1968 (unpublished).

[11] C. D. Bowman, G. S. Sidhu, and B. L. Berman, Phys. Rev. 163, 951 (1967); B. L. Berman, G. S. Sidhu, and C. D. Bowman, Phys. Rev. Letters 17, 761 (1966).

[12] R. L. Van Hemert, C. D. Bowman, and B. L. Berman, University of California Radiation Laboratory Report No. UCRL-70939 (to be published); R. L. Van Hemert, thesis, University of California Radiation Laboratory Report No. UCRL-50501, 1968 (unpublished).

[13] W. Bertozzi, C. P. Sargent, and W. Turchinetz, Phys. Letters 6, 108 (1963).

[14] J. A. Biggerstaff, J. R. Bird, J. H. Gibbons, and W. M. Good, Phys. Rev. 154, 1136 (1966).

[15] R. R. Harvey, J. T. Caldwell, R. L. Bramblett, and S. C. Fultz, Phys. Rev. 126, B136 (1964).

PHOTOPROTON REACTIONS THROUGH ISOBARIC ANALOG STATES IN ^{88}Sr AND ^{90}Zr

K. Shoda, M. Sugawara, T. Saito, and H. Miyase
Laboratory of Nuclear Science, Faculty of Science, Tohoku University, Tomizawa, Sendai, Japan

(Received 7 July 1969)

We have measured the photoproton cross sections of ^{88}Sr and ^{90}Zr for production of ground and low-energy residual states. The results are in agreement with predictions of the particle-hole model for isobaric analog states. Strong and broad resonances are found around 21 MeV in ^{88}Sr and around 20 and 22 MeV in ^{90}Zr which agree with coherent states expected by the theory.

Isobaric analog states (hereafter referred to as IAS) have already been found in (γ, p) and (p, γ) reactions.[1-4] These electric dipole states are useful for studying the particle-hole nature of IAS. Goulard, Hughes, and Fallieros[5] and Hughes and Fallieros[6] applied the particle-hole model to the dipole states in heavy nuclei. Their calculation includes not only one-particle, one-hole configurations but also two-particle, two-hole excitations so that the states obtained have good quantum numbers. They made numerical calculations[5,6] for the nuclei ^{88}Sr and ^{90}Zr and obtained many $E1$ IAS including coherent states. In the following an experiment using these targets is described; the results are compared with the predictions of Refs. 5 and 6.

Self-supporting metal foils of natural Sr (7.6 mg/cm^2 thick) and ^{90}Zr (97.8% enriched, 5.1 mg/cm^2 thick) were bombarded by the electron beam from the Tohoku University linear accelerator. The energy distributions of photoprotons from the $(e, e'p)$ reaction were measured by means of a broad-range magnetic spectrometer which contained 50 solid-state detectors. Electron energies of 16.8, 18.0, 19.5, 21.5, and 30.0 MeV were used for the ^{88}Sr and energies varying in 1-MeV steps from 16.0 to 24.0 MeV for the ^{90}Zr. The energy resolutions of the spectra of protons were about ±120 keV for ^{88}Sr and ±85 keV for ^{90}Zr at 8 MeV of proton energy.

The (γ, p_0) cross sections can be made from the components obtained from the maximum-energy part of the spectra by dividing by the number of virtual photons[7] under the assumption that only p_0 emission (to the ground state) contributes. Contributions of photoprotons which leave the residual nucleus in excited states are not strong in these maximum-energy parts of the proton spectra, therefore the above assumption seems to be reasonable. The validity of this assumption is shown by the following two facts. First, the maximum proton energy in every spectrum just agrees with that calculated for p_0 from the Q value. Second, each component cross section mentioned above joins smoothly with its neighbors. This condition would not be met if protons leaving the residual nuclei in excited states contribute very much. In the region above 21 MeV for ^{88}Sr, the cross section is estimated from the data from the 30-MeV irradiation after subtraction of a smooth proton spectrum corresponding to population of excited states of the residual nucleus. The cross section below 15 MeV on ^{90}Zr is obtained only from the 16-MeV data under the assumption of pure p_0 emission. In the case of ^{90}Zr, $\sigma(\gamma, p_2+p_3)$ is also calculated by a method analogous to that for $\sigma(\gamma, p_0)$ after subtraction of the p_0 component.

