Reactions $^3He(\pi^-,n)^2H$ and $^4He(\pi^-,n)^3H$ at Pion Energies of 100, 200, and 290 MeV

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Differential cross sections for the (π^-, n) reactions in ^{3}He and ^{4}He have been measured at energies of 100, 200, and 290 MeV. The angular distributions for ^{3}He and ^{4}He are different, with ^{4}He characterized by an oscillatory pattern with a dip at a fixed angle of $\simeq 70°$. The forward-angle cross sections show a simple dependence upon momentum transfer for both ^{3}He and ^{4}He. These results are discussed in the context of single-nucleon and multinucleon reaction diagrams.

The pion absorption reaction (π,N) in nuclei as well as the inverse pion production reaction (p,π) have attracted interest recently as possible probes of nuclear structure. The distinguishing feature of these reactions is the large momentum transfer (Q) involved in the process, $\simeq 400$ Mev/c and larger. This fact along with theoretical analyses based on a reaction model allowing only one basic pion-nucleon interaction, a one-nucleon transfer or so-called nucleon-pickup reaction diagram,[1] have stimulated hope that one could learn about the high-momentum components of the nuclear wave function. Distortion effects,[2] however, have been found to be important to an extent that modifies the dynamics of the reaction from those prescribed by the simple pickup approximation. The same situation of relaxed requirements on high-momentum components has been obtained by explicitly introducing various multinucleon interactions in the reaction model.[3,4] We have studied the (π^-,n) reaction in ^{3}He and ^{4}He for which the one-body structure of the involved nuclear states is somewhat known from other reactions like elastic electron scattering. This Letter reports on the first results from such a study performed over the energy range 50–290 MeV which reveal features not observed in earlier measurements (for references to previous works see Fearing[5]).

The detailed angular distributions were measured using the EPICS pion channel[6] at the Clinton P. Anderson Meson Physics Facility which provided 3×10^5–3×10^6 π^-/s at energies between 50 and 290 MeV. The targets[7] were liquid ^{3}He and ^{4}He kept in identical cells ($12.5\times12.5\times0.64$ cm^3) at a temperature of 1.4°K giving densities of 81 and 145 mg/cm^3. The detector consisted of three plastic scintillators and a wire chamber which provided for particle identification (based on time-of-flight and total-energy measurements). Pulse-height spectra were recorded for protons, deuterons, and tritons so that the recoiling nucleus was detected for the reactions $^3He(\pi^-,n)^2H$ and $^4He(\pi^-,n)^3H$. The cross sections obtained have an estimated overall uncertainty of less than ±15% besides the statistical uncertainties presented for each point.

The angular distributions for the reaction $^3He(\pi^-,n)^2H$ at $T_\pi = 100$, 200, and 290 MeV are shown in Fig. 1. In particular, we note that there

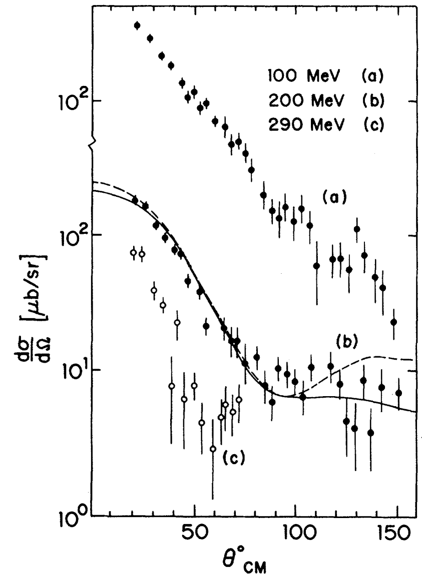

FIG. 1. Angular distribution for $^3He(\pi^-, n)^2H$ measured at 100, 200, and 290 MeV compared with calculations. The full line is a calculation of Fearing, Ref. 5, and the dashed line is obtained using the formulation of Gibbs and Hess, Ref. 8, and the predicted $\pi^+ + d$ elastic cross sections of Ref. 9. The calculation of Fearing has been multiplied by a factor of 2 for reasons of shape comparison.

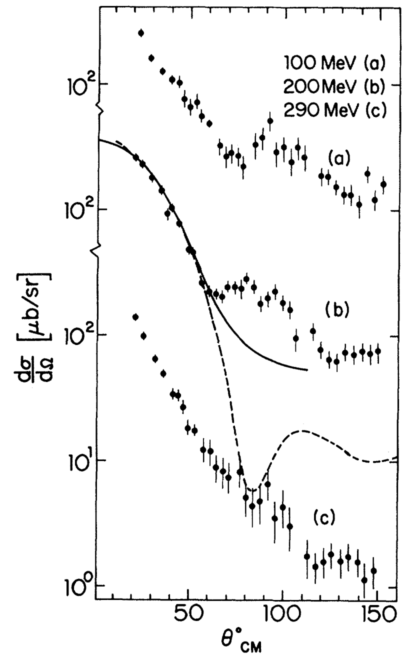

FIG. 2. Angular distribution for $^4He(\pi^-, n)^3H$ measured at 100, 200, and 290 MeV compared with calculations. The full line is the results of Fearing, Ref. 5, at $T_\pi = 180$ MeV and the dashed line is obtained using the formulation of Gibbs and Hess, Ref. 8, and the predicted $\pi^- + {}^3H$ cross sections at 200 MeV (see Ref. 11).

