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Study of Pion-Absorption Mechanisms in ^{4}He and Other Nuclei

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The spectrum and yield of protons produced by 60-, 100-, and 200-MeV π^+ and π^- beams on targets of ^{4}He, ^{12}C, ^{62}Ni, and ^{181}Ta have been measured at 45° and 90°. A distinct high-energy component is seen in the protons from ^{4}He, which is consistent with a two-body absorption mechanism. Its cross section at 220 MeV is somewhat larger than calculated from the $\pi^+ + D$ process. Possible evidence is also seen for multinucleon absorption modes. The data on heavier nuclei are consistent with earlier experiments.

Our knowledge and understanding of mechanisms whereby pions interact and are absorbed in nuclei is still very nebulous. In order to study such processes the present measurements included the simplest of "complex nuclei," ^{4}He, as one of the targets. The pion beam of the LEP channel at LAMPF (Clinton P. Anderson Meson Physics Facility) were used to study proton spectra under the conditions described in the abstract.

The experimental techniques were similar to those described in a recent paper.[1] A liquid He target was used; it was constructed such a way that the cryostat contributed $\lesssim 6\%$ of the protons seen by the counter telescopes. Protons were detected at 45° and 90° to the beam. Both telescopes consisted of two plastic ΔE scintillators followed, at 45°, by a 20.3-cm-long NaI detector, sufficient to stop ~280-MeV protons, and, at 90°, by a 12.6-cm NaI crystal. Beam monitoring was accomplished by two independent techniques, as in Ref. 1, measurement of induced ^{11}C activity, and the integration of the photocathode current of a scintillator placed in the beam. At 60 MeV the contaminants in the beam were such as to require the use of the activation measurement exclusively; at the higher energies the two methods gave consistent results.

The proton spectra observed with a ^4He target, corrected[2] for losses in the NaI, are shown in Fig. 1. The most dramatic feature is seen on the upper right in the 45° spectrum with 220-MeV π^+. Here a clear peak is seen at a proton energy of ~220 MeV, which is about the energy expected at this angle for protons from pion absorption on

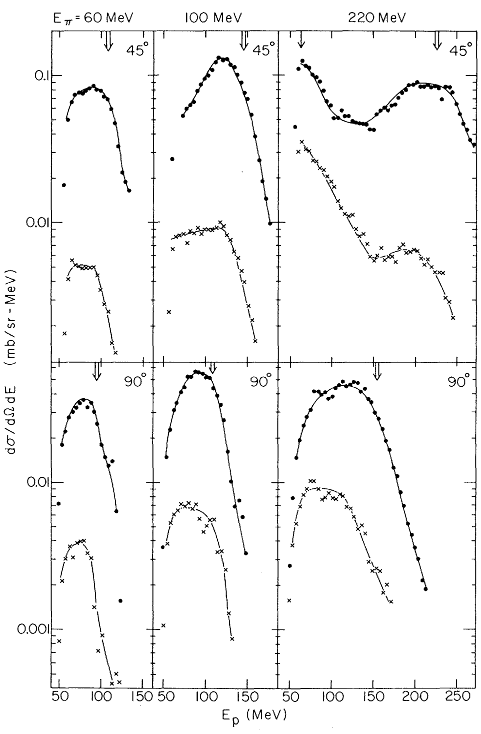

FIG. 1. Proton spectra from pions on ^4He, with an energy-dependent correction, as in Ref. 2, for losses in the NaI. The upper curve in each box is for π^+, the lower for π^-. The deviations between the points and the smooth curves are statistical. The overall uncertainty in yield is ~20%; 5% in the energy scale. The double-stemmed arrows indicate the proton energy one would get from $\pi^+ + {}^2H \to 2p$ absorption; the single arrow on the upper right indicates the proton energy from $\pi + N \to \pi + N$.

deuterium. A rising yield of lower-energy protons is also present. Similar, though less well defined, peaks are seen in the 45° spectra with 100- and with 60-MeV π^+ at proton energies of ~125 and ~100 MeV, respectively; the energies from the $\pi^+ + D$ reaction would be slightly higher. Some indication of such peaks, though of much lower intensity, is seen in the π^- spectra.

