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ISOSPIN INVARIANCE IN THE REACTION $n+p \rightarrow \pi^0+d$ *

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A measurement of the differential cross section for the reaction $n+p \rightarrow d+\pi^0$ has been made using a neutron beam with kinetic energies up to 720 MeV. The angle and momentum of the deuterons were measured using an analyzing magnet and wire spark chambers with a magnetostrictive readout. The photons from the decaying π^0 were not detected. The neutron energy was calculated from the measured deuteron angle and momentum. The cross sections are compared to those for the reaction $\pi^++d \leftrightarrow p+p$ as a test of isotopic spin invariance in strong interactions. The symmetry of the cross sections about 90° is also investigated, and an upper limit of about 1% is placed on the real part of the ratio of isospin-violating to isospin-conserving amplitudes.

A measurement of the differential cross sections for the reaction $n+p \rightarrow d+\pi^0$ has been made at the L. R. L. 184-inch cyclotron with incident neutron energies from threshold to 720 MeV. The results serve as a test of isotopic spin invariance of strong interactions. The experiment was set up primarily to test time reversal invariance in the photodisintegration of the deuteron by measuring the cross section for the reaction $n+p \rightarrow d+\gamma$ [1], but, with very little extra effort, about 4.5×10^5 events were taken to obtain the $n+p \rightarrow d+\pi^0$ cross section. After accidentals were eliminated and fiducial cuts applied, about 2.5×10^5 events remained. Half of these events were the desired $d+\pi^0$ production with ~1% contamination from the $d+\gamma$ reaction. The remaining events were from neutron elastic and inelastic scattering.

The experimental layout is shown in fig. 1. A neutral beam with an intensity of $\sim 10^6$ neutrons/sec and a 0° takeoff angle was created by bombarding a beryllium target with protons circulating inside the cyclotron. The deuterons from the $d+\pi^0$ production have a maximum laboratory angle of 14° and were detected in spark chambers with a magnetostrictive readout system [2]. These were fired when a coincidence between D_1 and D_2 occurred. The photons from the decaying π^0 were not detected. An on-line PDP-5 computer was used to continuously monitor the experiment and record the magnetostrictive scalar readings, beam monitor scalars, and time of flight between D_1 and D_2.

For each event the locations of the sparks were reconstructed, and the orbits were integrated through the spectrometer to obtain the particle momentum. The data were binned according to laboratory angle, momentum, and time of flight. For particles of the same momentum, the time of flight information was used to separate the faster moving protons from the deuterons. The neutron energy was calculated from the measured deuteron angle and momentum.

Detection efficiencies of the apparatus were computed by a method similar to the usual Monte Carlo technique. Included in this calculation were corrections for energy loss and multiple Coulomb scattering. Further corrections to the

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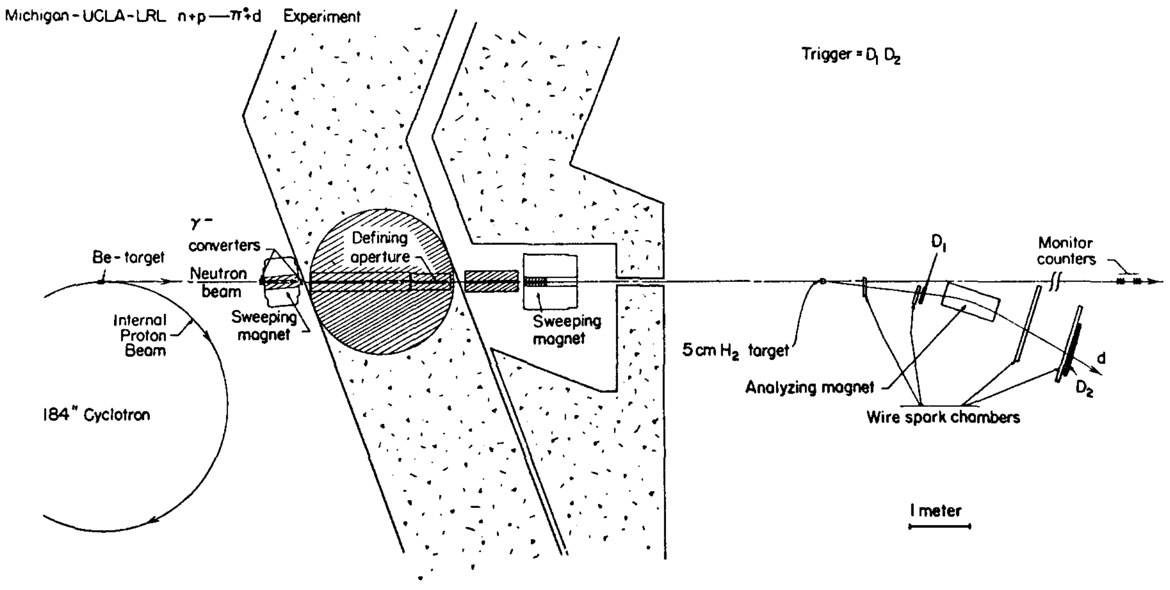

Fig.1. Experimental arrangement.

data (~10%) were made for d+γ contamination, scattering from the target walls, and deuteron absorption.

