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How Many Nucleons are Involved in Pion Absorption in Nuclei?

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The proton yields from the interaction of pions on nuclear targets with $12 \leq A \leq 181$ were measured in the region of the $\Delta(3,3)$ resonance. The shift in proton energies with angle is analyzed in terms of the average number of nucleons that have participated in absorbing the pion's momentum and total energy. The effective number of interacting nucleons, for both π^+ and π^- incident, is found to be ~ 3 for ^{12}C and increasing to ~ 5.5 for ^{181}Ta. These effective numbers of nucleons are also consistent with the ratio of proton yields from π^+- and π^--induced reactions.

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Systematic investigations of the general features of the interaction of pions with nuclei in the energy region of the $\Delta(3,3)$ resonance have only recently been undertaken.[1] One important aspect of this interaction is pion absorption, in which the incident pion is absorbed and no pions are present in the final state. Measurements of the absorption cross section σ_{abs} in this energy region have recently been performed on many nuclei.[2] They indicate that σ_{abs} scales as $\sim A^{0.75}$ with nuclear mass and increasingly dominates the reaction cross section in heavier nuclei ($\sigma_{react} \sim A^{0.58}$).

There have also been some partial measurements of inclusive proton spectra from pions incident on a variety of nuclear targets.[3,4] In pion-induced reactions in the Δ region, high-energy ($E_p^{lab} > 60$ MeV for $\theta^{lab} > 45°$) protons can only arise from absorption, where the pion rest mass is available as kinetic energy. These protons constitute the best evidence we have on the absorption mechanism, if we accept the relatively long mean free path for ~100-MeV nucleons in nuclei that is suggested by most experiments (4–9 fm),[1] rather than the very short value built into cascade calculations.[5] An important result of these measurements is that a prominent peak corresponding to the kinematics of the quasifree two-nucleon absorption (as observed in deuterium) is only evident in the lightest nuclei (e.g., ^{4}He). In heavier nuclei ($A \geq 12$) it is a minor feature of the proton energy spectrum and is barely evident in very heavy nuclei such as Ta. The $A^{0.75}$ dependence of σ_{abs} and the missing two-nucleon absorption peak both seem to suggest qualitatively that pion absorption in nuclei proceeds through a mechanism more complex than the simple two-nucleon process.

In this Letter, we report an analysis of a rather complete set of measurements of the inclusive $(\pi^\pm, p)$ reaction on ^{12}C, ^{27}Al, ^{58}Ni, and ^{181}Ta at $T_\pi = 100$, 160, and 220 MeV. The experiment was performed at the LEP channel of the Clinton P. Anderson Meson Physics Facility at Los Alamos with an apparatus similar to that reported in Ref. 3. Protons were detected in telescopes consisting of two thin plastic scintillators followed by a thick NaI(Tl) scintillator for total-energy measurement. The thin counters defined the acceptance solid angle and provided ΔE measurements for particle identification. The proton energy spectra were corrected for target energy loss, dead-time loss, and NaI detector response. Angular distributions between 30° and 150° were obtained for proton kinetic energies from ~40 to ~250 MeV (laboratory energies and angles).

Typical proton spectral are shown in Fig. 1. The spectra can generally be characterized as monotonically decreasing with increasing proton energy and containing little or no further structure. The kinematics of these spectra can be displayed on a rapidity plot, where contours of constant invariant cross section $(c/p)d^2\sigma/d\Omega\, dE$ are plotted in the plane defined by the coordinates $p_\perp$ (component of proton momentum perpendicular to the beam direction) and the rapidity $y \equiv \tanh^{-1}(\beta_\parallel)$ (here $\beta_\parallel = v_\parallel/c$, and $v_\parallel = p_\parallel c^2/E$ is the proton velocity parallel to the beam direction). Such a plot is shown in Fig. 2 for protons from $\pi^-(T_\pi = 220$ MeV) incident on a Ta target. The curves correspond to isotropic emission of protons in a Lorentz frame moving at a laboratory velocity of $0.072c$ ($y \approx \beta$ for $\beta \ll 1$) along the beam direction. The line $y = 0.072$ is a symmetry axis representing a preferred coordinate system in which the nucleon emission process is most nearly isotropic. All the experimental data show such an approximate symmetry axis in the rapidity plots. The only deviation from isotropy is a tendency for a shallow depression in the contours (slightly lower energies) at ~90° in this preferred frame.

