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AUTHOR(S) M. D. Cooper, H. Baer, R. D. Bolton, R. L. Burman, F. H. Cverna, M. B. Johnson, N.S.P. King, W. W. Kinnison, M. Leitch, and R. Wiringa, Los Alamos National Laboratory, Los Alamos, NM 87545; Ch. Gregoire, University of Louvain; and R. E. Anderson, University of North Carolina

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

SEARCH FOR THE REACTION $^{40}Ca(\pi^+,\gamma\gamma)$ AT T_π = 50 MeV AND CRITICAL OPALESCENCE*

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ABSTRACT

We have searched for the inclusive process $^{40}Ca(\pi^+,\gamma\gamma)$ at T_π = 50 MeV in order to look for nuclear critical opalescence in the double radiation capture. The reaction appeared to offer several advantages over others, including the high nuclear transparency of 50 MeV pions in a relatively heavy nucleus and the longitudinal coupling of the captured pion to the nucleus. The coincident γ-rays were detected in the arms of the LAMPF π^0 spectrometer, which consist of active converters and multi-wire proportional chambers to locate the direction of the photons as well as total absorption lead glass counters to measure their energy. Backgrounds from the beam were reduced by demanding a positive signature of interaction in the target from four arrays of 10 scintillators each before and after the target. Data were acquired for momentum transfers of 140 MeV/c and 280 MeV/c and over the lowest 125 MeV of excitation of the final state.

Theoretical estimates of the free cross section $p(\pi^-,\gamma\gamma)n$ are 23 nb/sr^2 in the experimental acceptance, a result which has been successfully linked to the measured $^{12}C(\pi^-,\gamma\gamma)$ stopping rate. Being an inclusive experiment at large momentum transfer, it was expected that the $^{40}Ca(\pi^+,\gamma\gamma)$ cross section would be some multiple of the free cross section. DWBA estimates of the cross section have been made in a relativistic momentum space treatment. These calculations indicate the cross section should be 100 nb/sr^2.

The preliminary result for 140 MeV/c shows no signal for the reaction at a 90% confidence limit of 32 nb/sr^2. The discrepancy between the calculations and the measurement possibly suggests a more complex reaction mechanism for in-flight radiative capture than for stopped capture.

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SEARCH FOR THE REACTION $^{40}Ca(\pi^{+},\gamma\gamma)$ AT T_{π} = 50 MeV AND CRITICAL OPALESCENCE*

M. D. Cooper, H. Baer, R. D. Bolton, R. L. Burman, F. H. Cverna,
M. B. Jackson, N. S. P. King, W. W. Kinnison, M. Leitch, and R. Wiringa,
Los Alamos National Laboratory, Los Alamos, NM 87545.

Gh. Gregoire, University of Louvain.

R. E. Anderson, University of North Carolina.

Critical opalescence is the premature onset of pion-like behavior in real nuclei induced by the proximity of a pion-condensed state at roughly twice nuclear matter density. The nature of the precursor of the condensed state is that the pion field, which is always present around nuclei, is enhanced by medium corrections. The enhanced field introduces a spin-isospin correlation among the nucleons. Since the density is below criticality, the range of the pion field is still fairly short and only modest effects in real nuclei are expected. This theoretically predicted phenomenon is manifested by enhanced cross sections for processes involving virtual pions of low energy and momenta near 300 MeV/c.[1]

The inclusive $^{40}Ca(\pi^{+},2\gamma)$ reaction at 50 MeV appeared to be a good candidate to use in a search for this phenomenon because of: (1) the large atomic mass of ^{40}Ca, (2) the high nuclear transparency of 50-MeV pions, (3) the longitudinal coupling of the pion interaction with the nucleus, (4) the ability to reach 300-MeV/c momentum transfer, and (5) the use of many final states to remove uncertainties in nuclear wave functions.

Even in the absence of any observable precursor phenomenon, the measurement of this reaction presents several interesting challenges. Some of the processes contributing to the cross section involve understanding pion absorption far off the mass shell. Additionally, the role of the delta resonance must be accounted for in the radiative capture, a phenomenon usually ignored in the interpretation of stopping experiments.

