Interpretation of the High-Energy Processes $^{16}O(\gamma,p_0)^{15}N$ and $^{16}O(\gamma,n_0)^{15}O$

Berthold Schoch
Institut für Kernphysik, Universität Mainz, 6500 Mainz, West Germany
(Received 30 January 1978)

Calculations based on a two-nucleon (n-p) absorption mechanism show that the form factor of the residual nucleus plays an important role in determining the shape of the photoproduction cross section in a wide energy range 60 MeV $\leq E_\gamma \leq$ 300 MeV.

In recent papers[1,2] the (γ,p_0) reaction has been considered a good source of information of the high-momentum components of nucleon wave functions. Assuming a single-step knockout mechanism, momentum distributions are extracted from the data.[1] With this kind of model, however, it is not possible to describe (γ,n_0) cross sections which are of the same order of magnitude as the (γ,p_0) reactions.[3,4] A promising approach, which gives a good description of the data below the meson threshold, is a model with a one-pion-exchange force.[5] In this model the photon is absorbed mainly by a correlated neutron-proton pair; it is similar to the quasideuteron model used for the description of (γ,np) processes or other processes, e.g., $^4He(\gamma,{}^{n_0}_{p_0})$.[6] In this Letter it is demonstrated by using the quasideuteron model, that the form factor of the residual nucleus plays an essential role in the interpretation of the measured data in a wide energy range.

Figure 1(a) shows the $^{16}O(\gamma,p_0)^{15}N$ cross sections in a wide range of photon energies for proton angles of 45°, 90°, and 135°.[2] A common feature of the cross sections is the exponential decrease at low photon energies and a change in the slope in the logarithmic plot approximately at 180, 120, and 90 MeV for 45°, 90°, and 135°, respectively.

Momentum conservation in the quasideuteron model yields

$$\vec{\omega}+\vec{p}_n+\vec{p}_p=\vec{p}_n'+\vec{p}_p', \tag{1}$$

with $\vec{\omega}$ the momentum of the photon and with $\vec{p}_n$, $\vec{p}_p$, $(\vec{p}_n',\vec{p}_p')$ the momentum of the correlated neutron and photon before (after) the reaction. If we look for the (γ,p_0) process, by definition the neutron remains in the nucleus in its initial state and only accepts a momentum transfer $\vec{q}$,

$$\vec{q}=\vec{p}_n'-\vec{p}_n=\vec{\omega}+\vec{p}_p-\vec{p}_p'. \tag{2}$$

$\vec{q}$ is just the momentum transferred to the whole residual nucleus since the $(A-2)$ system acts only as a spectator. Thus I try the following *Ansatz* for the cross section[7]:

$$\frac{d\sigma(\vec{\omega},\theta_p)}{d\Omega}=\frac{L}{A}\frac{d\sigma(\vec{\omega},\theta_p)}{d\Omega}C(\vec{\omega},\theta_p) \tag{3}$$

with

$$\frac{d\sigma(\vec{\omega},\theta_p)}{d\Omega_d}=\frac{d\sigma}{d\Omega_{d\,\mathrm{c.m.}}}JP_s.$$

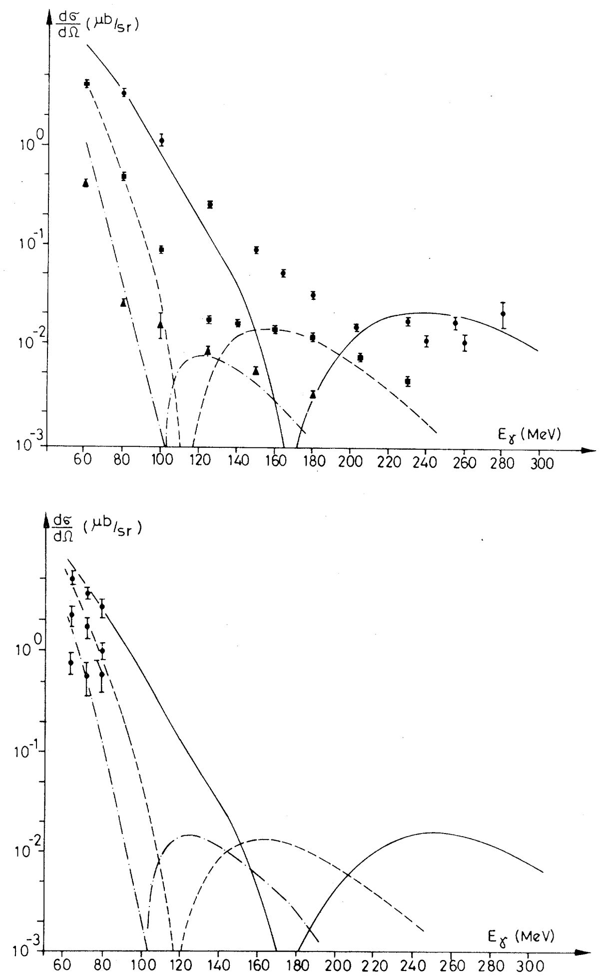

FIG. 1. The calculated and measured cross sections: Full line 45°, dashed line 90°, and dash-dotted line 135°. (a) $^{16}O(\gamma,p_0)^{15}N$, (b) $^{16}O(\gamma,n_0)^{15}O$.

