LA-UR-87-3206

CONF-8708102--3

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

LA-UR--87-3206

DE88 000488

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SUBMITTED TO Proceedings of the International Workshop on Pion Nucleus Physics, Los Alamos National Laboratory, August 17-21, 1987

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MONTE CARLO ANALYSIS OF PION ABSORPTION

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ABSTRACT

Recent pion absorption data with the observation of two protons in coincidence have been interpreted to yield a small fraction of absorption on two-nucleon pairs compared with absorption on multinucleon clusters. The present work demonstrates that a considerable broadening of the two-nucleon correlation function, and concurrent reduction of observed events, arises from Fermi motion, nucleon binding, pion scattering before absorption and nucleon scattering after absorption. The width of the calculated pp angular correlation distribution agrees well with that observed experimentally. After correction for these effects in the assumed two-body absorption process we find that there is a residual mechanism which must account for ~30 % of the true-absorption events.

I. Introduction

The mechanism of pion absorption in nuclei has been studied for several years. Recent interest has centered around the number of nucleons involved in the absorption process.[1] To study this issue two experiments have recently been performed[2,3] in the resonance region in which two protons are observed in coincidence following pion absorption. A distinct peak is seen in the correlation function at the angle between the two protons corresponding to absorption on a free-nucleon pair ("free kinematic value"). By integrating the measured cross sections over all angles, a total "two-nucleon" absorption cross section is obtained. The authors of reference 1 conclude that only about 20% of pion absorptions occur on a pair of nucleons, a surprisingly small number.

In extracting this probability, however, they must decide how much of the angular distribution around the free kinematic value should be included as part of the two-nucleon, as distinct from a multi-nucleon, absorption mechanism. Since the shape of the curve is not Gaussian, but has "wings", they decided to remove a "background" from the curve. The subtraction is made from $d\sigma/d\Omega$ and assumes symmetry about the free kinematics point. The solid-angle factor makes the background correction substantial (factors of 2 to 5) and not just a few percent, as it might appear on their plot.

The "quasideuteron model" assumes that pions annihilate on pn pairs having quantum numbers of the deuteron, i.e., I=0, L=0, and S=1. It was pointed out by Ritchie *et al.*[4], that, if one takes this model seriously then π-absorption data on ^{12}C may be understood qualitatively (in PWIA) without the need of a multinucleon absorption mechanism. The deuteron may be in a state with angular momentum either zero or two relative to the ^{10}B core. The $\ell = 0$ component gives a peak similar to the central peak observed, while the $\ell = 2$ component gives a broader distribution resembling the wings and having a minimum at the two-body kinematic point. The calculation is difficult to extend to heavier nuclei because the spectroscopic factors for $\ell = 0$ and $\ell = 2$ (or higher) deuterons are not known. Also the inelastic pion and nucleon scattering, not treated rigorously in Ref. 4, become more important as A increases.

The present talk takes a different approach, that of an intranuclear cascade (INC) model. In its present form the technique does not give detailed attention to the shell structure; it is more appropriate for heavier nuclei. In this article we analyze recent data on ^{58}Ni.[3] In contrast to the work of ref. 4 the INC method has the advantage of including "distortions" due to the inelastic scattering of pions and the scattering of the outgoing nucleons.

We should note that there are a large number of techniques used to calculate nuclear reactions. The methods vary according to the degree of "exclusivity" involved. For elastic scattering, or transitions leading to a definite final state, a totally quantum-mechanical description must be used since phase information is very important. For reactions in which there are thousands of final states it is assumed that the phase information is largely lost and semi-classical calculations may represent the process well. Table I gives the spectrum of calculations on the left, matched with processes on the right. Of course unitarity gives us relations among these quantities and there is the famous "end-run", which is to use the optical theorem on the elastic amplitude on one end to obtain the total cross section on the other.

II. Calculational Technique

We first sketch the intranuclear cascade model, which is more fully described elsewhere[5].

We assume all nucleons move classically in a Woods-Saxon potential. Each particle is chosen to have a definite total energy, depending on its shell. For the case treated here, the shells and their binding energies are shown in Table II. The nucleons are initially cast in a uniform spherical distribution with the

Quantum Mechanics	
Optical model, DWIA, coupled channels	Elastic scattering, inelastic scatt. to a single state, pion absorption to a given final state
Sum of DWIA or Fermi gas model	Reactions to several final states
DWIA to single density	Giant resonances, single particle states
Sum of DWIAs	Reaction to final states in several nuclei
INC+Pauli Blocking+three body absorption	Inclusive absorption on 3 nucleons
INC+Pauli Blocking	Inclusive absorption on two nucleons
Intra-Nuclear Cascade	Total cross section
Classical Mechanics	

Table I. Spectrum of calculational techniques matched to the reaction types.

