Photoemission of Two Nucleons from ^{9}Be in the $\Delta(1232)$ Resonance Region

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Coincidence measurements of two nucleons from the reactions $^9\mathrm{Be}(\gamma,pn)X$ and $^9\mathrm{Be}(\gamma,pp)X$ have been made in the $\Delta(1232)$ resonance region with a tagged-photon beam. From the momentum and angular correlations between the two nucleons, two quasifree reactions, $\gamma+{}''pn'' \rightarrow p+n$ and $\gamma+{}''pp'' \rightarrow p+p$, are clearly identified. The separation energy and the momentum distribution of the quasifree deuteron in ^{9}Be are determined together with the ratio between cross sections of the two quasifree reactions.

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Up to now, data on the reaction (γ,pn) in various nuclei have been accumulated by various authors, especially in the energy region below meson threshold.[1] Since in this energy region photons are considered to be absorbed by the nucleus mainly through electric dipole transitions, the results of the (γ,pn) reactions usually have been analyzed by use of a phenomenological quasideuteron model developed by Levinger[2] and extended by Gottfried.[3] At energies around 300 MeV, however, the wavelength of the photon is less than the internucleon distance, so that the photon interacts and is absorbed predominantly with a single nucleon to form the Δ rather than with the nucleus as a whole. The formed Δ then decays in the nucleus $(\Delta \rightarrow N+\pi)$ or interacts with a nearby nucleon in the nucleus $(\Delta+N \rightarrow N+N)$. As a consequence, a nucleon and pion or two nucleons are emitted from the nucleus. Since the probability of the latter mechanism depends strongly on the short-range behavior of the nuclear wave function, the reactions (γ,pn) and (γ,pp) in the Δ region are very important in the studies of the nuclear structure of the nucleus. Until now few experiments have been performed in this energy region.[4–8]

The present experiment is the continuation of our previous experiment,[4,5] and aims to confirm the interpretation of the second peak observed in the momentum spectrum of photoemitted protons from the beryllium nucleus and to determine the momentum distribution and the separation energy of the quasideuteronlike two nucleons in the nucleus.

In the present experiment, therefore, two nucleons photoemitted from ^{9}Be are detected in coincidence. Momenta and emission angles of both nucleons are precisely measured together with the incident photon energy. This semiexclusive measurement enables us to identify the quasifree reaction,

$$\gamma+{}''pN'' \rightarrow p+N, \tag{1}$$

which is dominant in the (γ,pN) reaction.

The experiment was done by use of a tagged-photon beam at the 1.3-GeV electron synchrotron of Institute for Nuclear Study (INS), University of Tokyo. The incident photon energy ranged from 187 to 427 MeV with an energy bin of 10 MeV. Protons emitted at $\theta_p = 30°$ were detected by a magnetic spectrometer having a solid angle of 34 msr and a momentum resolution of 4.5% at 600 MeV/c. The nucleon (proton or neutron) in coincidence with the spectrometer proton was detected by a hodoscope consisting of 64 plastic scintillation counters (sixteen columns by four layers) placed 1.5 m apart from the target. The hodoscope covered the angular range from 90° to 170° on the opposite side of the spectrometer. Each scintillator block of the hodoscope had a cross section of 10×10 cm^2 and a thickness of 30 cm. In front of the hodoscope, 1.5-cm-thick scintillators were placed for proton or neutron identification. Pulse height and time-of-flight (TOF) information for each scintillator were recorded for particle mass identification. The TOF information was used also for determination of the momentum of the nucleon detected by the hodoscope. The time resolution was 0.6 ns which corresponded to a momentum resolution of 5% at 400 MeV/c for nucleons.

Overall calibration of the present detection system was made by use of the reaction

$$\gamma+d \rightarrow p+n, \tag{2}$$

where liquid deuterium was used as a target. The detection efficiency of the hodoscope for neutrons was measured to be 35% at 400 MeV/c when the threshold level was set at 2 MeV by use of an electron beam.