Here $d\sigma/d\Omega_{d\,\mathrm{c.m.}}$ is the differential cross section for the photodesintegration of the deuteron in the c.m. system. J is the Jacobian for the transformation from the c.m. to the laboratoy system. P_s corrects for the different phase space in the $(p,A-1)$ system compared to the (n,p) system. A is the mass number and L the Levinger constant.[8] The number of $(n$-$p)$ pairs is contained in C. The factor $C(\vec{\omega},\theta_p)$ represents the ability of the nucleus to absorb the transferred momentum $\vec{q}$; in this model it represents the ability of the neutron from the quasideuteron to absorb $\vec{q}$. This factor may be written as[7] $C(\vec{\omega},\theta_p)=|M(\vec{\omega},\theta_p)|^2$, where the matrix element $M(\vec{\omega},\theta_p)$ is given by the overlap integral of the nuclear wave function in the inital state and for this particular final state. Plane waves are used for the outgoing nucleon. The nucleus is described by a single-particle product wave function. In momentum space we have

$$M(\vec{\omega},\theta_p)=\sum_{n_i,m_j}\int d^3p_p\,d^3p_n\,d^3p_1\ldots d^3p_{A-2}\,d^3p_p'\,d^3p_n'\,\Psi_{A-2}^*(\vec{p}_1,\ldots,\vec{p}_{A-2})\Psi_{m_j}'^*(\vec{p}_p')$$
$$\times\Psi_{n_i}^*(\vec{p}_n')\Psi_{m_j}(\vec{p}_p)\Psi_{n_i}(\vec{p}_n)\Psi_{A-2}(\vec{p}_1,\ldots,\vec{p}_{A-2})\delta(\vec{\omega}-\vec{q}+\vec{p}_p-\vec{p}_p'). \quad (4)$$

The sum n_i is to be taken over all neutrons in the nucleus and m_j sums the two $p_{1/2}$-shell protons. Integrating over the $(A-2)$ particles yields a factor of 1. The wave function of the proton emitted with the momentum $\vec{p}_{p0}$ is the δ function $\delta(\vec{p}_p'-\vec{p}_{p0})$ which allows integration over d^3p_p':

$$M(\vec{\omega},\theta_p)=\sum_{n_i,m_j}\int d^3p_p\,d^3p_n\,d^3p_n'\Psi_{n_i}^*(\vec{p}_n')\Psi_{m_j}(\vec{p}_p)\Psi_{n_i}(\vec{p}_n)\delta(\vec{\omega}-\vec{q}+\vec{p}_p-\vec{p}_{p0}). \quad (5)$$

The δ function together with Eq. (1) can be used for integrating over $\vec{p}_n'$; one gets the expression

$$M(\vec{\omega},\theta_p)=\sum_{m_j}\int d^3p_p\Psi_{m_j}(\vec{p}_p)F^{A-1}(\vec{q}=\vec{\omega}+\vec{p}_p-\vec{p}_{p0}), \quad (6)$$

where

$$F^{A-1}(\vec{q})=\sum_{n_i}\int d^3p_n\psi_{n_i}^*(\vec{p}_n+\vec{q})\psi_{n_i}(\vec{p}_n),$$

which is just the form factor of the neutrons in the ground state of the $(A-1)$ system. The sum over m_j yields a factor of $Z_{1/2}$ (the number of protons in the $p_{1/2}$ shell). For normalized wave functions the form factor equals N (the number of neutrons in the nucleus) for $|\vec{q}|=0$.

Using this model I calculate the ratio of the $p_{3/2}$- to the $p_{1/2}$-knockout cross section to be roughly $(\frac{4}{2})^2=4$. This number is closer to the observed ratio[9] of about 6 than to the calculated ratio 2 which assumes the impulse approximation. In this calculation I assume that the form factor due to the neutron distribution for $^{15}N_{g.s.}$ (in the case of proton emission) and correspondingly the form factor due to the proton distribution of $^{15}O_{g.s.}$ (in the case of neutron emission) are the same as the charge form factor of ^{16}O which are taken from Donnelly and Walker.[10] A harmonic-oscillator wave function is used for ψ_{m_j} (oscillator parameter $b=1.77$ fm). The cross sections for the deuteron breakup are taken from Partovi[11] ($E_\gamma \leq 100$ MeV) and Kose *et al.*[12] ($E_\gamma \geq 100$ MeV). The results of this calculation are shown in Figs. 1(a) and 1(b) for the reactions $^{16}O(\gamma,p_0)^{15}N$ and $^{16}O(\gamma,n_0)^{15}O$, respectively, together with data points from Refs. 1–4. The value 2.2 for the Levinger constant was used in the calculation. Taking an overall absorption factor of 0.4 for the outgoing proton[1] would bring the value of the Levinger constant to 5.4 in fairly good agreement with the value of 6.4 given in Ref. 8.