Shell	Number of Nucleons in Shell	ℓ	Binding Energy (MeV)
1s	4	0	40
1p	12	1	30
1d	20	2	25
2s	4	0	10
1f	18	3	10

Table II. Standard binding energies used in the present calculation.

magnitude of their momenta dictated by their binding energies and their potential energy within the well. The initial directions of these momenta are chosen isotropically. In one version the nucleons in a shell with angular momentum ℓ are selected so as to have the angular momenta in the range (ℓ, ℓ+1). This procedure simulates the quantum mechanical shell structrure. The angular momentum of each nucleon is conserved by its equation of motion in the absence of collisions with other nucleons. While the model nucleus has, on average, zero angular momentum, it is made up of nucleons with finite ℓ, as in nature. There will, of course, also be a distribution of pairs with angular momenta, usually non-zero, given by the classical rules outlined above, so that the effect of ref. 4 is included, but in a classical manner. Neutrons and protons are distinguished only in a statistical sense.

The mean field described in the previous paragraph represents the average of the long-range part of the nucleon-nucleon interaction. The short-range part of the force is represented by nucleon-nucleon collisions, which occur if the nucleons approach each other within a distance corresponding to a cross section of σ_{NN}, a parameter in the model. The nucleons propagate relativistically and the N-N collisions are isotropic in the NN center-of-mass frame.

The pion, treated with relativistic kinematics, collides with nucleons with a probability governed by the pion-nucleon total cross section at the appropriate laboratory energy. The angular distribution of the scattering is taken from a representation of experimental data.[6]

No absorption is allowed on the first pion-nucleon collision. In subsequent collisions absorption takes place with a fixed probability P_a, another parameter in the model. The energy and momentum of the absorbed pion are shared by the current and previous nucleon. The additional canceling nucleon momenta, corresponding to the pion mass, are chosen along the direction of the pion motion between the two nucleons. If $P_a = 1$ (and two collisions occur) then the pion will be absorbed on the first pair it encounters.

III. Extraction of Observables

The analysis is performed by selecting all pairs of nucleons which have the sum of their kinetic energies greater than some fixed value E_c. If the momentum of the incident pion is $\vec{k}$ and the two nucleon momenta are $\vec{p}_1$ and $\vec{p}_2$ then the angle, θ, between $\vec{p}_2$ and $\vec{k}-\vec{p}_1$ measures the deviation from absorption on a free nucleon pair. The effects of refraction of the outgoing protons, Fermi motion, nucleon-nucleon collisions and interaction of the pion with nucleons before absorption will lead to a dispersion in this angle. The first two effects are treated under the general title of Fermi motion.

There are four principal sources of reduction of the two-nucleon correlation functions relative to absorption as free nucleon pairs.

1. Fermi motion A large fraction of the two-nucleon absorption takes place when the angle of one of the nucleons in the center of mass is about 30°. The backward moving nucleon, in motion contrary to the center-of-mass movement of the composite system, has a relatively low kinetic energy, of the order of 65 MeV. Because of the Fermi motion of the pair this energy is spread. Consequently some fraction of the lower-energy members of the pair fall below the cut-off energy of the counters (25 MeV in this case), and hence the nucleon pair is not observed.

2. Binding Energy While the binding energy of the last nucleon is moderate (10 MeV in this case) the binding of the interior nucleons is much greater. Since even "two-nucleon"

interior nucleons is much greater. Since even "two-nucleon" absorption is a multinucleon process (in the sense that the pion typically hits several nucleons during the absorption event) it is not predominantly a surface process. Thus the interior nucleons may be expected to play a large role in pion absorption. In the present model the number of nucleons participating in absorption in a given shell is proportional to the number of nucleons in that shell, independent of binding energy, i.e., no appreciable shadowing is observed. The binding energy of each shell is well known from knock-out reactions[7]. For a pion absorbed on a pair of nucleons in the 1s shell the loss is substantial. Approximately 20% of the two-nucleon absorptions are lost to observation from the Fermi motion and binding alone.