It is therefore of interest to compare the cross section for $\pi^+ + {}^4He$ to those for $\pi^+ + D^2$ and $\pi^- + {}^4He$. If one were to assume a simple model in which the absorption went through a two-step process of $\pi + N \to \Delta$ and $\Delta + N \to 2N$, adding incoherently at every stage, and ignoring differences in wave functions, then, following Ref. 1, the ratios of these cross sections would be 21:5:1. The observed values are 7.5, 1.14, and 0.35 mb/sr in the laboratory frame; the $\pi^+:\pi^-$ ratio is correctly given but the observed ^4He:^2H ratio is somewhat larger than calculated. Possibly this difference in ratios is associated with the decrease in two-nucleon separation in ^4He, compared to the more loosely bound deuteron.

At the other angles and energies protons from the entire observed energy range should be from absorptive events. The results are summarized in Table I. It is interesting to observe that the ratio between ^4He and ^2H is about constant with angle, but decreases with decreasing energy to 2.7 at 60 MeV. Perhaps the fact that the pion wavelength is becoming comparable to the two-nucleon separation implies changing coherences

TABLE I. Cross sections, in laboratory coordinates, for proton yields ($E_p \gtrsim 60$ MeV) from $\pi^+ + {}^4He$; ratio of laboratory cross sections between π^+ and π^- + He; ratio of π^+ cross sections on ^4He and ^2H (from Ref. 3); ratio of π^+ cross sections on ^{12}C and ^4He. Uncertainties are about 20%.

E_π	θ_{lab}	$\frac{d\sigma}{d\Omega}$ (mb/sr)	$\frac{d\sigma(\pi^+)}{d\sigma(\pi^-)}$	$\frac{d\sigma(^4He)}{d\sigma(^2H)}$	$\frac{d\sigma(^{12}C)}{d\sigma(^4He)}$
220	45°	7.5 [a]	21	6.6	1.4
		6.1 [a]	3.6		3.8
	90°	3.9	6	8.7	2.7
100	45°	8.4	12	4.7	2.7
	90°	3.0	8	4.3	3.4
60	45°	4.4	22	2.7	3.0
	90°	1.6	13	2.7	3.2

[a]The upper line represents the high-energy proton component, the lower the low-energy protons, as shown in Fig. 1. The uncertainties in this division are somewhat larger, ~30%.

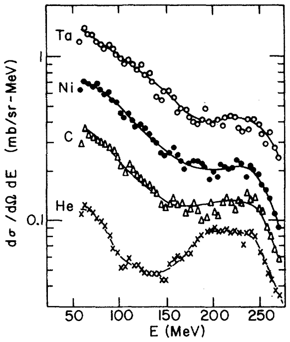

FIG. 2. Proton spectra at 45° from 220-MeV π^+ on various targets; errors are the same as in Fig. 1.

in the process. The π^+/π^- ratios at 90° are much less than 21, and here the protons must come from absorption. This ratio seems to indicate that mechanisms other than simple two-nucleon absorption must play a role.

The lower-energy protons seen in the 45° spectrum with 220-MeV π^+ are of approximately the correct energy to be produced by either quasifree π-N scattering or, possibly, by $\pi + {}^4\text{He} \rightarrow 4N$ four-body absorption. The proton energy from three-body absorption would peak at about the energy of the minimum in the 220-MeV, 45° π^+ spectrum. The measured ratio of proton yields with π^+ to π^- is 3.6; the calculated ratio from the quasifree process, using the experimental π-N cross sections,[4] is 7.6; and that from four-nucleon absorption is 3. Protons from quasifree scattering are expected to be too low in energy to be seen at the lower pion energies.

The spectra from heavier targets at 45° for 220 MeV are shown in Fig. 2. The A dependence of the high-energy component of the proton spectrum is clearly different from that of the low-energy part. Specifically, there is a pronounced difference in the shapes of the spectra in Fig. 2 between ^{4}He and ^{12}C, as the high-energy proton peak increases by only a factory of ~1.4, while the lower-energy proton yield increases by a much larger factor. It is difficult to understand this unless one were to assume that the larger aggregate of nucleons in ^{12}C caused a qualitative change in the relative importance of competing absorption mechanism. ^{12}C is too light a nucleus for the high-energy protons to be substantially depleted, in comparison to ^{4}He, by multiple scattering. The ratio of proton yields between ^{12}C and ^{4}He, for all cases other than the one where the kinematics define the two-nucleon absorption mode, is about 3, as is seen in Table I; this is the ratio of the number of nucleons in the targets. The interpretation of the other features of the data seems less clearcut, but they are consistent with earlier results,[1] including the approximate 3:1 $\pi^+:\pi^-$ ratio.