The experiment needed a calculation of the expected cross sections to aid in planning the experiment, and as a first step in the data interpretation. The experiment proposed was to measure the double differential cross section $d^2\sigma/dqdx$ for the process $^{40}Ca(\pi^+,2\gamma)$ in the region of quasi-elastic dominance. The range of momentum transfer q was from 1.0 to 2.0 m_π, and the range of the photon energy-sharing parameter $x = (E_1-E_2)/(E_1+E_2)$ was from -0.65 to 0.65. The reaction was supposed to be most sensitive to critical opalescence for x = 0 and $q \approx 2.2m_\pi$.

In response to the need for a detailed calculation of the $^{40}Ca(\pi^+,2\gamma)$ reaction and the medium modifications, a two-part theoretical effort was undertaken. The goals of this effort were (1) to calculate the cross section for $^{40}Ca(\pi^+,2\gamma)$ using the distorted wave impulse approximation (DWIA) for one-nucleon processes, and (2) to include the medium modifications to the propagators.

This report gives a summary of the formalism that has been developed to meet the first part of our requirements. It has been incorporated into a computer program that takes a few hours to compute a cross section. Some remaining theoretical uncertainties, such as the role of the delta and the inclusion of the Pauli principle remain to be sorted out.

The starting point for the calculation is the fundamental $\pi N \rightarrow N\gamma\gamma$ matrix element, which we denote by

$$\langle p'kk'|m|pq\rangle \qquad (1)$$

for incident nucleon p and pion q, outgoing nucleon p′, and photons k and k′. There are 18 one-nucleon graphs included in Eq. (1), and the direct terms are illustrated in Fig. 1. These matrix elements follow closely the development of Cammarata,[2] using pseudovector coupling and the tree approximation. They differ in the following respects:

1. Magnetic photon coupling is not included
2. The incident particles are π^+ and neutron

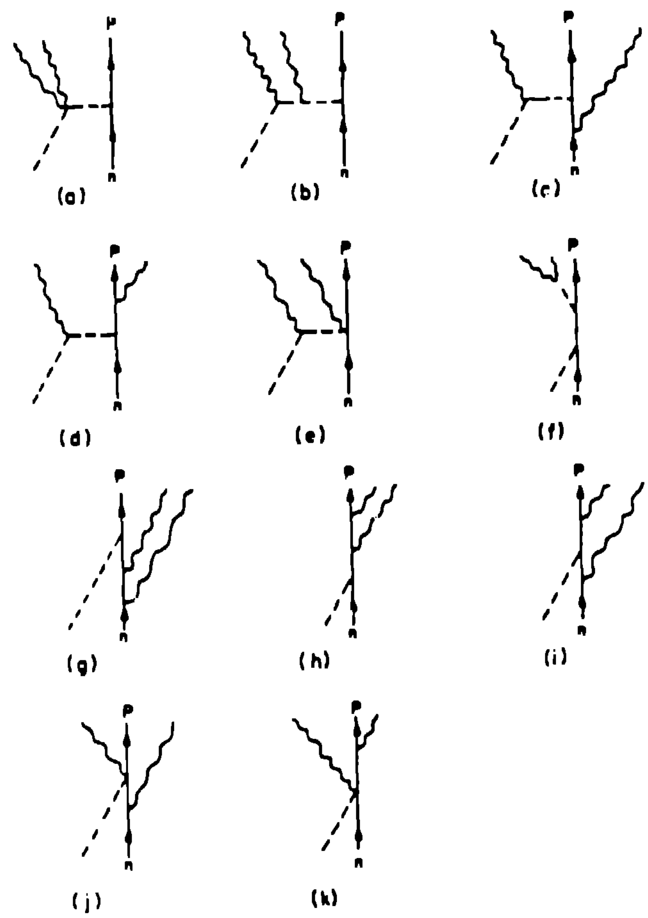

Fig. 1

The one-nucleon Feynman graphs. All excepc f are included in the DWIA matrix element. Each graph leads to two terms due to photon exchange.