3. Nucleon Scattering After Absorption Either nucleon (or both) may be scattered before leaving the nucleus. There has been some debate about the importance of this effect because of the long mean-free-path (mfp) inferred from optical potentials derived from proton scattering[8]. This long mfp is presumed to be due to the Pauli blocking of the struck nucleon.[9]

For this reason we discuss in some detail our method for calculating the nucleon collisions. The present calculation divides the nucleon-nucleon interaction into two parts. The first part is long range and makes up the attractive well which binds the nucleus. The effect of this potential has already been included since it is the source of the binding energy in (2) above. There remains a strong short-range interaction which leads to the high-energy scattering cross section of ~40 mb. Thus the cross section used in these calculations is only a fraction of the total cross section for low energy nuclear collisions. The mfp in nuclear matter corresponding to this value is about 1.7 fm. The effect of Pauli blocking is taken into account by ignoring any collision which would lead to a final state in which either nucleon would have an energy such that it would be bound by more than a fixed energy E_P (the "Fermi level", typically 10 MeV in our calculations). This lengthens the mfp considerably. We have ascertained, by recording the histories of the two nucleons receiving the absorption energy, that about one half of the collisions are Pauli blocked. Thus the actual mfp in nuclear matter would be ~3.5 fm. Of course many of the reactions are not in the center of the nucleus so the effective density is smaller and the actual "mfp" is longer. Despite the strong dependence of the mfp on Pauli blocking of the NN collisions, this effect plays a rather small role in the reduction in the number of correlated proton pairs seen. If the Pauli blocking were turned off the only collisions affected would be those in which the outgoing nucleon transfers a small amount of energy to the bound one. The result would be a slight broadening of the correlation function and not a loss in the number of pp pairs observed. For the optical model any nucleon-nucleon elastic scattering, no matter how soft, would lead to a loss of flux if allowed to occur. The fact that the small-energy-loss (small-angle) inelastic scatterings are the ones suppressed may be seen directly in the angular distribution discuss the relationship of corrections to the two-nucleon correlation function in terms of the nucleon mfp without specifying more details of the nucleon scattering.

4. Pion-Nucleon Collisions The pion must make at least two collisions before it can be absorbed on the last two nucleons with which it collided. The probability per collision is P_a in the calculation. This value is chosen to reproduce the observed two-nucleon cross section. The pion may collide with 0, 1, 2, ... nucleons before being absorbed on the final pair. Thus it may lose a sufficient fraction of its kinetic energy so that the event is not counted in the two-nucleon correlation measurement. This effect was discussed by Girija and Koltun.[10]

IV. Results

The present intranuclear cascade code includes all of the effects described in the previous section. We can study each separately by means of parameter changes. The results are summarized in Table III for pion absorption on ^{58}Ni with an incident pion laboratory momentum of 270 MeV/c. The losses are composed of several small effects, all acting in concert until only about 20% of the events remain.

These results are expressed in terms of a reduction factor defined by $R = \sigma(E_c, E_0)/\sigma_a$ where $\sigma(E_c, E_0)$(is the inclusive $(\pi, N_1 N_2)$ cross section summed over all $N_1 N_2$ pairs. The cross sections are subject to the energy cut $E_1 + E_2 > E_c$, which selects only high energy pairs, and the energy cuts $E_1 > E_0$ and $E_2 > E_0$, which correspond to the low-energy cutoff of the detectors. σ_a is the total pion absorption cross section. For comparison with ref. 3 we have chosen $E_c = 160$, 230 MeV and $E_0 = 25$ MeV.

R is commonly less than one because inelastic scattering of the incident pion or rescattering of the nucleons on which the absorption takes place lower the energy of the observed nucleon pair. It is also possible that one member of the nucleon pair is left in a bound state and so is not observed. Because the sum extends over all nucleon pairs, the absorption results in one very fast and one slow nucleon. The slower nucleon may strike another, knocking it out of the nucleus. Provided E_c is not too great, either of the two slow nucleons may be paired with the fast one to satisfy $E_1 + E_2 > E_c$. Some of this "overcounting" occurs even if $E_c = 230$ MeV. The reduction factor is not very sensitive to the detailed parameters of the nucleon collision process and, as can be seen from Table III, actually increases slightly when the nucleon collision cross section is increased.

In Table III the first run (row 1) corresponds to a "PWIA" calculation. Since P_a is unity the pion must annihilate on the first two nucleons it encounters. There is no "initial state interaction". The condition $\sigma_{NN}=0$ means that the outgoing nucleons interact only with the potential well. There are no secondary knock-out processes. The reduction factor comes completely from the Fermi motion and binding energy corrections as discussed in III.1 and III.2.

Fermi motion and binding energy corrections as discussed in III.1 and III.2.

