(γ,p) Reaction on Light Nuclei in the $\Delta(1232)$ Resonance Region

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Momentum spectra of protons from the (γ,p) reaction have been measured at $\theta_p = 30°$ for ^{1}H, ^{2}H, ^{4}He, ^{9}Be, ^{12}C, and ^{16}O with a tagged photon beam with energies from 187 to 427 MeV. By analysis of these inclusive proton spectra, cross sections for the pion photoproduction from the quasifree nucleon in the target nucleus and those for the photodisintegration of the quasifree two-nucleon system have been obtained as a function of the photon energy and of the target mass number.

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Momentum spectra of protons from the (γ,p) reaction have long been studied to get information on the nuclear structure and on the photonuclear reaction mechanism.[1] In the $\Delta(1232)$ resonance region, however, precise spectra with fine energy resolution were measured only recently by use of a tagged photon beam.[2-5] From these studies, two main mechanisms of the (γ,p) reaction for light nuclei have been established: pion photoproduction from the quasifree nucleon "N,"

$$\gamma + \text{“}N\text{”} \rightarrow p + \pi, \quad (1)$$

and photodisintegration of the quasifree two-nucleon system "pN,"

$$\gamma + \text{“}pN\text{”} \rightarrow p + N, \quad (2)$$

in the nucleus. At the proton forward angles, two peaks corresponding to the above two quasifree reactions are clearly observed in the proton momentum spectrum.

The purpose of the present experiment is to obtain the photon energy and mass-number dependences of cross sections for the above quasifree reactions on light nuclei in the $\Delta(1232)$ resonance region. Elementary reactions,

$$\gamma + p \rightarrow p + \pi^0 \quad (3)$$

and

$$\gamma + d \rightarrow p + n, \quad (4)$$

are also measured with a hydrogen target in water and with a liquid-deuterium target, respectively. Direct comparison between elementary reactions and quasifree reactions can provide important information on the mechanism of the photon-nucleon interaction in the nucleus.

The experiment was done with the 1.3-GeV electron synchrotron at the Institute for Nuclear Study (INS), University of Tokyo. A tagged photon beam with an energy bin of 10 MeV was used at the intensity of typically 2×10^5 photons/s over the photon energy range from 187 to 427 MeV. Momenta of protons emitted at $\theta_p = 30° \pm 4°$ were analyzed with a magnetic spectrometer having a solid angle of 34 msr. The spectrometer detected protons with momenta greater than 300 MeV/c with the momentum resolution of 4.5% at 600 MeV/c. Proton identification in the spectrometer was made by the time-of-flight measurement. Since reactions (1) and (2) were clearly separated kinematically by the position of the peak in the proton momentum spectrum, pions and neutrons in the final state were not detected in the present experiment.

Targets used in the present experiment were liquid deuterium (^{2}H, 2.18 g/cm^2), liquid helium (^{4}He, 1.38 g/cm^2), beryllium (^{9}Be, 2.12 g/cm^2), carbon (^{12}C, 2.10 g/cm^2), and water (^{1}H and ^{16}O, 2.42 g/cm^2).

Momentum spectra of protons were analyzed in the photon energy bin of 20 MeV. Typical examples at the photon energy of 357 ± 10 MeV are shown in Fig. 1. In the deuterium target data, two separate peaks are observed at the position corresponding to the kinematics for the elementary reactions (3) and (4). Hereafter, the lower momentum peak is called the first peak and the higher momentum peak is called the second peak. Similar peaks

