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PION PHOTOPRODUCTION OFF NUCLEI: A SENSITIVE TEST OF THE NUCLEAR TRANSITION DENSITIES

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It has been shown recently [1,2] that definite refinements like the correct treatment of the momentum-dependent terms of the elementary amplitude, pion multiple rescattering and the gauge invariance of the nuclear photoproduction amplitude are necessary to ensure the reliability of the theoretical model of the pion photoproduction off nuclei. In the present letter we would like to demonstrate that the nuclear structure input is most probably responsible for the main discrepancies of the recent calculations [3,4] of the $^{16}O(\gamma,\pi)^{16}N$ (bound) reaction with data. Since the argument applies to other light nuclei as well, it seems worth presenting it at a greater length here.

Starting with the multiple scattering theory one can manipulate [2] the DWIA partial-wave photoproduction amplitude into the form

$$\mathcal{F}^{j}_{n0}(L_\pi, q; L_\gamma, k\lambda) = V^{j}_{n0}(L_\pi, q; L_\gamma, k\lambda)\, e^{i\kappa_{L_\pi}} \cos(\kappa_{L_\pi}), \qquad (1)$$

where V^{j}_{n0} is the partial plane-wave photoproduction amplitude and $\kappa_{L_\pi} = \delta^{c}_{L_\pi} + \delta_{L_\pi}$ stands for the Coulomb and strong phase-shifts of the π-nucleus scattering. L_π $(\vec{q})$ and L_γ $(\vec{k})$ are angular momenta (momenta) of the pion and photon-respectively, j is the total momentum. We shall use $\vec{Q} = \vec{k} - \vec{q}$ for the momentum transfer. The derivation of (1) is described in detail in our earlier paper [2]. The construction obeys the requirements of the relativistic and gauge invariance and takes into account the nucleon Fermi motion. These effects appear numerically important [2], and it seems that the method of ref. [2] provides us with a realistic pion photoproduction amplitude. The calculations performed for the ^{12}C and ^{16}O targets show a good agreement with the data at $T_\pi \geq 30$ MeV.

In terms of (1) the integral pion photoproduction cross section reads [2]

$$\sigma_{n0} = \frac{q}{2k}\,\frac{1}{2J_0+1} \sum_{\lambda L_\pi L_\gamma j} \frac{2j+1}{2L_\gamma+1}\, |\mathcal{F}^{j}_{n0}(L_\pi, q; L_\gamma, k\lambda)|^2, \qquad (2)$$

where J_0 is the total momentum of the nuclear initial state. For the differential cross section one finds

$$\frac{d\sigma_{n0}}{d\Omega} = \frac{q}{2k}\,\frac{1}{2J_0+1}\sum_{\lambda M_0 M_n}\Big|\sum_{L_\pi L_\gamma j}\begin{bmatrix}L_\pi & J_n & j\\ M_\pi & M_n & m\end{bmatrix}\begin{bmatrix}L_\gamma & J_0 & j\\ \lambda & & M_0\ m\end{bmatrix} \times Y_{L_\pi M_\pi}(\Omega_{\vec{q}})\,\mathcal{F}^{j}_{n0}(L_\pi, q; L_\gamma, k\lambda)\Big|^2 \tag{3}$$

with [: : :] for the Clebsch-Gordan coefficients and $Y_{LM}(\Omega)$ for the spherical harmonics.

To demonstrate our point, we have calculated the amplitude of eq. (1) using two popular parametrizations /7,8/ of the transition densities which both describe correctly the available (e, e′) data. The corresponding differential cross sections are plotted in figs. 1 and 2*. One notices immediately that the two sets of results differ very considerably for $Q > 1.0\ \mathrm{fm}^{-1}$. We have observed the same dramatic difference also for the larger pion angles not shown in fig.2. Using eq. (2) the total cross sections were calculated for the two sets of the transition densities. Though the integrated characteristic is slightly less sensitive to the imput, the difference of the two results amounts typically to 50%.