is no back-angle peaking indicated in our results. This observation is worth mentioning since a previous measurement[10] of $^2H(p, \pi^+)^3H$ at $T_p = 470$ MeV has indicated such a sharp back-angle peaking on the basis of two high data points at $\theta = 154$ and 160°. This (p, π^+) reaction is related to the reaction $^3H(\pi^+, p)^2H$ at 176 MeV [or, assuming charge independence, $^3He(\pi^-, n)^2H$] through detailed balance. Our data at the adjacent energy of 200 MeV are in general agreement with those of (p, π^+) apart from the extreme back angles. A measurement at $\theta = 160°$ was done to look for a rise in cross section; only an upper limit of less than 12 μb/sr could be established.

The angular distributions for the reaction $^4He(\pi^-, n)^3H$ at 100, 200, and 290 MeV are shown in Fig. 2. An oscillatory pattern is clearly demonstrated that is present for all but the highest energy studied. There is a well-marked dip at $\theta \simeq 70°$ in the angular distributions with a location independent of incident energy. Since this dip is found at fixed angle rather than fixed momentum transfer it is not likely to be a signature of a nuclear structure. It is interesting to note that it occurs at an angle close to the energy-independent minimum at $\theta \simeq 70°-80°$ found in pion elastic scattering for ^3He and ^4He. The latter is not considered a diffraction minimum but an effect of the predominance of the (3, 3) resonance in the pion scattering off nucleons.[8] This apparent relationship between the $A(\pi^-, n)(A-1)$ and $(A-1)(\pi, \pi)(A-1)$ data is discussed below within a simple rescattering model for the (π^-, n) reaction.

In order to assess the importance of pion rescattering we compare the angular distributions at 200 MeV with predictions of the pion-core rescattering model shown in Fig. 3(a). Gibbs and Hess[8] have recently made such calculations assuming that the upper vertex is given by $\pi + (A-1)$ elastic scattering and the nuclear vertex is evaluated at its maximum, i.e., the momentum

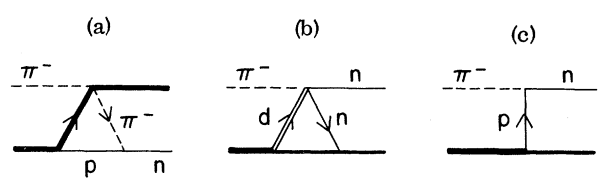

FIG. 3. Reaction diagrams for the (π^-, n) reaction illustrating (a) the pion-core rescattering model (see Refs. 4, 8), (b) the Ruderman model, Ref. 12, and (c) the nuclear pickup model (see Ref. 1).

wave function ψ at $q=0$. This means that the momentum transfer of the reaction is provided for by the scattered pion which is greatly forced off its mass shell. The results of such a calculation are shown in Figs. 1 and 2 for ^{3}He and ^{4}He. We note that the model indeed reproduces the ^{3}He data. For ^{4}He the main features are predicted by the model but the second maximum is an order of a magnitude too low and shifted in angle. We feel that the general variation with θ, i.e., also with Q, is sensitive to the momentum balance within the triangle diagram which in the approach of Gibbs is dictated by the pion off-shell behavior since the nuclear vertex is frozen at its value of $q=0$. Here, one would like to see calculations with the nuclear single-particle dynamics taken into account which might be of different importance for ^{4}He$(\pi^-,n)^3$H and ^{3}He$(\pi^-,n)^2$H since the angular variation for $\pi^- + {}^3$H scattering is much greater than for $\pi^- + {}^2$H.

It is also interesting to compare these results with a calculation based on the Ruderman model[12] [Fig. 3(b)], where the momentum balance between the triangle legs is determined by the two nuclear vertices. Fearing[5] has performed calculations with realistic wave functions which are compared with our data in Figs. 1 and 2. Like the rescattering model, this model is most successful for the cases shown, i.e., for energies around the (3,3) resonance. We note that the results of Gibbs and Fearing are quite similar for ^{3}He but differ in the region of the second maximum for ^{4}He. Fearing's calculation does not show the detailed structure of the data but agrees better in magnitude than the rescattering calculation.