Because the incident neutron energy was unknown and the three components of momentum of the π^0 were unmeasured, we have a zero constraint fit to the n+p→d+π^0 reaction. The identification of the deuteron is a sufficient signature for the n+p→d+π^0 reaction because, except for the small n+p→d+γ contribution, this is the only significant reaction producing deuterons at these beam energies in the range of angles and momenta studied. Deuterons from n+p→d+2π were estimated to be <0.01% of the sample. The resulting corrections to the cross sections would range from 0 to 0.3% and were neglected.

In the neutron energy calculation there is a two-fold ambiguity for certain ranges of deuteron angle and momentum as shown in the shaded region of fig. 2. In this region deuterons of two different energies in the center of mass can have the same laboratory angle and momentum. Because of the zero constraint fit, this ambiguity cannot be explicitly resolved. However the data in the ambiguous region serve as a consistency check for the cross sections measured in the non-ambiguous region.

Typical results are shown in fig. 3 with the ambiguous points plotted as open circles. Results from Princeton [3] for the reaction n+p π^0+d and from CERN [4] for p+p ⇄ π^++d are shown as well; for clarity, only a few typical errors are displayed. The CERN data are reflected about 90° and plotted twice. Since the normalization of our data cannot be established very accurately it was adjusted by eye to fit the Princeton and CERN data.

The errors in our data in the ambiguous region are large because of the sensitive dependence upon systematics. To get the systematic errors, we varied the laboratory momentum measurement by 0.5% and the angle measurement by

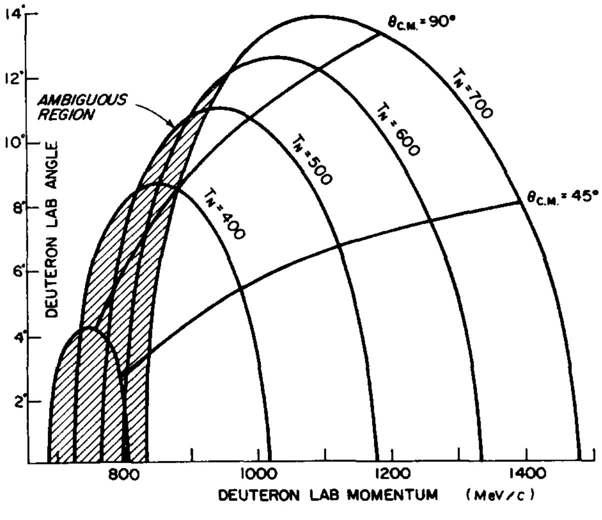

Fig.2. Deuteron kinematics for n+p→ π^0+d.