3. Photons are coupled to neutrons via an effective charge
4. The π-nucleon vertex has a form factor $\exp(-Q^2/\Lambda^2)$ included (Q^2 is the square of the pion three momentum that attaches to the nucleon).

To imbed the matrix element in finite nuclei, we define m′ as

$$\langle p'kk'|m'|IK\rangle \equiv \int \frac{d^3\vec{q}}{(2\pi)^3} \int \frac{d^3\vec{p}}{(2\pi)^3} \langle p'kk'|m|pq\rangle \left(\frac{M}{2E_k E_p} \right)^{1/2}$$

$$\times \psi_K(\vec{q})\psi_I(\vec{p})(2\pi)^3\delta^{(3)}(\vec{p}' + \vec{k} + \vec{k}' - \vec{p} - \vec{q}) \quad . \qquad (2)$$

The kinematic variables are illustrated in Fig. 2. The initial nuclear state ψ_I is characterized by a binding energy $-\varepsilon$ and momentum $\vec{p}$, and is normalized to one nucleon. The distorted pion wave $\psi_K(\vec{q})$, where K is the incident momentum, is given as

$$\psi_K(\vec{q}) = (2\pi)^3\delta(\vec{q} - \vec{K}) + \frac{(2\pi)^3}{q^2}$$

$$\times \left\{\delta(q - K) \sum_\ell P_\ell(\cos\theta_q) \left[\phi_\ell^{(0)}(K) - \frac{2\ell + 1}{4\pi} \right]\right.$$

$$\left. + \frac{\mathbb{P}}{q - K} \sum_\ell P_\ell(\cos\theta_q)\phi_\ell^{(1)}(K,q) \right\} \quad . \qquad (3)$$

The values for $\psi_K(\vec{q})$ are obtained from the program PIPIT,[3] a momentum-space optical-model program, using the π-nucleon form factor $\exp(-Q^2/\Lambda^2)$. The parameters of the optical potential are adjusted to fit 50-MeV elastic π^+-^{40}Ca scattering data.[4] All three terms of Eq. (3) contribute substantially to m′.

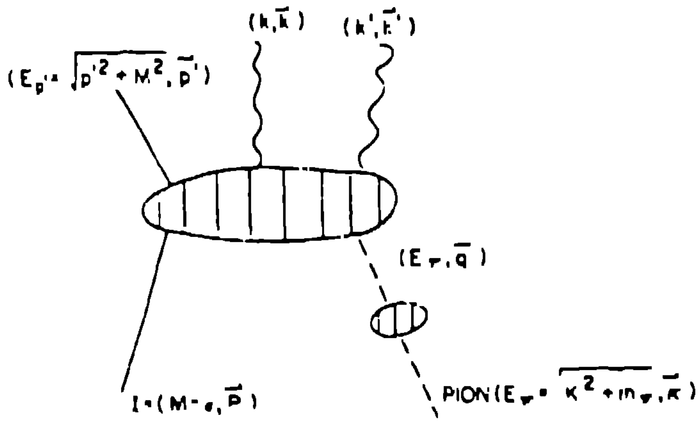

Fig. 2

The graph corresponding to m′ for a nucleus, showing the distortion that puts the pion off the mass shell. The initial nucleon is also off the mass shell.

The triple differential cross section, which is needed for comparison to experiment, is given by

$$\frac{d\sigma}{d\Omega_1 d\Omega_2 dx} = \frac{(1-x^2)}{(2\pi)^6} \frac{1}{16\ \beta_\pi} \sum_I \int d^3\vec{p}\,' \frac{M}{E_{p'}} g_{p'_F}(p') \left(\frac{\omega_I}{2}\right)^3 n_I \theta(\omega_I > 0)$$

$$\times \sum_{\substack{\text{nucleon spins} \\ \text{photon polarizations}}} |\langle p'kk'|m'|IK\rangle|^2 \ . \qquad (4)$$

In Eq. (4) the symbols have the following definitions:

x ≡ Energy-sharing parameter $\frac{E_1 - E_2}{E_1 + E_2}$,

E_i are photon energies.