In the following, results on the proton-neutron coincidence events from ^{9}Be are mainly described, because results on the photodisintegration of the quasideuterons,

$$\gamma + ''pn'' \rightarrow p + n, \qquad (3)$$

can be compared directly with the free target reaction (2). Figure 1 shows the correlation between proton momentum and neutron momentum at a photon energy of 247 ± 20 MeV. The proton and neutron momenta corresponding to the kinematics for the reaction (2) are shown by arrows. The events are clearly clustered in the momentum region expected from the kinematics for the reaction (2). These events are considered to be due to the photodisintegration of the quasideuteron in the nucleus, reaction (3). The other p-n coincidence events scattered in the lower momentum region are interpreted to be due to the photoproduction of pions from a single nucleon in the nucleus,

$$\gamma + ''N'' \rightarrow p + \pi, \qquad (4)$$

followed by pion-nucleon interactions in the nucleus. Figure 2 shows the angular correlation between the spectrometer proton and the neutron in the hodoscope, where events in the cluster region in Fig. 1 were selected. Again the angular distribution of neutrons shows a peak centered at the neutron angle for the kinematics of the reaction (2). These results confirm that p-n coincidence events in the cluster region are due to the photodisintegration of the quasideuteron in ^{9}Be.

Since in the present experiment on the reaction $^9\mathrm{Be}(\gamma,pn)X$, the energy and the momentum vector of the incident photon, $(E_\gamma, \vec{k})$, and those of two nucleons in the final state, $(E_p, \vec{p}_p)$ and $(E_n, \vec{p}_n)$, are measured, the energy and the momentum vector of the undetected system X, $(E_X, \vec{p}_X)$, can be determined from energy and momentum conservation. The separation energy of the $''pn''$ system in the nucleus is defined as

$$E^s_{pn} = (M_X + M_p + M_n) - M_{\mathrm{Be}}, \qquad (5)$$

where M_p, M_n, and M_{Be} denote the masses of the proton, the neutron, and the beryllium, respectively, and M_X is the invariant mass of the system X given by $M_X = (E_X^2 - \vec{p}_X^{\,2})^{1/2}$. When the impulse approximation is assumed for reaction (4), the momentum of the initial $''pn''$ system in the nucleus is given by

$$\vec{p}_{pn} = \vec{p}_p + \vec{p}_n - \vec{k}. \qquad (6)$$

Figure 3 shows the distribution of the separation energy E^s_{pn} for events in the photon energy region between 187 and 307 MeV. In this plot, events are selected by imposing cuts in the proton and neutron momenta as $p_p \geq (1.5E_\gamma + 50)$ MeV/c and $p_n \geq 200$ MeV/c, respectively, in order to reduce the background from the pion production reaction (4). A Gaussian-like distribution is obtained with a peak at $E^s_{pn} = 35 \pm 5$ MeV and with a full width at half maximum (FWHM) of 51 MeV. From the experiment on the free-target reaction (3), the FWHM resolution in the measurement of E^s_{pn} is estimated to be

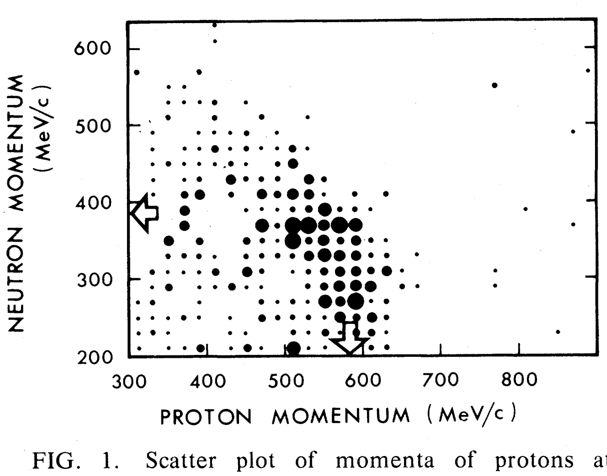

FIG. 1. Scatter plot of momenta of protons at $\theta_p = 30° \pm 4°$ and momenta of neutrons at $\theta_n = 130° \pm 40°$ for the reaction $^9\mathrm{Be}(\gamma,pn)X$ at $E_\gamma = 247 \pm 20$ MeV. Arrows indicate the momenta corresponding to kinematics of the free-target reaction $\gamma + d \rightarrow p + n$. The sizes of dots are proportional to the number of events in the momentum bins.