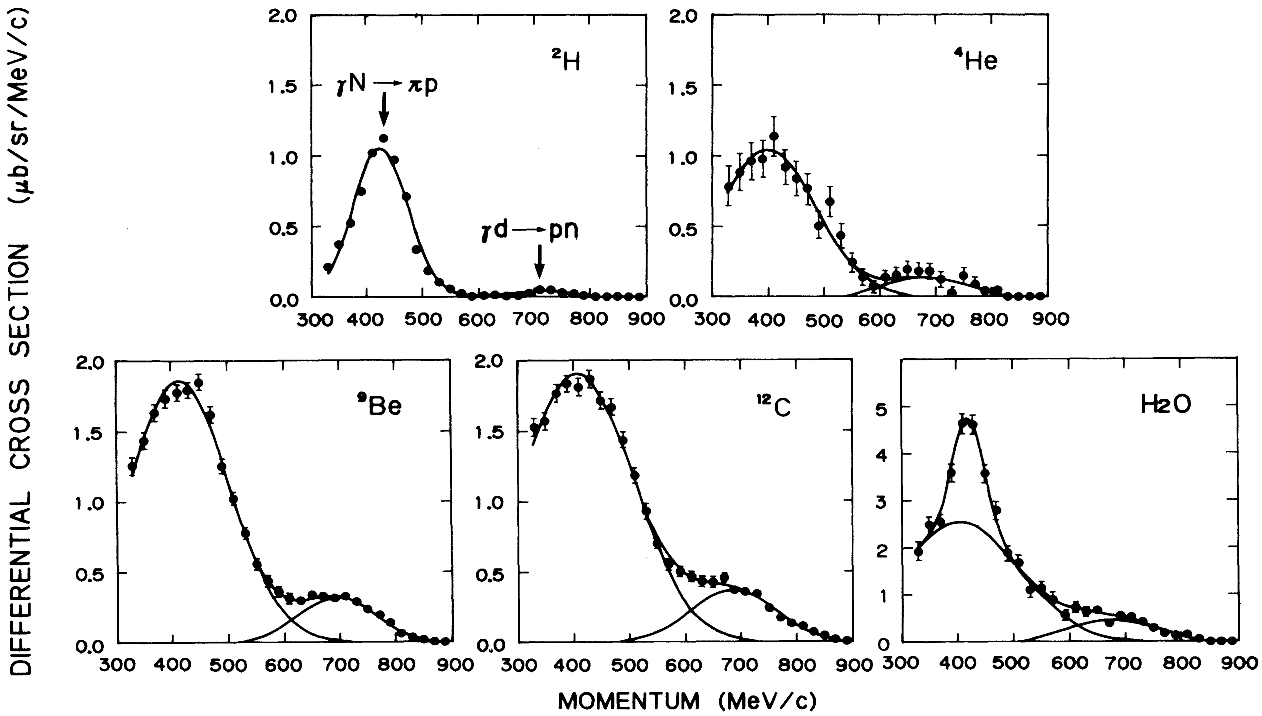

FIG. 1. Momentum spectra of protons from the (γ,p) reaction at $E_\gamma = 357 \pm 10$ MeV and at $\theta_p = 30° \pm 4°$ for ^{2}H, ^{4}He, ^{9}Be, ^{12}C, and H_2O. Curves are the best fits with two (for ^{2}H, ^{4}He, ^{9}Be, and ^{12}C) and three (for H_2O) Gaussian functions. Arrows indicate proton momenta corresponding to the elementary reactions $\gamma + N \rightarrow p + \pi$ and $\gamma + d \rightarrow p + n$.

are also observed for ^{4}He, ^{9}Be, and ^{12}C targets, which indicates that the main mechanisms of the (γ,p) reaction on light nuclei are the same as those on the deuteron. In the case of the water target, a narrow peak corresponding to reaction (3) is superposed on the broad peak due to reaction (1) on ^{16}O.

To extract the quantitative information on these peaks, proton spectra were fitted with two Gaussian functions for each target except for the water target, for which three Gaussian functions were used. Results of the fitting are shown in Fig. 1 by solid curves. The overall features of the spectra are well reproduced. Locations of peaks for nucleus targets shift to the lower momentum side from those expected for the elementary reactions. The amount of this shift does not depend on the photon energy: about 15–25 MeV/c for the first peak and 35–40 MeV/c for the second peak. These shifts are interpreted as the nuclear binding effect of the target nucleon "N" and the two-nucleon system "pN" in the nucleus. Widths of peaks for ^{9}Be, ^{12}C, and ^{16}O are much broader than the ones for ^{1}H and ^{2}H. The width of each peak is attributed to the smearing of the proton momentum due to the final-state interactions and the momentum distribution of the target particles "N" and "pN" of reactions (1) and (2), as well as the experimental resolution of the detection system. The separation of these three causes was not made in the present experiment, since it is not enough to extract some physics from the present data alone.