β_π ≡ Incident pion velocity

$g_{p'_F}(p')$ ≡ Factor that excludes the occupied states forbidden by the Pauli principle

ω_I ≡ $E_1 + E_2$ for photons produced from an initial neutron in state I

n_I ≡ Number of neutrons in state I

It is useful here to delineate the kinematics used to evaluate Eq. (4). They are

$\vec{q}, \vec{q}\,'$ Arguments of integration representing the pion's off-shell momentum and the final nucleon's momentum

E'_p = $\sqrt{p'^2 + M^2}$ final nucleon on the mass shell

E_π Given incident pion energy, off the mass shell

x, Ω_1, Ω_2 Measured energy-sharing parameter and photon angles

$$\omega = E + E_\pi - E_{p'}$$

$$k = \frac{1+x}{2}\,\omega \qquad k' = \frac{1-x}{2}\,\omega$$

$$\vec{p} = \vec{p}\,' + \vec{k} + \vec{k}' - \vec{q} \text{ off the mass shell}$$

In order to make the calculation tractable, m′ has been taken to be independent of I; $\phi_I(p)$ has been chosen as the Fourier transform of a bound s-state Woods-Saxon wave function of average binding energy,

$$26 \text{ MeV} = \sum_I E_I n_I / n \quad .$$

It is believed that the momentum composition of s- and d-state wave functions is similar enough so that this is not a severe approximation. It remains to be checked.

The integrations are done numerically using Monte Carlo techniques. With the above approximation, a cross section for one value of x, Ω_1, and Ω_2 can be calculated to about 10% accuracy using a few hours of VAX CPU time.

There are two other approximations implicit in Eq. (4). The first is that a simple form for $\rho_{p'_F}(p')$ exists. In nuclear matter, it is just a theta function. In a finite nucleus, it has a diffuse edge at p'_F, which is still being studied. The other is that plane waves are an adequate description of the final state when the integral in p′ is cut off by p'_F and $\Theta(\omega_I > 0)$. It is expected that it will be a good description in the region of momentum transfer where the nuclear response function, as measured in electron scattering, is dominated by quasi-free scattering. The electron-scattering data for ^{40}Ca show this to be largely true for $q > 0.5\, m_\pi$, and this is where the calculations will be valid.[5]

The results of these calculations for $q = 0.7$ and $2.0m_\pi$ are shown in Fig. 3 along with the values for $p(\pi^-,\gamma\gamma)n$ of Ref. 2. The curves reflect typical infared divergences near $x = \pm 1$, but are more filled in near $x = 0$ in the nuclear ease. The results for ^{40}Ca are 3 to 4 times the hydrogen predictions. Preliminary results predict that the opalescence phenomenon fills in the curves near $x = 0$.

During July and August 1981, five weeks were devoted to measuring the ^{40}Ca $(\pi^+,2\gamma)$ reaction at the Low Energy Pion Channel at LAMPF. About three weeks of this time were devoted to data taking. The two photons we detected using the LAMPF π^0 spectrometer.[6] As the reaction is expected to have a very small cross section, random backgrounds were expected to be trouble. The preparations for three anticipated problems worked very well. Shielding for the required close geometry protected the counters adequately. Two photon backgrounds from π^0 decay were completely eliminated by placing the detectors inside the

