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Mechanism of pion absorption in complex nuclei

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We analyze, using basic geometrical arguments, the A dependence of the total pion absorption cross section, the effective number of nucleons sharing the pion momentum and energy, and the proton yields from π^+ and π^- induced reactions. The results are consistent with the pion penetrating some distance through the nuclear volume and annihilating on a pair of nucleons.

[NUCLEAR REACTIONS transport theory applied to true pion absorption in nuclei.]

An analysis of (π, p) inclusive spectra for pion energies between 100 and 220 MeV by McKeown *et al.*[1] have shown that the effective number of nucleons, N, sharing the momentum and energy of the annihilated pion increases from 3 to 5.5 as A increases from 12 to 181. They suggested that this was evidence against two-nucleon absorption as the dominant reaction mechanism. How much of N pertains to the absorption mechanism and how much of N comes from multistep processes involving rescattering and final state interactions depends critically upon the mean free paths of both the pion and proton. A related question is whether the pion absorption is surface dominated or spread through the nuclear volume. The purpose of this paper is to present the alternative to the McKeown interpretation. Specifically, we will show that a simple two-nucleon volume absorption model with rescattering can reproduce the systematics of the pion absorption data.

Navon *et al.*[2] have observed that the pion true absorption cross section scales as A^x with $x = 0.72$. We can estimate the A dependence of the pion absorption cross section using a semiclassical model of pion transport in the nuclear volume, which is an extension of the model used in Ref. 3. We assume a Fermi two-parameter nuclear density distribution of the form

$$\rho(r) = \rho_0 \left[1 + \exp \frac{r - r_0 A^{1/3}}{c} \right]^{-1} \tag{1}$$

with $r_0 = 1.2$ and $c = 0.65$ fm. The probability for absorption of the pion is assumed to be proportional to either $\rho(r)$ or $\rho^2(r)$. Consider first the $\rho(r)$ dependence with the propagation of a pion incident on a nucleus at an impact parameter b. The probability that it reaches the point G in the nucleus (see Fig. 1), ignoring large angle pion scattering, is

$$P = \exp\left\{ - \int_{-(R^2-b^2)^{1/2}}^{x} dx' \rho[(b^2 + x'^2)^{1/2}] \sigma \right\}. \tag{2}$$

The probability that it is absorbed at that point is then $P\sigma\rho(x)dx$. Here σ is the "cross section" for absorption of the pion in nuclear matter. Integrating this along the line AB and over all impact parameters, we get the total pion absorption cross section:

$$\sigma_{\rm abs}^{\rm total} = 2\pi \int_0^R b\, db \int_{-(R^2-b^2)^{1/2}}^{(R^2-b^2)^{1/2}} dx\, \rho(x^2 + b^2)^{1/2} \sigma \, \exp\left[- \int_{(R^2-b^2)^{1/2}}^{x} dx' \rho(x'^2 + b^2)^{1/2} \sigma \right]. \tag{3}$$

This integral has been evaluated numerically to obtain the total pion absorption cross section. The calculated cross section varies with A approximately as A^x, the value of x being a function of the assumed value of σ. The value of σ is chosen so as to reproduce the measured magnitude of the absorption for medium mass nuclei ($\sigma = 18$ mb). The calculated absorption cross section is plotted in Fig. 2 along with the data.[2] We see that the A dependence of the total absorption cross section is well reproduced by the calculation. Using a ρ^2 dependence for the probability of absorption leads to nearly the same result. Basically, this simple model gives a parameter free relationship between the magnitude of the absorption cross section and its A dependence, and this relationship is insensitive to the ρ dependence of the absorption process. This calculation gives a mean free path for pion absorption of $1/\sigma\rho_0 = 3F$ corresponding to a volume re-

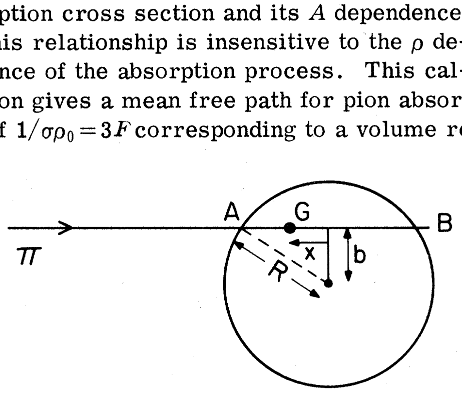

FIG. 1. The geometrical diagram for Eqs. (2) and (3).

action. This is a factor of 3 larger than the mean free path calculated by Hüfner and Thies.[4]