Let us now discuss the possible origin of the differences just observed. It is clear that the nuclear transition densities which were inconsistent with the electromagnetic data would be meaningless for the photoproduction work. It appears, however, that such a limitation is actually rather weak: the (e, e′) data are normally (i) limited to the momentum transfers smaller than those typical for the photoproduction process, (ii) not separated with respect to their longitudinal and transverse parts, and (iii) composed of contributions of several nuclear levels of different spins. (The ^{12}C(e, e′) reaction is a rare exception, indeed, where rather complete and well separated data exist for several transitions).

Proceeding to the case of $A = 16$ nuclei we shall describe the two densities used. Donelly and Walecka /7/ have shown that by admixing the particle-hole ($1\hbar\omega$) configurations via residual interaction one reproduces the electromagnetic form factors for the $T = 1$ states in ^{16}O provided that certain reduction factors are introduced which simulate the effects of more complicated configurations left out of the model space. The same data, namely, the form factors

$$F^2(Q) = \Big[\frac{1}{2} + \mathrm{tg}^2\Big(\frac{1}{2}\Theta\Big)\Big]^{-1} F_L^2(Q) + F_T^2(Q) \tag{4}$$

(with self-explaining notation) for the 2_1^- and 3_1^- levels at $Q < 1\ \mathrm{fm}^{-1}$ and the unresolved form factor for the "14 MeV complex" (1_1^-, 2_1^-, 3_1^-) at $0 < Q < 3\ \mathrm{fm}^{-1}$, have been successfully fitted also by the generalized Helm-model in ref. /1/. The quality of the fit is very good in both the cases (see refs. /7,8/). The two parametrizations result, however, in very different individual form factors in the region $Q > 1\ \mathrm{fm}^{-1}$. One of the features is demonstrated in fig.3: The importance of the longitudinal and transverse contributions to the 3_1^- form factor is reversed in the two parametrizations. Besides, we have also observed that a smaller 3_1^- contribution to the "14 MeV complex" (at $Q > 1.5\ \mathrm{fm}^{-1}$)

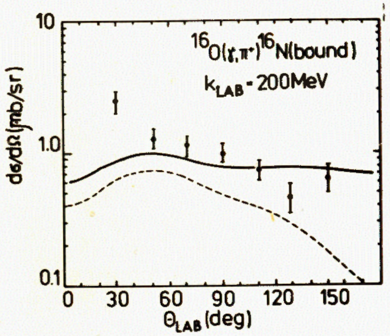

Fig.1. Pion angular distributions at k = 200 MeV. The solid curve is calculation with shell-model densities /7/, for the dashed curve the Helm-model densities /8/ were used. Experimental data are from Yamazaki et al. /9/.

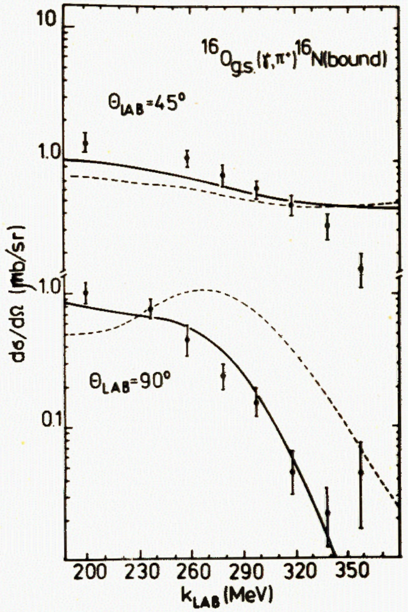

Fig.2. Energy dependence of the differential cross-sections of the ^{16}O(γ,π$^+$)^{16}N (bound) reactions. Calculations as in fig.1. Data are from Bosted et al. /10/ (dots) and from Yamazaki et al. /9/ (open circles). The corresponding ranges of the momentum transfer are $0.7 < Q < 1.4\ \mathrm{fm}^{-1}$ ($\theta = 45°$) and $1.2 < Q < 2.5\ \mathrm{fm}^{-1}$ ($\theta = 90°$) for $200 < k < 380$ MeV.