In conclusion, the 45° data seem to indicate some evidence, especially in ^{4}He, for pion absorption on two nucleons through the Δ; the probability for this process seems to be a function of pion wavelength and of two-nucleon separations. Evidence for more complicated mechanisms is seen in ^{4}He in the 90° data and the ^{12}C/^{4}He ratio. At 90° the $\pi^+:\pi^-$ ratio is not consistent with two-nucleon absorption through the Δ, yet the Δ must be dominant in this energy range. If, for instance, the pion's total energy were shared among all four nucleons a significant fraction of the time, this might account for the observed results. The clean high-energy peak in the 45°, 220-MeV π^+ spectrum from He and the observation of the expected 21:1 $\pi^+:\pi^-$ ratio suggests that rescattering, charge-exchange, or other final-state effects are not very important. The indication against a three-body absorption mode is the minimum in the 45°, 220-MeV data. Multinucleon modes would compete more effectively against two-nucleon absorption as the total number of nucleons was increased; this would tend to be in the right direction to explain the ^{12}C/^{4}He ratio. Experiments on π + He in which all charged reaction products are detected, with bubble chambers or streamer chambers, could be very valuable in testing the above conjectures regarding more complicated modes. If one could develop a better qualitative theoretical understanding of pion absorption on He it would undoubtedly shed light on the mechanism in heavier nuclei.

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Anomalous Optical-Model Potential for Sub-Coulomb Protons for $89 < A < 130$

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The (p,n) cross sections for fourteen nuclei from $A = 89$ to $A = 130$ were measured from about 2.5 to 5.8 MeV in order to obtain total reaction cross sections. These cross sections disagree with optical-model predictions in that the predicted $3p$ resonance is missing near $A = 105$ and the peak near $A = 90$ is replaced by a valley. The data can be described by introducing an anomalous A dependence into the depth of the absorptive potential.

We present arguments with supporting data that certain experiments should be exploited to learn more about the optical-model potential (OMP) for protons. The experiments are to measure (p,n) cross sections for protons incident below the Coulomb barrier. Data from initial experiments of this type show that the OMP for $89<A<130$ has an anomalous behavior which merits more study.

A strength function $\langle\gamma_{lJ}^2\rangle/\langle D_{lJ}\rangle$ is the ratio of the reduced particle width to level spacing averaged over the closely spaced compound-nuclear states of spin J formed by l-wave particles. Our contribution deals with protons, but first we comment on the familar neutron strength functions.[1] Neutron single-particle states give rise to giant "size" resonances that are observed in plots of the strength function versus mass number for s waves near $A = 55$ and 160 and for p waves near $A = 95$. One can describe the resonances approximately by the OMP by "tuning" the volume of the real well to fit the resonant masses and by adjusting the imaginary part and the diffuseness to give the height and width of each resonance. As for the $A = 160$ resonance, the $3p$ resonance near $= 95$ may be split. Although a splitting was attributed to vibrational motions,[2] the early-found strength-function data have been questioned,[1] and recent precision total-cross-section measurements suggest that the resonance is smooth and without structure.[3]

We would like to emphasize the complementary information on the nucleon OMP to be obtained from protons incident below the Coulomb barrier. There is a dearth of precision sub-Coulomb data, perhaps because workers recognize the barrier's problems more than its benefits. There are problems. Resonances are difficult to resolve because the energies needed for barrier penetration are much larger than the level spacings. Even so, Bilpuch *et al.*[4] obtained strength functions by resolving resonances for $A<65$. For higher masses for which individual levels cannot be resolved, useful data can be obtained if the average energies and cross sections are measured accurately and the Coulomb penetrabilities are divided out to reveal the nuclear effects.

The Coulomb barrier has two beneficial effects. The first, which seems not to be fully appreciated, is that the barrier, by virtue of its height relative to the spreading width from the absorptive potential, can quasibind a single-particle