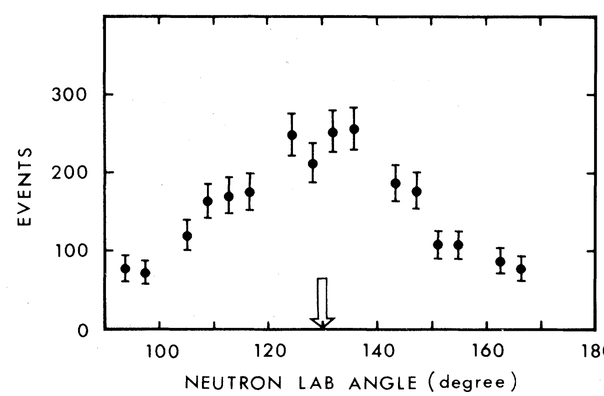

FIG. 2. Angular correlation between protons and neutrons for the reaction $^9\mathrm{Be}(\gamma,pn)X$ at $E_\gamma = 247 \pm 60$ MeV. Protons are detected at $\theta_p = 30° \pm 4°$. The arrow shows the neutron laboratory angle expected for the free target reaction $\gamma + d \rightarrow p + n$.

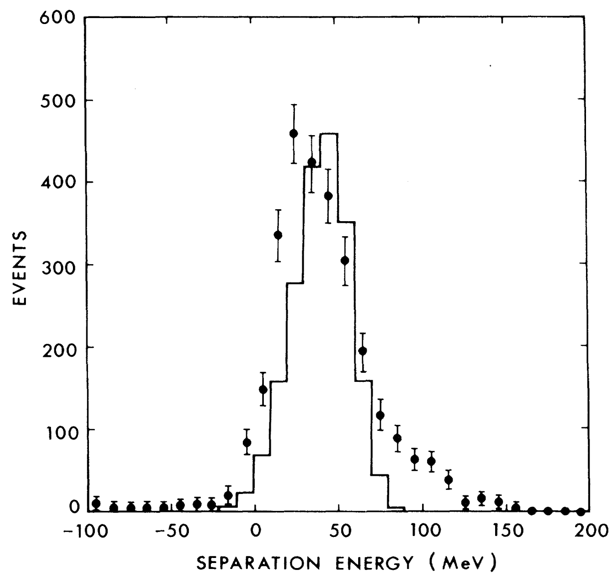

FIG. 3. Distribution of the separation energy of the "pn" system in ^{9}Be. Events for the quasifree reaction $\gamma + ''pn'' \rightarrow p + n$ at $E_\gamma = 247 \pm 60$ MeV are selected by applying cuts in the proton momentum, $p_p \geqslant (1.5E_\gamma + 50)$ MeV/c. A histogram shows the result of the Monte Carlo calculation based on the independent-particle model. The parameter σ_N is chosen to be 80 MeV/c. For details see the text.

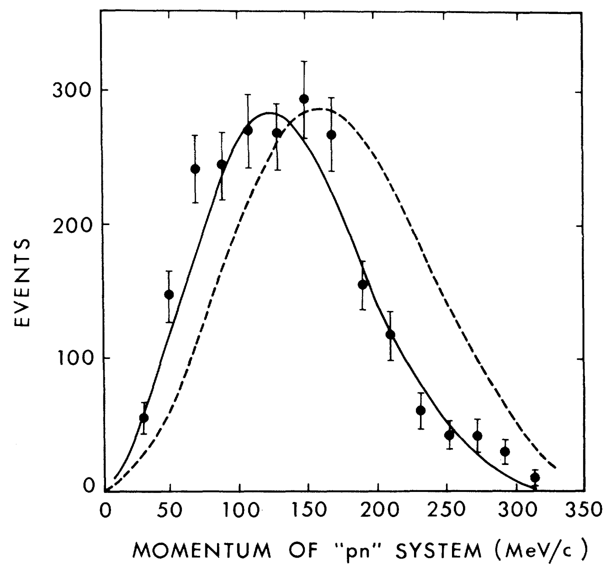

FIG. 4. Momentum distribution of the "pn" system in ^{9}Be obtained from the quasifree reaction $\gamma + ''pn'' \rightarrow p + n$ at $E_\gamma = 247 \pm 60$ MeV. Events with the separation energy E^s_{pn} in the region 0 MeV $\leqslant E^s_{pn} \leqslant 100$ MeV are used. Results of the Monte Carlo calculation are shown by the solid line ($\sigma_N = 80$ MeV/c) and by the broken line ($\sigma_N = 120$ MeV/c).

about 34 MeV, and the systematic uncertainty in the determination of the peak position is estimated to be less than 5 MeV. The tail at the high-energy side is interpreted to be due to the final-state interactions in the nucleus.

Figure 4 shows the momentum distribution of the quasifree "pn" system in ^{9}Be, where the momentum of "pn" system is given by $p_{pn} = |\vec{p}_{pn}|$. When the experimental result is fitted with the distribution function of the form $F(p_{pn}) = p_{pn}^2 \times \exp(-p_{pn}^2/\sigma_{pn}^2)$, σ_{pn} is obtained to be 123 ± 2 MeV/c.