In the calculation we have ignored the quasifree backscattering of the pion from the nucleus. The effect of this scattering is to reduce the total pion absorption cross section, since the scattered pion is likely to exit the nucleus, and the value of $\sigma = 18$ mb is likely to be an underestimate. By examining the large angle total differential scattering cross section of Ref. 2, which is 60 mb/sr for ^{209}Bi compared to the geometric cross section $\pi R^2 = 1700$ mb, we estimate that the backscattering of the pion removes only 10 to 20% of the flux. Compensating for this effect by increasing $\sigma_{\rm abs}$ in Eq. (3) and Fig. 2 by 20% results in a 6% decrease in x from 0.70 to 0.66, and an increase in σ to 23 mb. A more exact treatment of this backscattering is given by Schneider and Koltun,[5] but the correction appears small enough to leave intact our conclusion of volume absorption.

We can use this concept of a volume absorption to explain the data of McKeown.[1] Considering the interactions of pions with nuclei at $E = 160$ MeV, we make the following assumptions:

(i) The energy transfer due to pion scattering from nucleons before absorption is not significant.

(ii) π^+ or π^- absorption takes place on an np pair, creating two high energy protons or neutrons, respectively, moving in opposite directions. Here we have ignored the absorption of the pion on a pp or a nn pair for π^- and π^+, respectively. The experimentally obtained ratio of stopped π^- absorption on an np pair vs a pp pair varies between 3 and 10 depending on the author.[6] In addition, in both the (π^-, nn) (Ref. 7) and (π^+, pp) (Ref. 8) reactions, the population of $\Delta T = 0$ transitions is much stronger than the population of $\Delta T = 1$ transitions. From isospin symmetry, this is indicative of the importance of the pion absorption on an np pair relative to that on a pp or nn pair.

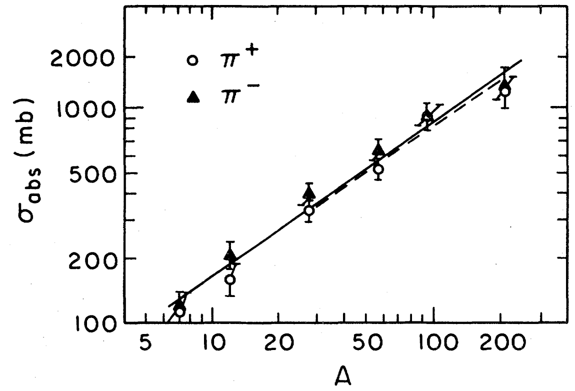

FIG. 2. Pion total absorption cross section for π^+ and π^- at 125 MeV from Ref. 2. The solid line is a least squares fit to the data. The dashed line is calculation using Eq. (3). (See text.)

(iii) The two nucleons, which absorb the pion, traverse the nucleus, knocking out the nucleons with which they scatter. The combined distance traversed by these two primary nucleons in the nucleus is on the average $4R/3$, being the average length of a chord through a sphere of radius R.

(iv) We ignore the further collisions of the secondary nucleons.

(v) We ignore surface effects. For example if the reaction takes place on the surface of the nucleus, one of the nucleons will escape without passing through the nucleus. We do not treat the two nucleons separately, but only their average behavior. Our justification for this is that the A dependence of the absorption cross section suggests a volume absorption. Furthermore, a two nucleon mechanism with an approximate ρ^2 dependence will disfavor the surface region.

The number of nucleons N which have shared the momentum and energy of the pion, in the limit that $N-2$ is small, is then given by

$$N = 2 + \tfrac{4}{3} r_0 A^{1/3} \sigma_{\rm av} \cdot \rho \, ,$$

where

$$\begin{aligned} \sigma_{\rm av} &= (Z\sigma_{pp} + N\sigma_{pn})/A \text{ for } \pi^+ \\ &= (Z\sigma_{np} + N\sigma_{nn})/A \text{ for } \pi^- \end{aligned} \tag{4}$$

Here, σ_{pp} and σ_{pn} are the pp and pn integrated cross sections that lead to knockout of the scattered particle (its energy >30 MeV). In the energy region of interest ($E = 80-200$ MeV), σ_{pp} and σ_{pn} are on the average equal to 25 and 18 mb, respectively. This corresponds to a mean free path of 2.5 to 3.5 fm for scattering a nucleon. Further confirmation of the use of free NN data for estimating the mean free path of nucleons comes from DiGiacomo *et al.*,[9] who have correctly predicted proton-nucleus total reaction cross sections from 25 MeV to 1 GeV using a Glauber model. However, Schiffer[10] points out that a wide variety of data suggests a mean free path larger than 6 fm.

