 (1975).

[7] H. Taneichi, H. Ueno, K. Shoda, Y. Kawazoe, and T. Tsukamoto, Nucl. Phys. A350, 157 (1980).

[8] K. Shoda, M. Sugawara, T. Saito, and H. Miyase, Nucl. Phys. A221, 125 (1974).

[9] B. F. Gibson and H. T. Williams, Nucl. Phys. A163, 193 (1971); J. M. Eisenberg, Phys. Rev. 132, 2243 (1963).

[10] S. C. Fultz, R. L. Bramblett, J. T. Caldwell, and R. R. Harvey, Phys. Rev. 133, B1149 (1964).

[11] R. E. Sund, M. P. Baker, L. A. Kull, and R. B. Walton, Phys. Rev. 176, 1366 (1968).

[12] H. Tsubota, S. Oikawa, J. Uegaki, and T. Tamae, Nucl. Phys. A321, 157 (1979).

[13] W. R. Dodge, R. G. Leicht, E. Hayward, and E. Wolynec, Phys. Rev. C 24, 1952 (1981).