Experimental results are compared with a Monte Carlo calculation based on an independent-particle model of the nucleus, in which following assumptions are made: (1) The quasifree "pn" system is formed by a random combination of a proton and a neutron in the nucleus. (2) The separation energy of the "pn" system is given by a sum of the separation energies of the proton and the neutron, $E^s_{pn} = E^s_p + E^s_n$. The values of E^s_p used for ^{9}Be are 26 MeV for 1s protons and 17 MeV for 1p protons, which come from the results of the $(e,e'p)$ experiments.[9] The value of E^s_n is assumed to be equal to E^s_p for each state, whereas E^s_n of a valence neutron in the 1s state is taken to be 2 MeV. (3) A harmonic-oscillator-type nuclear wave function is assumed, so that the momentum distribution of individual nucleons in the nucleus is given by $f(\vec{p}_N) = \exp(p_N^2/\sigma_N^2)$ for 1s nucleons and $f(\vec{p}_N) = p_N^2 \exp(p_N^2/\sigma_N^2)$ for 1p nucleons, where σ_N is a parameter to be determined from the experiment. In the Monte Carlo calculation, resolution and efficiency of the detection system were taken into account, but final-state interactions in the nucleus were ignored.

The result of the calculation on the separation energy is shown in Fig. 3 by a histogram together with the experimental data, where the parameter σ_N is taken to be 80 MeV/c. The agreement between the experimental data and the calculated result is rather good except for the peak position which shifts to higher energy by about 10 MeV. This discrepancy may be due either to the relatively enhanced contribution of the 1p nucleons in forming pn pairs or to crudeness of the assumption on the separation energy, $E^s_{pn} = E^s_p + E^s_n$. The choice of the parameter σ_N has no appreciable effect on the distribution of the separation energies.

The momentum distribution of the "pn" system in ^{9}Be is also well reproduced by the assumption that $\sigma_N = 80$ MeV/c. It is interesting to note that the parameter σ_N obtained by fitting the inclusive proton momentum spectra for the reaction $^9\mathrm{Be}(\gamma,p)X$ in the quasifree pion photoproduction region is 120 MeV/c. The value of σ_N obtained from other single-nucleon interactions such as $(e,e'p)$ and $(p,2p)$ is also around 120 MeV/c. This difference may indicate that "pn" system in the nucleus is not formed by a simple combination of two independent nucleons, or that some correlations of nucleons should be taken into account.

In the present experiment, two protons from the reaction $^9\mathrm{Be}(\gamma,pp)X$ were measured with the same apparatus. Although the cross section of this reaction is smaller than that of $^9\mathrm{Be}(\gamma,pn)X$, the angular correlation between two protons with high momenta is very similar to the one between the proton and the neutron in the $^9\mathrm{Be}(\gamma,pn)X)$ reaction. The cross section ratio

$$R=\frac{d\sigma(\gamma+''pp''\rightarrow p+p)/d\Omega}{d\sigma(\gamma+''pn''\rightarrow p+n)/d\Omega}$$

shows no energy dependence in the present photon energy region and the averaged value of R is determined to be 0.06 ± 0.02. This result is consistent with the prediction by Wakamatsu and Matsumoto.[10]

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[1]For a survey, see G. Ricco, in *Photonuclear Reactions I,* edited by S. Costa and C. Schaerf, Lecture Notes in Physics Vol. 61 (Springer-Verlag, Berlin, 1977), p. 223.

[2]J. S. Levinger, Phys. Rev. **84**, 43 (1951).

[3]K. Gottfried, Nucl. Phys. **5**, 557 (1958).

[4]S. Homma *et al.*, Phys. Rev. Lett. **45**, 706 (1980).

[5]S. Homma *et al.*, Phys. Rev. C **27**, 31 (1983).

[6]K. Baba *et al.*, Phys. Lett. **113B**, 459 (1982).

[7]R. A. Schumacher *et al.*, Phys. Rev. C **25**, 2269 (1982).

[8]J. Arends *et al.*, Z. Phys. A **298**, 103 (1980).

[9]G. Jacob and T. A. Maris, Rev. Mod. Phys. **45**, 6 (1973).

[10]M. Wakamatsu and K. Matsumoto, Nucl. Phys. **A392**, 323 (1983).