In the calculation of row 2, P_a is reduced to 0.4. This allows scattering of the incident π^+ before its annihilation. The π^+ shares its kinetic energy among several nucleons during the "pre-scatters" so there is a depletion of the high energy (230 MeV) events. The lower energy events increase because of there now may be several pp pairs.

A large reduction in (especially high energy) events due to the final NN scatters in seen in row 3. Rows 4 and 5 include both π prescattering and NN scattering.

The relative insensitivity to Pauli blocking mentioned in III.3 may be seen by comparing 5, 6, and 7. The $E_B = 10$ MeV case corresponds to full blocking of the highest shell, while the $E_B = 60$ MeV case corresponds to no blocking. The case in which $\Sigma E>230$ MeV is hardly affected. The case for which $\Sigma E>160$ MeV is more affected because "soft" scatters of the outgoing proton may enhance the overcounting previously discussed.

A comparison of rows 6 and 8 show the lack of sensitivity to small changes is σ_{NN}. Rows 5 and 9 show insensitivity to the precise value of P_a. Runs 9 and 10 differ only in that the angular momentum selection is not imposed on run 10; the direction of the momentum is chosen randomly for each nucleon.

Case	σ_{NN}(mb)	P_a	E_B(MeV)	Reduction Factor $\Sigma E>230$ MeV	Reduction Factor $\Sigma E>160$ MeV
1	0	1.0	10	0.80	0.80
2	0	0.4	10	0.70	0.86
3	40	1.0	10	0.30	0.53
4	40	0.6	10	0.24	0.51
5	40	0.5	10	0.21	0.45
6	40	0.5	20	0.21	0.45
7	40	0.5	60	0.25	0.65
8	50	0.5	20	0.23	0.41
9	40	0.35	10	0.20	0.47
10	40	0.35	10(a)	0.16	0.47

Table III. Dependence of the reduction factor on the various mechanisms in the calculation. The label "a" indicates that the individual shells were not required to have a specific angular momentum corresponding to that shell. Different shapes result for the individual shell densities.

We note that ref. 3 measured only the p-p pairs following annihilation so that it is necessary to correct for the n-p pairs, which we will assume have the same reduction factors. We note, from ref. 1, that the high energy proton spectrum, near the quasi-two-body kinematical point, from π^+ projectiles (leading to pp pairs) is nine times larger than the corresponding proton point from π^- projectiles (leading to np pairs). Taking into account that there are two protons for each π^+ event and only one for each π^- event the np pairs are 22% of the pp pairs. Since ^{58}Ni has nonzero isospin, a correction (the number of np pairs over the number of pp pairs) must be applied which leads to a factor to obtain all two nucleon events of 1.25, i.e., the cross section observed in ref. 3 should be increased 25%. as should the inferred two nucleon absorption cross section.

Yet another possible correction arises from the fact that the counters used in ref. 3 had a loss of energy discrimation for protons with energy greater than 200 MeV. This involves about 12% of the pairs with summed energy greater than 230 MeV. However only about 2% would be lost to the cross section, the other 10% still having enough energy (after counting all energies greater than 200 MeV to be only 200 MeV) to satisfy the energy criterion at 230 MeV. We do not include this correction in the present work.

The results are summarized in Table IV. If one now uses values of the total true-absorption cross section as measured by Ashery *et al.*[11], or Nakai *et al.*[12], a residual absorption cross section can be inferred. A substantial fraction remains but we see that the errors cause the effect to be marginal in statistical terms. We have not included, as errors, the uncertainty due to the calculation. We show instead two variations corresponding to angular momentum selection (which correspond in turn to changes in shapes of the individual shell densities).

Two proton σ (mb)	Two nucleon σ (mb)	Residual Absorption Cross Section Ashery(577±90 mb) (mb)	Nakai(527±109mb) (mb)
285±20	357±25	220±93 (38±16)%	170±108 (32±20)%
356±25	446±31	131±95 (23±16)%	81±109 (15±21)%

Table IV. Results of the analysis.

The figure shows the angular correlation functions for ^{58}Ni for two different energy selection conditions chosen for comparison with ref. 3. While the contributions from the nucleon collision and pion collision effects change with the cut on energy, the Fermi motion broading does not. Note that, due to the solid angle factor, the larger angles are very important.

The distinction between two-nucleon absorption and multi-nucleon absorption in such a classical calculation is somewhat arbitrary. All of the results presented here are in the two-nucleon category in the sense that when the pion is absorbed all of the energy corresponding to its rest mass is given to two nucleons only.