Differential cross sections for each quasifree reaction were obtained by the integration of Gaussian functions over the proton momentum. Results are shown in Figs. 2 and 3 as a function of the photon energy. Photon energy dependences of cross sections for elementary reactions show broad peaks around the photon energy of 300 MeV, which are considered to be due to the excitation of the $\Delta(1232)$ resonance. For nucleus targets, enhancement of cross sections for both quasifree reactions are also observed in this energy region, which indicates that the contribution of the Δ resonance is also important in these reactions. The photon energy dependence of cross sections differs slightly in each reaction channel and for each target nucleus. For reaction (1), the photon energy which gives the maximum cross section becomes higher as the target mass number increases. Whereas, for reaction (2), the shape of the photon energy dependence is

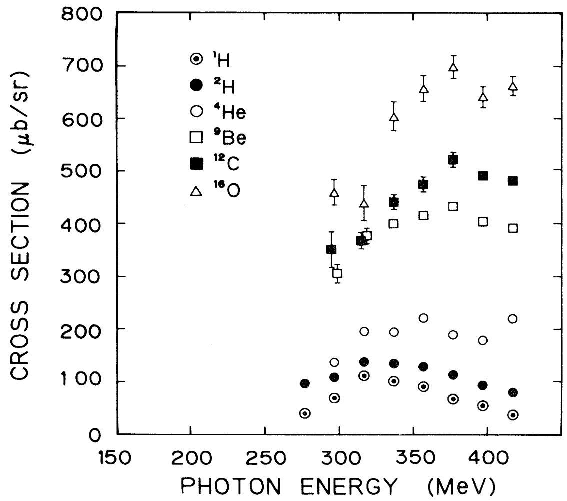

FIG. 2. Differential cross sections for the quasifree reaction $\gamma + ``N" \rightarrow p + \pi$ at $\theta_p = 30°$ for ^{1}H, ^{2}H, ^{4}He, ^{9}Be, ^{12}C, and ^{16}O as a function of the photon energy.

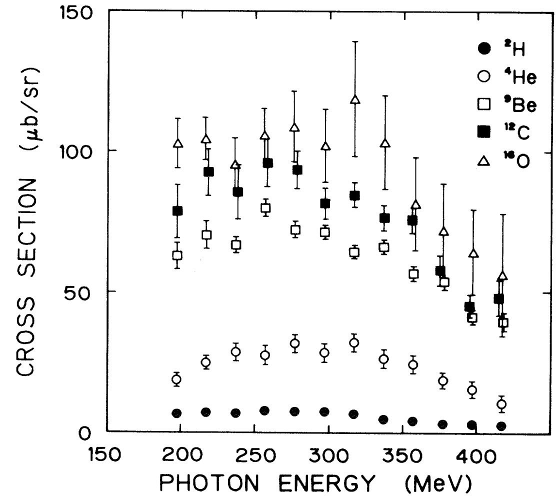

FIG. 3. Differential cross sections for the quasifree reaction $\gamma + ``pN" \rightarrow p + N$ at $\theta_p = 30°$ for ^{2}H, ^{4}H, ^{9}Be, ^{12}C, and ^{16}O as a function of the photon energy.

almost the same for all targets investigated.

The mass-number dependences of cross sections for quasifree reactions (1) and (2) are shown in Fig. 4, where averages of cross sections over the photon energy region from 287 to 427 MeV are used for reaction (1) and those from 187 to 427 MeV are used for reaction (2).

Generally, the observed cross section, $d\sigma/d\Omega|_{\rm obs}$, of the quasifree reaction on the nucleus target can be written in the following form:

$$\left.\frac{d\sigma}{d\Omega}\right|_{\rm obs} = \left.\frac{d\sigma}{d\Omega}\right|_0 T(A,P_p), \tag{5}$$

where $[d\sigma/d\Omega]_0$ is the reaction cross section and $T(A,P_p)$ is the probability that the proton with the momentum of P_p leaves the nucleus of the mass number A without suffering the final-state interaction. The functional form of $T(A,P_p)$ is expressed in the cylindrical coordinate as

$$T(A,P_p) = A^{-1}\int_V r\,dr\,d\theta\,dz\,\rho(r,\theta,z)\exp\left[-\sigma_T(P_p)\int_z^\infty \rho(r,\theta,z')\,dz'\right], \tag{6}$$