The overall agreement for both the proton and the neutron data is good. The slope at low energies is described correctly as well as the characteristic change in the slope. The inclusion of distorted waves for the outgoing nucleon should fill in the minima in the calculated cross sections; thus it is this q region where final-state interactions can be studied very well.

Better neutron data extended to higher energies are necessary to check the range of applicability of the described reaction mechanism. Another interesting check would be given by transitions to excited states of the residual nucleus. Where transition form factors are involved, the angular distribution of the emitted nucleons would show a different dependence on q than do the ground-state form factors.[13]

In conclusion I say that (γ,p_0) and (γ,n_0) processes can be described successfully by a quasideuteron model. The shape of the cross section is dominated by the form factor of the residual nucleus over a wide photon-energy range. The success of this description makes other interpretations of the absorption mechanism questionable, e.g., the single-particle absorption or the contributions from $\Delta(1232)$. The latter are believed to be responsible for the enhancement in cross section at higher photon energies.[14] However, in my opinion, this enhancement is probably due to the neutron form factor.

Part of this work was done during a stay at Massachusetts Institute of Technology. Stimulating discussions during this time with A. M. Bernstein, W. Bertozzi, and W. Turchinetz are gratefully acknowledged. It is a pleasure to thank J. Friedrich for many critical discussions.

[1]D. J. S. Findlay and R. O. Owens, Phys. Rev. Lett. 37, 674 (1976).

[2]J. L. Matthews, W. Bertozzi, M. J. Leitch, C. A. Peridier, B. L. Roberts, C. P. Sargent, W. Turchinetz, D. J. S. Findlay, and R. O. Owens, Phys. Rev. Lett. 38, 8 (1977).

[3]H. Schier and B. Schoch, Nucl. Phys. A229, 93 (1974).

[4]H. Schier and B. Schoch, Lett. Nuovo Cimento 12, 334 (1975).

[5]H. Hebach, A. Wortberg, and M. Gari, Nucl. Phys. A267, 425 (1976).

[6]C. T. Noguchi and F. Prats, Phys. Rev. C 14, 1133 (1976).

[7]M. L. Goldberger and K. M. Watson, *Collision Theory* (Wiley, New York, 1964), Chap. 11.

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

[9]W. Bertozzi, *International School of Electro and Photonuclear Reactions, Erice, Italy, 1976*, edited by S. Costa and C. Schaerf (Springer-Verlag, Berlin, 1977).

[10]T. W. Donnelly and G. E. Walker, Phys. Rev. Lett. 22, 1121 (1969).

[11]F. Partovi, Ann. Phys. (N.Y.) 27, 79 (1964).

[12]R. Kose, W. Paul, K. Stockhorst, and K. H. Kissler, Z. Phys. 202, 364 (1967).

[13]J. L. Matthews, D. J. S. Findlay, S. N. Gardiner, and R. O. Owens, Nucl. Phys. A267, 51 (1976).

[14]J. T. Londergan, G. D. Nixon, and G. E. Walker, Phys. Lett. 65B, 427 (1976).

Detection of Nuclear-Bag States

C. W. Wong and K. F. Liu
Department of Physics, University of California, Los Angeles, California 90024
(Received 10 February 1978)

We discuss the masses of nuclear bag states containing $3A$ quarks, the decay width of the deuteron bag, d^*, the appearance of dinucleon bags as resonances in nucleon-nucleon reactions, the inelastic form factor for the reaction $ed \to e'd^*$ and the differential cross section for $pd \to p'd^*$. Separation of bag signals from the background from pion production requires the detection of one or more decay nucleons.

It has been recognized for some time that the conventional nuclear theory of nucleons in nuclei relevant to the low-energy domain is inadequate in the intermediate-energy region. It should be supplemented there by additional degrees of freedom because of the presence of mesons and nucleon isobars,[1] and of quarks.[2,3] Quarks are particularly interesting because they provide a unifying picture of hadron and nuclear structures. One manifestation of quark dynamics in nuclei is the formation of "abnormal" nuclear states in which more than three quarks form a cluster or "bag" inside the nucleus.[4-6] The actual detection of these new nuclear-bag states is thus of considerable interest. We discuss in this Letter a number of questions related to the experimental detection of these nuclear bags, occurring either alone or as clusters in nuclei.

Masses.—Nuclear-bag states are so called because in the Massachusetts Institute of Technology bag model the quarks are confined in a "bag" by its surface pressure B. Model masses, calculated from Johnson's formula,[4] are given in Table I. These are not rest masses, however, but total masses including large kinetic energies of center-of-mass (c.m.) motion, which are $\simeq 0.1$–0.4 GeV for hadrons.[7] Table I also gives the rest masses after c.m. correction. Their calculation[7] requires a refit of model parameters to hadron masses, resulting in a reduction of the quark-quark interaction strength α_s and an almost complete elimination of the zero-point energy constant Z_0. Thus the original large Z_0 represents basically just this c.m. correction. It is then understandable (and reassuring) that model extrapolations for nuclear-bag masses are rather insen-