In our model, the number of protons emitted is

$$\text{for } \pi^+\text{:} \quad N^p_{\pi^+} = 2 + \tfrac{4}{3} r_0 A^{1/3} \frac{Z}{A} \rho \sigma_{pp} \, ,$$

$$\text{for } \pi^-\text{:} \quad N^p_{\pi^-} = \tfrac{4}{3} r_0 A^{1/3} \frac{Z}{A} \rho \sigma_{np} \, .$$

McKeown *et al.*[1] have data on the proton yield for proton kinetic energy >40 MeV ($\sigma^p_{\pi^+}$ or $\sigma^p_{\pi^-}$). The ratio R of these proton yields is given as

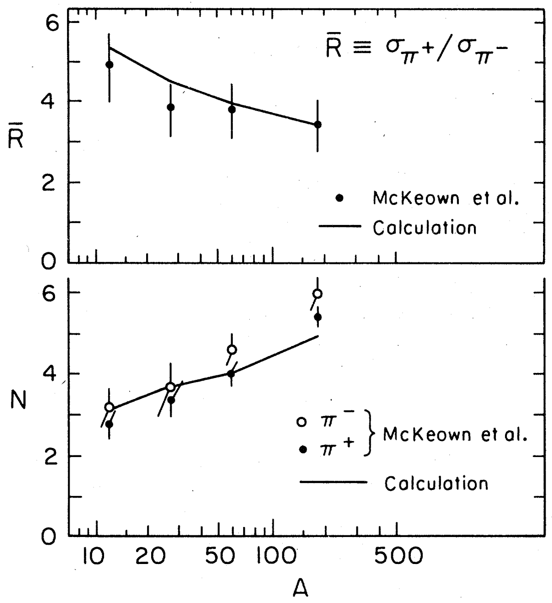

FIG. 3. (Top) Ratio of observed proton yields for π^+ and π^-. (Bottom) Effective number of nucleons involved in absorption as a function of atomic number. The circles are data from McKeown *et al.* The lines are the values from Eqs. (4) and (5).

$$R = \frac{\sigma^p_{\pi^+}}{\sigma^p_{\pi^-}} = \frac{\sigma^{\text{abs}}_{\pi^+}}{\sigma^{\text{abs}}_{\pi^-}}\,\frac{N^p_{\pi^+}}{N^p_{\pi^-}} = \frac{2 + \frac{4}{3} r_0 A^{1/3} \rho \frac{Z}{A} \sigma_{pp}}{\frac{4}{3} r_0 A^{1/3} \rho \frac{Z}{A} \sigma_{np}}\,, \tag{5}$$

where we have assumed that σ^{abs} is the same for π^+ and π^-. Equations (4) and (5) are plotted in Fig. 3 as functions of A; the experimental values[1] for N and R are also shown. These simple equations reproduce the trends of the data fairly well.

Equation (4) gives the same value of N for both π^+ and π^- in self-conjugate nuclei and a value of N which is 0.18 larger for π^- than π^+ in ^{181}Ta. The experiment suggests (see Fig. 3) that N_{π^-} is larger than N_{π^+} for all nuclei. This can be explained, using our model, by noting that the experiment detects only protons. In π^- absorption protons are produced only through secondary collisions, thereby weighting more heavily the events with larger N for π^- as compared to π^+. Alternatively, if N were interpreted as the number of nucleons in the absorption mechanism it would almost definitely be larger for π^+ than π^- because of the neutron excess.

We are proceeding with a Monte Carlo calculation to check some of our approximations and to try to reproduce the proton energy spectra. More sophisticated calculations and more data are needed to determine the mechanism of pion absorption. However, the data appear consistent with a two-nucleon volume absorption mechanism followed by final state interactions. The concept of volume absorption can be pursued experimentally. At lower pion energy the true absorption cross section is smaller. In our model, a factor of 2 decrease in the absorption cross section for $A = 50$ results in an increase in the A^x dependence from $x = 0.7$ to 0.85 for a $\rho(r)$ type absorption and from $x = 0.7$ to 0.90 for a $\rho^2(r)$ type absorption.

The pion absorption data in the $\Delta(3.3)$ resonance region is inconsistent with a dominant two-nucleon absorption mechanism on the surface of the nucleus. Either the initial absorption mechanism "usually" involves more than two nucleons or else the pion penetrates the nuclear volume before annihilating. The explanation of this data should have a profound impact on our understanding of pion nucleus interactions.

Note added in Proof. Nakai *et al.*[11] have published total absorption cross sections at lower energies, where $\sigma_{\text{abs}}(A = 50)$ for π^+ is half as large as σ_{abs} in the (3, 3) resonance region. They measured an approximate A^x dependence of $x = 0.87$ which agrees with our model prediction. However, our model has ignored Coulomb corrections which become important at low energy.

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