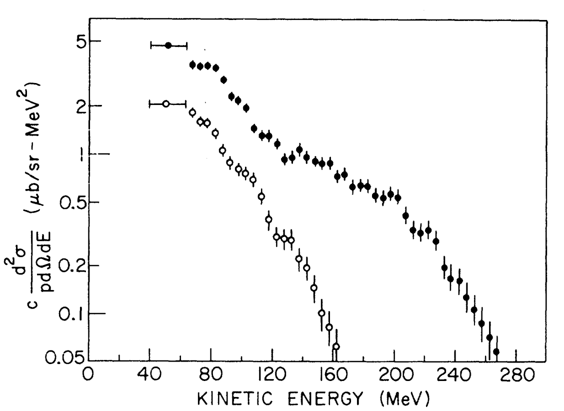

FIG. 1. Proton spectra from 160-MeV π^+ on Ni at 30° (solid points) and 150° (open circles). The data are binned at 5-MeV intervals, except for the lowest-energy point, where the bin size is shown in the figure. Only statistical errors are shown.

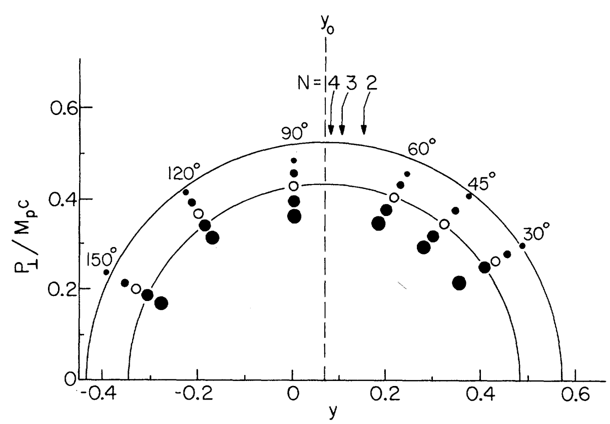

FIG. 2. Contours of the invariant proton cross section in the plane of rapidity $[y \equiv \tanh^{-1}(\beta_\parallel)]$ and $p_\perp$, for 220-MeV π^- on ^{181}Ta. The points of a given size represent a constant invariant cross section; the largest points are 1.05 μb/sr MeV^2), the smaller ones are 0.8, 0.6 (shown as open circles, to guide the eye), 0.4, and 0.2 times this value in order of decreasing point size. The rapidity (velocity) of the frame in which the cross section is most nearly isotropic (y_0) is indicated by a dashed line; the contours corresponding to isotropic distributions of protons in this frame with T_p = 82 and 122 MeV are shown as solid lines. The values of rapidity corresponding to the Lorentz frames where the pion is absorbed on 2, 3, and 4 nucleons is indicated by arrows. The laboratory angles of observation corresponding to the different groups of points are also shown.

We have extracted the values of rapidity y_0 which represent such symmetry axes for our experimental data by two independent procedures: (a) least-squares fit to isotropic curves, and (b) by calculating the mean value of y for several values of $p_\perp$ on a given contour and then averaging.

The two procedures give very consistent results (typically better than 20% agreement) for the determination of y_0. For a given target and pion beam, y_0 is found to be constant over the observed range of proton energies. The values of y_0 for incident π^+ are close to, but generally slightly greater than, those for incident π^- at the same beam energy and for the same target. In addition, for a given incident pion energy, y_0 decreases systematically with increasing A.