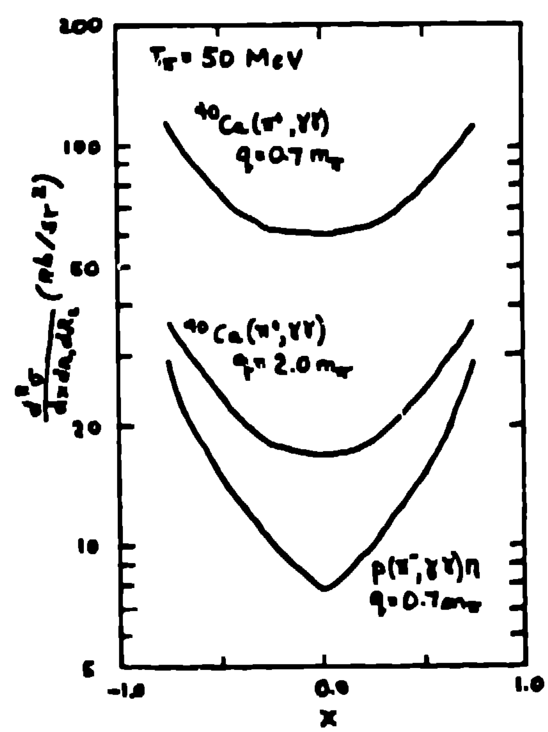

Fig. 3

The relative cross sections for the $(\pi,\gamma\gamma)$ reaction on Calcium at $q = 0.7$ and $2.0\ m_\pi$ based on the calculations in the text. Also shown are the cross section from hydrogen from Ref. 2. The primary effect of critical opalescence would be to fill in these distributions near $x = 0$.

kinematically forbidden region for π^0 decay. Randoms from two photons produced by two different pions in the target were rejected by a target hodoscope designed to observe multiple particles over a large beam spot. The result of this apparatus was complete elimination of cosmic ray coincidences beyond the measurable limit and a random background from the beam corresponding to a singles flux of seven high-energy photons per second.

The beam hodoscope performed remarkably well. It consisted of 40 scintillation counters which were approximately 1.5-mm thick by 8-mm wide by 100-mm long. Short-light guides connected the scintillators to 3/4" Amperex 1911 photomultiplier tubes. No rate effects were noticed up to 10^6 particles/second average. Individual counters were characterized by better than 99.5% efficiency, 15% pulse height resolution and 1.5-ns time resolution. The gap between counters was always less than 38 μm.

The use of the beam hodoscope is illustrated by two idealized events in Fig. 4. Figure 4 is a scale drawing of the hodoscope arrangement of the active area of the counters about the target and the solid rectangles are struck counters. Figure 1a displays a promising candidate where a pion disappears in the target and is in time with both γ-rays. Another extraneous particle goes

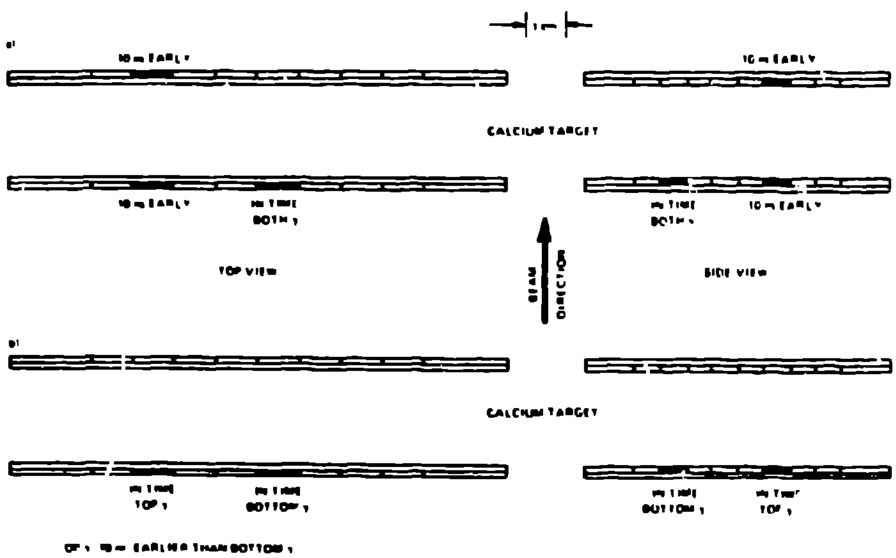

Fig. 4

Idealized events in the target hodoscopes that illustrate its principle of operation.

through about 10 ns earlier. Figure 2b protrays a rejected accidental where two pions interact in the target and each produce one photon in a gamma arm.