where $\rho(r,\theta,z)$ is the nucleon density in the nucleus, and $\sigma_T(P_p)$ is the total cross section for the proton-nucleon scattering. Since the nuclear shadowing effect for the incident photon is negligible, the original cross section for reaction (1), $d\sigma/d\Omega|_0$, is considered to be proportional to A. Therefore the probability $T(A,P_p)$ can be extracted from the A dependence of the observed cross sections. With simple assumptions that the nucleus has a spherical shape with the uniform density and that σ_T is constant in the present momentum region, experimental data for reaction (1) were fitted. The result is shown by the solid line in the figure, and the obtained value for σ_T is 31.5 mb, which corresponds to the proton mean free path of 2.3 fm in the nucleus. This value is quite consistent with the available data on the total cross sections of proton-nucleon interactions. From this analysis it can be concluded that, in ^{9}Be, about 44% of recoil protons are lost because of the final-state interactions in the nucleus.

The A dependence of cross sections for reaction (2) is also shown in Fig. 4. In this case, the general tendency is quite different from that for reaction (1). Namely, the observed cross section increases rather rapidly and starts to saturate at the mass number around 10. Since σ_T does not change strongly in the proton momentum region for reactions (1) and (2), the attenuation factor determined from the analysis of reaction (1) can be used for the analysis of reaction (2). Therefore the different A dependence is not due to the final-state interaction, and might originate from the essentially different reaction mechanism. Simple parametrization of the effective number of two-nucleon systems in the nucleus cannot be made in this small mass-number region. In the mass-number region above 10, however, the observed A dependence for reaction (2) is similar to that for reaction (1). This implies that the original reaction cross section is proportional to A in this region, and agrees with the expected A

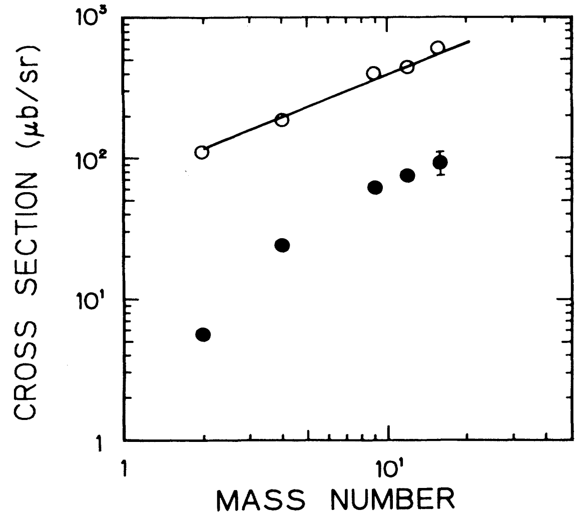

FIG. 4. The A dependence of differential cross sections for the quasifree reactions $\gamma + \text{``}N\text{''} \rightarrow p + \pi$ (open circles) and $\gamma + \text{``}pN\text{''} \rightarrow p + N$ (closed circles), where the averaged values of cross sections over the photon energy region from 287 to 427 MeV were used for the former reaction and those from 187 to 427 MeV were used for the latter reaction. The solid line shows the best fit to the data calculated using $\sigma_T = 31.5$ mb in Eqs. (5) and (6).

dependence from the quasideuteron model developed by Levinger,[6] although the photon energy region studied here is in the $\Delta(1232)$ resonance region. If we parametrize the reaction cross section according to the quasideuteron model,

$$\left.\frac{d\sigma}{d\Omega}\right|_A = \left(L\frac{NZ}{A}\right) \left.\frac{d\sigma}{d\Omega}\right|_d, \tag{7}$$

the L values are about 8.5 for ^{9}Be, ^{12}C, and ^{16}O. This L value is consistent with the previously obtained values[1] within the experimental accuracy. It should be noted that, in the present experiment, the proton yield from the reaction (γ,pp) is included in addition to that from the reaction (γ,pn). However, the contribution from the former channel is measured to be less than 10% in this photon energy region.[7]

It is also interesting to note that the cross section of reaction (2) for ^{4}He is 5.6 times larger than the one for the photodisintegration of deuteron. When we assume that the pair of nucleons contributing to reaction (2) is mainly the p-n pair, and that the effective number is given by the possible p-n combinations, the ratio between the cross sections for ^{4}He and deuteron is expected to be 4. For further quantitative discussions, microscopic analyses of these reactions will be necessary.

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