Certainly the case of Fermi motion alone corresponds to a pure two-nucleon absorption mechanism. The authors of ref. 2 do not consider the addition of final nucleon collisions to be multi-nucleon absorption but rather two-nucleon absorption with final state scattering. For the pion interactions before the absorption the same might be said.

We gratefully acknowledge several helpful discussions with B. Ritchie and R. Redwine.

This work was supported by the U. S. Department of Energy and the Associated Western Universities.

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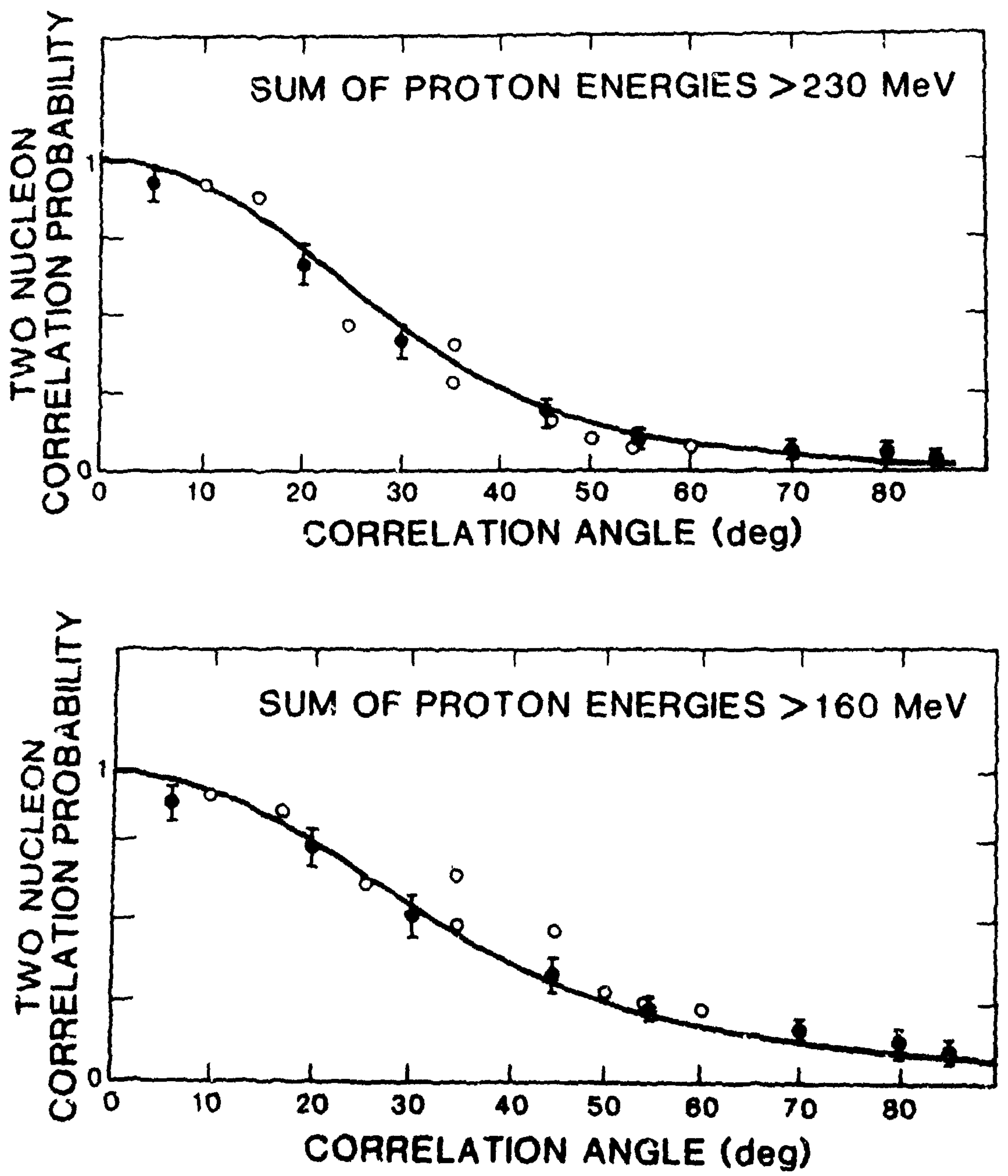

Figure. Predicted angular correlation function compared with the data[3]. The incident pion momentum is 270 MeV/c. The calculation averages over all angles of a single proton and out-, as well as, in-plane events. The data corresponds to only in-plane events and the first proton counter fixed at 30° (solid points) and 75° (open circles). The two points at 35° correspond to measurements to the left and right of the two-body kinematic point.