The results are shown in Figs. 1 and 2. In each figure, the theoretical results on IAS are shown for the particle-hole model.[5,6] The length of the vertical lines is proportional to Γ_γ, and the curve is an averaging of the radiative strength with Breit-Wigner functions and with a spreading width of 0.5 MeV as shown in the original paper.[6]

The position of the strong IAS in the present result seems to agree with the calculated results within several hundred keV which seems not

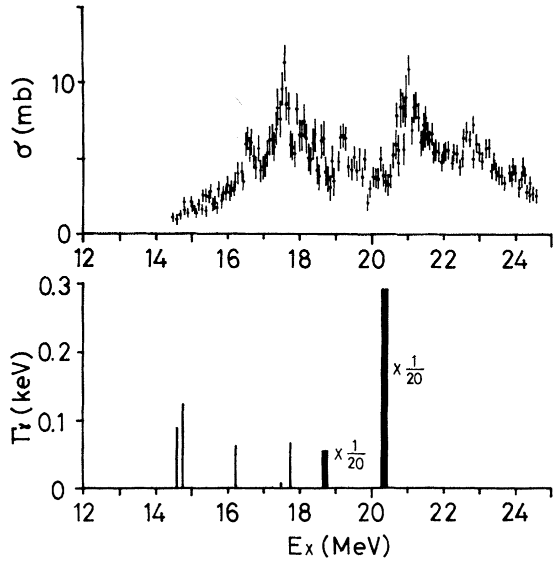

FIG. 1. Cross section of ^{88}Sr(γ,p_0). The vertical lines show the theoretical radiative widths of IAS from Ref. 5.

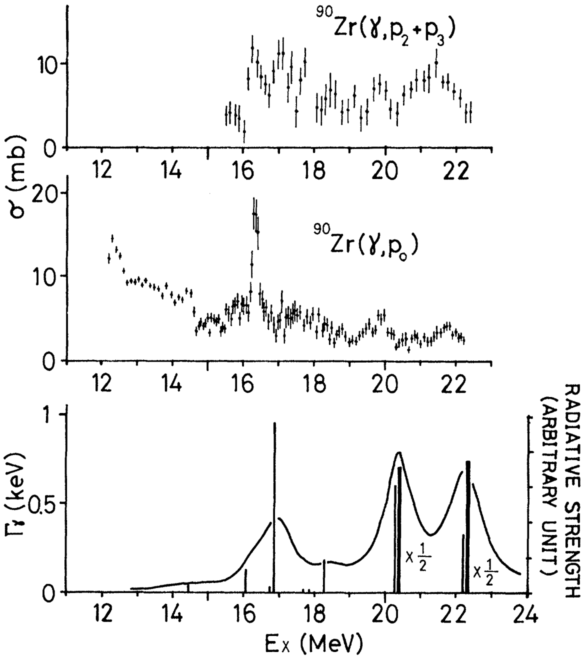

FIG. 2. (γ,p_0) and (γ,p_2+p_3) cross sections of ^{90}Zr. The vertical lines show the theoretical radiative widths of the IAS from Ref. 6. The smooth curve is an averaging of them (see Ref. 6).

large in comparison with the uncertainty of the calculated energy caused by ambiguities of the theoretical parameters. Better agreement can be obtained when the calculated lines are shifted about 0.5 MeV higher for ^{88}Sr and 0.5 MeV lower for ^{90}Zr. A quantitative comparison of the radiative width is difficult because the branching ratio for proton emission is not known. A group around 13 MeV in ^{90}Zr does not correspond energetically to IAS and it is not contained in the calculated result.

The theoretical calculations predict the existence of coherent IAS corresponding to an isospin splitting of the giant resonance.[5,6] In the present result, the strong and broad groups around 21 MeV in ^{88}Sr and around 20 and 22 MeV in ^{90}Zr are in good agreement with the position calculated theoretically. The cross sections for these groups in the present results do not seem so large as the theoretical expectation. However, from the analysis of the energy distributions, the proton yields through these IAS leaving the residual nucleus in excited states seem to be about 10-20 times as large as that of p_0 in ^{90}Zr. (The radiative width calculated from a preliminary yield curve is also obtained as several keV.)

The comparison reported here shows that the particle-hole model points to an electric dipole IAS in heavy nuclei.

The authors are very grateful to Professor Y. Kojima and his crew for the beam operation.

---

[1] J. L. Black and N. W. Tanner, Phys. Letters 11, 135 (1964).

[2] S. M. Shafroth and G. F. Legge, Nucl. Phys. A107, 181 (1968).

[3] P. Axel, D. M. Drake, S. Whetstone, and S. S. Hanna, Phys. Rev. Letters 19, 1348 (1967).

[4] K. Shoda, M. Sugawara, T. Saito, and H. Miyase, Phys. Letters 28B, 30 (1968).

[5] B. Goulard, T. A. Hughes, and S. Fallieros, Phys. Rev. 176, 1345 (1968).

[6] T. A. Hughes and S. Fallieros, private communication.

[7] W. R. Dodge and W. C. Barber, Phys. Rev. 127, 1746 (1962).