In one assumes that y_0 represents the velocity of the center of mass of the pion plus the nucleons which absorb the energy and momentum of the pion, one may write

$$y_0 = \tanh^{-1} \beta_{\text{c.m.}} = \tanh^{-1}[p_\pi c/(E + M_{\text{abs}} c^2)]. \quad (1)$$

Here p_π and E_π are the momentum and total energy of the incident pion and M_{abs} is the average mass of the absorbing nuclear matter. If we let $M_{\text{abs}} = NM$, where M is the nucleon mass and N the number of nucleons, we can calculate N for each value of y_0. The result is that N varies significantly with A (the target mass), but no significant variation is observed as a function of pion energy (though the uncertainties are large for the lower-energy pions). The values of N, averaged over incident pion energy, are plotted as a function of A for π^+ and π^- incident on C, Al, Ni, and Ta in Fig. 3(c).

Another interesting result can be obtained by comparing the proton yield for incident π^+ with that for π^-. The total proton yield (for proton kinetic energy >40 MeV) can be calculated by integrating the angular distributions; the estimated overall errors are ~20%. A typical example is shown in Fig. 3(a), where the proton yields ($\sigma_\pi{}^+$) for $T = 220$ MeV are plotted. The ratio $R = \sigma_\pi{}^+/\sigma_\pi{}^-$ can be obtained for each target and incident pion energy. Since no systematic trend of R with T_π is found, the values of R averaged over the three incident pion energies $\bar{R}$ is plotted in Fig. 3(b). Absorption proceeding through the Δ on two nucleons would lead to eleven times as many protons with π^+ as with π^-.[4] The observed ratios are much smaller and are consistent with absorption proceeding through the N nucleons deduced from the rapidity analysis and shown in