A Monte Carlo simulation of the hodoscope completely characterized the performance with the added assumption that 2% of the events fired neighboring counters. The quality of the agreement is reproduced in Table I. The entries are probability of producing a pattern of n particles upstream and m particles downstream for a given trigger of the γ detector. The agreement is excellent except for very rare off-diagonal events.

TABLE I (a)

MEASURED DATA ON PROBABILITY OF HIT COMBINATIONS

		Upstream Particles		
	m\n	1	2	3
	0	4.74×10^{-4}	0	0
Downstream	1	0.8836	0.0455	9.95×10^{-4}
Particles	2	0.0545	0.0118	5.68×10^{-4}
	3	0.0013	0.0011	1.45×10^{-4}

TABLE I (b)

MONTE CARLO RESULTS ON PROBABILITY OF HIT COMBINATIONS

		Upstream Particles		
	m\n	1	2	3
	0	4.45×10^{-4}	0	0
Downstream	1	0.8793	0.0504	2.02×10^{-4}
Particles	2	0.0538	0.0132	8.75×10^{-4}
	3	5.46×10^{-4}	0.0010	1.46×10^{-4}

Information from the hodoscope was analyzed with a tracking algorithm, which utilized both the time and amplitude information from the counters to identify interacting and non-interacting tracks. New tracking algorithms in the multi-wire proportional counters of the γ-detectors were very effective in eliminating cosmic ray showers.

Data was taken at central momentum transfers of 140 and 280 MeV/c with a resolution (FWHM) of 35 MeV/c. The data is normalized by a comparison of $p(\pi^-,\pi^0)n$ cross sections at $T_{\pi^-} = 140$ MeV. The connection between the two measurements is made with Monte Carlo simulations. The relative timing spectrum between the two photons due to charge exchange from hydrogen is shown in Fig. 5. The dominent source of background remaining from the Ca target were from an interacting beam particle and two asynchronous photons coming through the shielding.

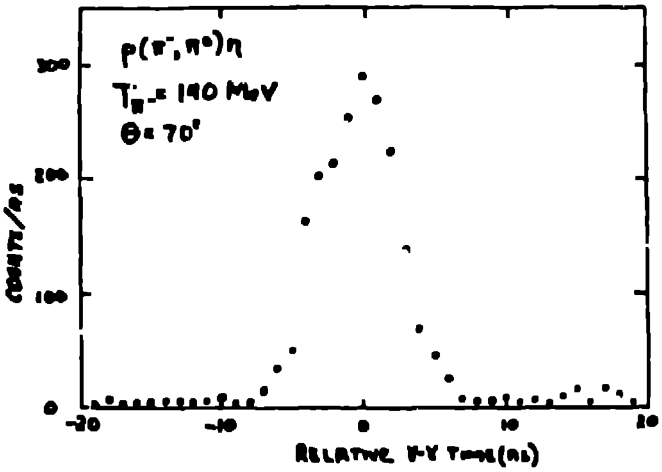

Fig. 5

The relative timing distribution for $p(\pi^-,\pi^0)n$ at $T_{\pi^-} = 140$ MeV. The events plotted pass all cuts on the Ca data, and the peak corresponds to events with coincidences between both γ detectors and the beam hodoscope. By contrast, no peak could be identified for the $(\pi,\gamma\gamma)$ process.

The preliminary result for 140 MeV/c shows no signal in the comparable relative timing spectrum at a level roughly 100,000 times smaller than the hydrogen charge exchange. This places an upper limit on the cross section with a sensitivity of 20 nb/sr^2.

The discrepancy between the calculations and measurements is problematic. Quasi-elastic processes generally show up with substantially greater cross sections in nuclei than off of nucleons. However, no $(\pi^+,\gamma\gamma)$ was observed in ^{40}Ca down to a level of the hydrogen predictions. One possibility is that the hydrogen cross section requires a more complex reaction mechanism for the in-flight radiative capture than for the stopped capture. The role of the delta, which is usually neglected in stopping radiative capture, may be important here.

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