The variation of the differential cross section with momentum transfer Q is illustrated in Fig. 4; Q is taken as $|\vec{p}_\pi - \vec{p}_n|$ of the (π^-,n) reaction in the laboratory so that nuclear momenta $q=Q$ are sampled by the reaction within the simple pickup model [Fig. 3(c)] without distortion. There is essentially no difference in slope between the ^{3}He and ^{4}He data considering only the forward angular range $\theta \lesssim 70°$. Typical for both nuclei is that the shape changes very little with incident energy while the magnitude does. Apart from the magnitude variation it is striking how close the data are to being just a simple function of Q with very little structure indicated in the range $Q=420-650$ MeV/c. The observations made about the E_π and Q dependences of the cross sections are consistent with distortion effects that increase the cross section with increasing E_π while the particular effects due to dispersion are more constant for different energies.

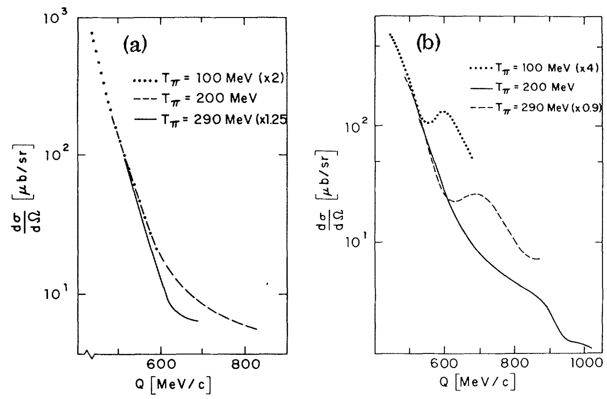

FIG. 4. The measured differential cross sections 100, 200, and 290 MeV plotted vs momentum transfer Q for (a) ^{3}He$(\pi^-,n)^2$H and (b) ^{4}He$(\pi^-,n)^3$H. The curves presented come from eyeball fits through the data points of Figs. 1 and 2 where the cross-section magnitudes have been normalized to illustrate the shape dependence.

In summary, we have presented new results on the (π^-,n) reaction. On the basis of phenomenological arguments illustrated with some model predictions, we find that the prominent features of the data manifest the importance of reaction dynamics effects. In order to clarify the roles of reaction and nuclear-structure dynamics effects one would like to have information from complementary reactions like (p,d) and (γ,p). For the $\pi+A$ interaction part of the (π,N) reaction, one would also like to see detailed distorted-wave calculations performed with optical potentials determined from elementary $\pi+N$ interactions. Such potentials have been successfully[11,12] applied to pion elastic scattering for ^{2}H, ^{3}He, and ^{4}He; when applied to the (π,N) reaction this could test, for instance, the off-shell treatment of the $\pi+N$ interaction and the different prescriptions for the πNN absorption vertex.

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*M*3 Suppression in Hartree-Fock Theory

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With a zero-range interaction a valence spin-up neutron will not interact with core spin-up neutrons and hence will not deform them; it will deform spin-down neutrons. This introduces a spin-quadrupole correlation. An ideal operator for probing this correlation is the $M3$ operator, since this operator is crudely $E2 \times M1$. The suppression of the $M3$ moment in ^{17}O due to this effect, as well as due to the spin dependence of the interaction, is considered.

It has been found by Bertozzi and others[1] that the $M3$ part of magnetic scattering in ^{17}O is strongly suppressed in the region of momentum transfer where it is expected to be strong when a single-particle picture, of a closed ^{16}O core plus a valence $d_{5/2}$ neutron, is used. A similar suppression in ^{51}V has been reported by Enomoto.[2]

It is not the intent of this work to reproduce the momentum transfer dependence of $M3$ scattering. Rather, only the zero momentum-transfer limit will be considered. The intention is to show that by keeping in mind a Hartree-Fock picture to describe a valence particle and a polarized core, the physical reason for $M3$ spin suppression becomes transparent.

The spin part of the $M3$ operator is basically a product of an $E2$ operator and an $M1$ operator. This ties in nicely with a correlation between quadrupole deformation and spin which had been noted by Zamick, Golin, and Moszkowski (ZGM).[3]

Let us recall the argument which was concerned with the quadrupole deformation of the core due to the presence of a valence nucleon, e.g., ^{16}O core and $d_{5/2}$ nucleon. A simple model of the deformed ^{16}O is one in which all orbits have the same deformation. For example, if one uses harmonic oscillator wave functions, then all orbits in the core would have the same oscillator length parameters $b_x = b_y \neq b_z$.

Such a model had indeed been considered by Mottelson.[4] By also assuming that the potential followed the density he was able to show that the quadrupole moment of the core protons is $(Z/A)Q_{\text{valence}}$. One could also express this result in terms of an effective charge

$$e = Q_{\text{core}}/Q_V = Z/A .$$

But ZGM[3] pointed out that if the interaction between the valence particle and the core is a zero-range interaction, then the above "trial solution" must be modified. Let the valence particle be a spin-up neutron. With a zero-range interaction this valence neutron cannot interact with spin-up neutrons in