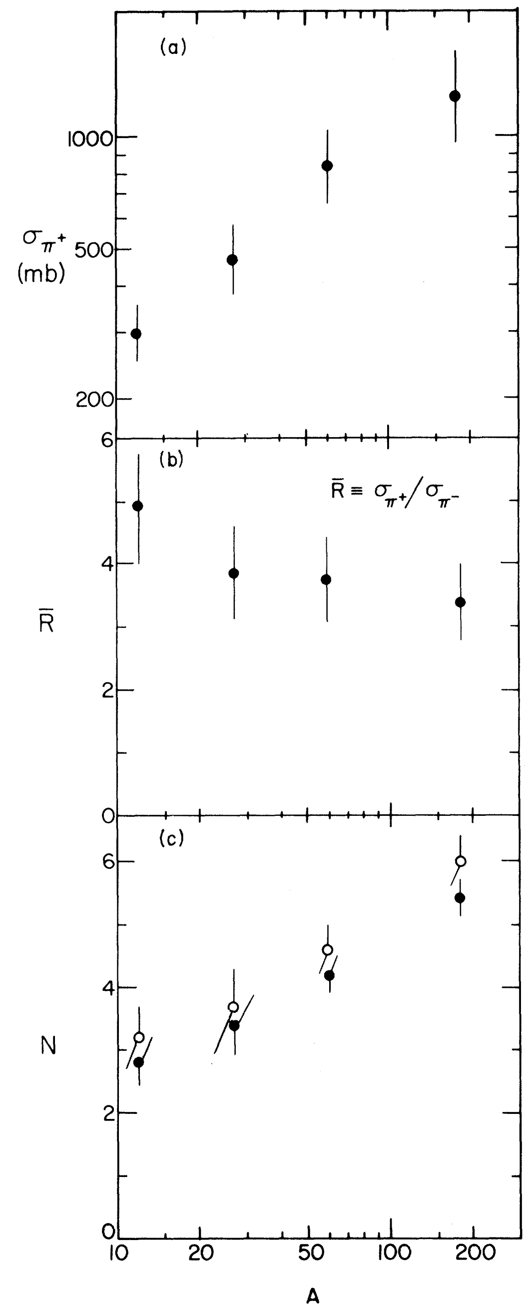

FIG. 3. Three properties of the proton spectra are shown as a function of the atomic weight. On top, (a) the angle integrated proton cross section is shown for 220-MeV π^+; in the middle, (b) the ratio of angle integrated proton yields seen with π^+ to those seen with π^-, averaged over the three incident pion energies is plotted; at the bottom, (c) shows the values of the average number of nucleons participating in the process, as deduced from the rapidity shifts for π^+ (solid circles) and π^- (open circles), both averaged for the three incident energies.

Fig. 3(c).

If one estimates the mean proton energies by dividing the total available energy E_π by the values of N in Fig. 3(c), the results are consistent with the observed proton energy distributions. It is difficult to make this statement more quantitative, because of the uncertainties involved in estimating the shape of the proton spectrum in the unobserved, $T_p < 40$ MeV, region. The mean proton energy in the observed region is ~15 MeV higher with π^+ than with π^-, although the shapes of the spectra are similar. The number of *observed* protons per absorption is given by dividing σ_π by the absorption cross section of Ref. 2. The numbers are smaller than those implied by the N values in Fig. 3(c) $[\sigma_{\pi^+}/\sigma_{abs} < (Z/A)N+1]$ by a factor of ~0.7 for ^{12}C and ~0.3 for ^{181}Ta; presumably this is a measure of the number of nucleons below 40 MeV, as well as the nucleons which never leave the nucleus.

The present analysis seems to indicate that the nucleons emitted subsequent to pion absorption on nuclei are reasonably well described by a model in which they are approximately isotropic in a center-of-mass frame corresponding to absorption by an average nuclear mass of 3–6 amu. This average mass, which might be interpreted as the average number of nucleons absorbing the energy and momentum of the pion, increases systematically with the mass of the absorbing nucleus.

If pion absorption is initiated by the quasifree, two-nucleon $\pi + 2N \rightarrow \Delta + N \rightarrow 2N$ mechanism, this is not evident in the observed distribution of nucleons. The high-energy proton yield at forward angles is very small and the observed ratios, $R \approx 3-4$, are far from the value of 11 expected through the two-nucleon mechanism. The large value of $R = 11$ for the $2N$ process implies that a combination of this mechanism with another absorption mechanism (with smaller R) would yield very different angular distributions (and rapidity contours) for protons from π^+ and π^- absorption. In fact, the differences in y_0 between π^+- and π^--induced protons are very small and barely significant, and the ratio of the energy-integrated proton yields as a function of angle is constant to better than 15%. [The inclusive inelastic pion cross section is large but we see no correspondingly large, low-energy proton yield at forward angles. The proton yield at 30° for $T_\pi = 220$ MeV from the quasifree process would be centered at ~90 MeV, with almost twice the yield observed between 40 and 140 MeV; by 60° the proton energy would be ~30 MeV, outside the range measured. We have not attempted any correction and included *all* observed protons in the present analysis. The effect of protons from quasifree scattering must be to give apparently *larger* rapidity shifts to the proton distributions, and if one could subtract them, the N values would be even larger than obtained in the present analysis.]

The experimental data suggest that perhaps a mechanism different from two-nucleon absorption is indicated. Perhaps when the Δ is formed in the nuclear medium, it prefers to decay via "soft"-pion exchanges with several nearby nucleons rather than a "hard"-pion exchange with one other nucleon. If the dominant absorption mode requires many nucleons to surround the Δ, this may provide an explanation of why σ_{abs} becomes an increasingly larger fraction of the reaction cross section in heavier nuclei as the number of available nucleons increases. In any case, it appears that new theoretical calculations of pion absorption on nuclei are desirable to determine whether, in fact, our current understanding of this process is as inadequate as the experimental data seem to indicate.

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