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*Results of some earlier calculations (e.g., refs. /5,6/) performed with the Helm-model densities differ considerably from ours. There the "proton-size factor" $(1 + Q^2/0.71)^{-2}$ which is indeed a part of the elementary electron-nucleon amplitude (rather than the nuclear one) has erroneously not been extracted before using the corresponding density in the photoproduction work.

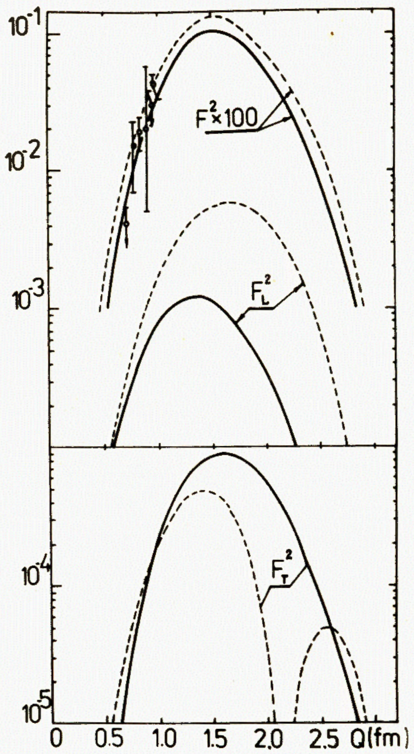

Fig.3. Total, longitudinal and transverse form factors of the 3^-_1(T= 1) level in ^{16}O calculated with the shell-model/7/ (full line) and Helm-model/8/ (broken line) transition densities. For the data see ref./8/.

calculated in ref./7/ is counter-balanced by the larger 1^-_1 and 2^-_1 terms. At the same time in the Helm-model the composition of the complex is based on the strong 3^-_1 contribution. These features are undistinguishable in the available (e, e′) data. The photoproduction reaction selectively accentuates the higher-spin levels (3^-_1 in this case), and, due to the resonance character of the non-spin-flip (γ,π) amplitude, blows up the differences in the longitudinal part of the transition densities shown in fig.3. This explains qualitatively and quantitatively the results displayed in figs. 1 and 2.

If a decision is to be made between the two densities, we would prefer the microscopically-oriented fit by Donnelly and collaborators. The comparison of theoretical and experimental/9,10/ differential cross-sections performed in figs.1 and 2 supports strongly this choice.

In conclusion one notes that the nuclear structure input of the pion photoproduction nuclear calculation deserves much deeper attention than it was generally believed. The constraint by the available electromagnetic data is indeed conditio sine qua non, still not sufficient to guarantee the success of the work. Indeed, new (e, e′) data measured for a broad Q-range for several light nuclei would help much in understanding the photoproduction reaction if F_L and F_T components are separated.

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Чувствительность процесса фоторождения пионов
к выбору ядерных переходных плотностей

Современные (e, e′)данные в большинстве случаев не позволяют однозначно определить ядерные переходные плотности, что проявляется при исследовании других процессов. В качестве примера рассмотрена реакция $^{16}O(\gamma,\pi^+)^{16}N$ /св.сост./ для двух наборов ядерных матричных элементов. Существующая неоднозначность позволяет нам устранить разногласия с данными по фоторождению, имеющиеся в расчетах других авторов. Для прояснения ситуации необходимы новые эксперименты по исследованию неупругого электронного рассеяния на ядрах.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Pion Photoproduction Off Nuclei:
A Sensitive Test of the Nuclear Transition Densities

The available (e, e′) data in most cases constrain just weakly the nuclear transition densities. As an example we have analysed the $^{16}O(\gamma,\pi^+)^{16}N$ (bound) reaction using two sets of nuclear matrix elements both consistent with the electromagnetic constraint. The freedom left allows us to account fully for the disagreement of recent photoproduction calculations with data. New precise electron scattering experiments are needed to elucidate the situation.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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