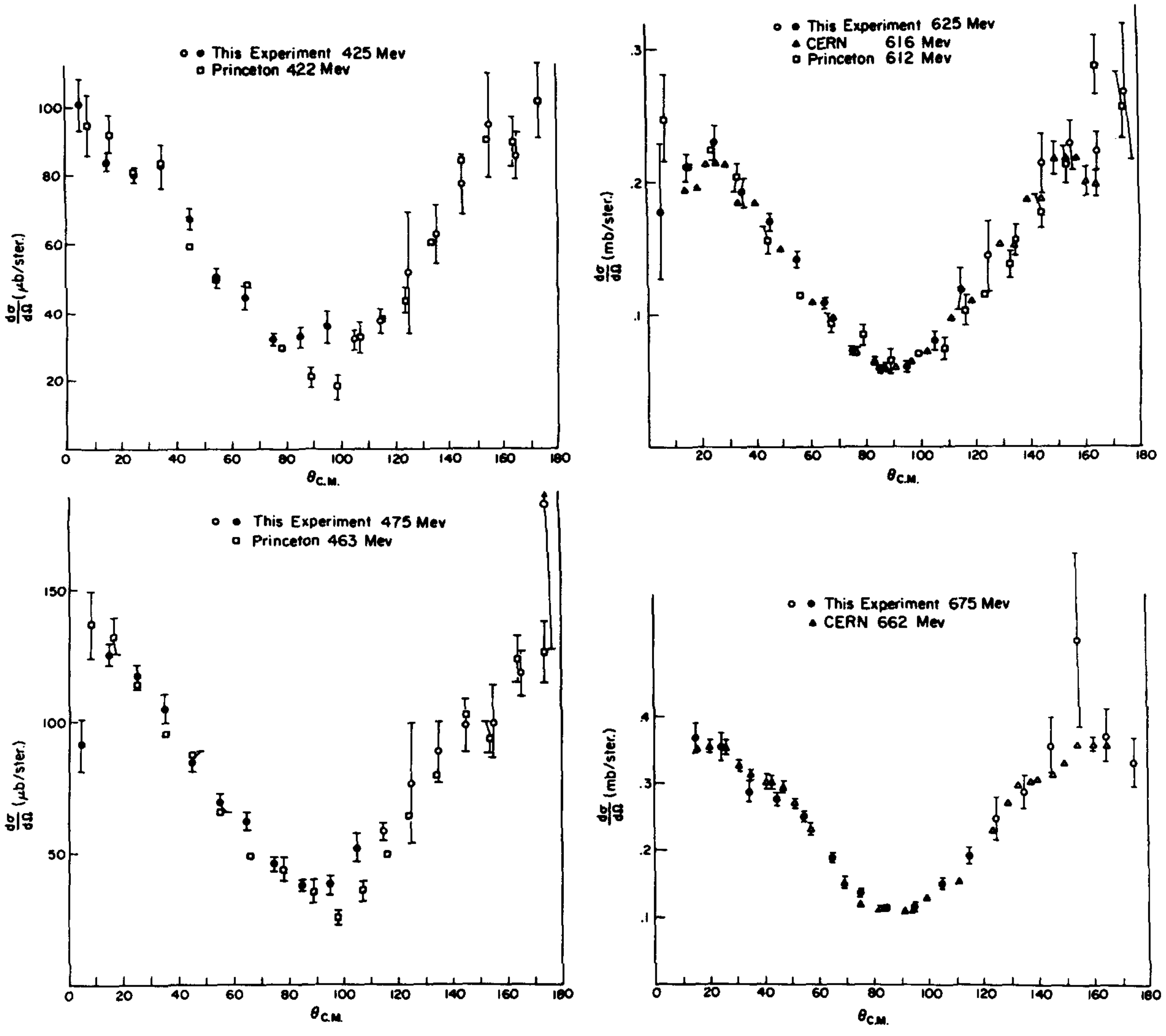

Fig.3. Cross sections. The results from a previous measurement of n+p $\to\pi^0$+d at Princeton are shown [3]. The CERN data [4] were obtained from a measurement of π^++d$\to$p+p; detailed balance was used to transform to p+p $\to$ π^++d, and the cross sections were divided by two to facilitate comparison with n+p$\to\pi^0$+d. Our data have been normalized to the Princeton and CERN data.

0.05°, corresponding to estimated systematic uncertainties in these quantities, and recomputed the various cross sections. The resulting variation of the cross section was combined with the statistical errors to give the quoted errors.

The prediction of isotopic spin invariance is that the cross sections for n+p$\to\pi^0$+d should be one-half those for p+p$\to\pi^+$+d at all angles and energies [5]. There are two specific consequences which we investigate:

1. The shape of the angular distribution for this experiment should be the same as that found in p+p$\rightleftharpoons\pi$+d experiments. Thus we fit our angular distributions to the function

$$\sigma(\theta) \propto A + \cos^2\theta + B\cos^4\theta \quad . \qquad (1)$$

The A and B coefficients are plotted as a function of energy in fig. 4 along with results from CERN [4]. Our data are also consistent with all the other

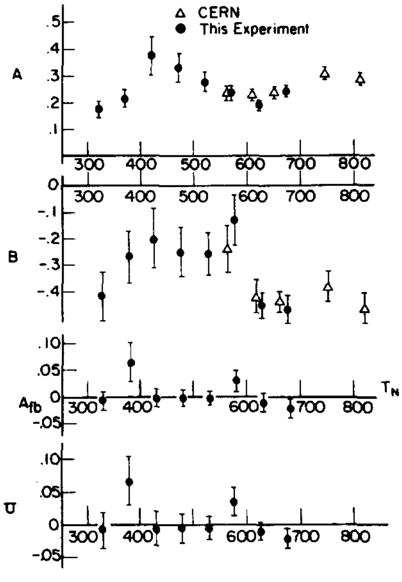

Fig.4. Coefficients obtained in fitting the cross sections to $\delta \propto A + \cos^2\theta + B\cos^4\theta$ and A_{fb}, the forward-backward asymmetry.

N+N⇌d+π experiments, though the accuracies of their B coefficients are poor enough that this is not a very fruitful comparison. (A summary of these other experiments can be found in ref. [4].)

2. Our angular distributions should be symmetric about 90° as they are for $p+p \rightarrow \pi^+ + d$ (because of the identity of the two protons in the initial state). Thus we check the size of the asymmetry of our angular distributions by fitting our cross sections to a function with an antisymmetric term U:

$$\sigma(\theta) \propto A' + U\cos\theta + \cos^2\theta + B'\cos^4\theta \ .$$

Fig. 4 shows that U is consistent with zero. This test does not require knowledge of the results of other N+N⇌π+d experiments, and is sensitive to the requirement that total isospin is conserved. The forward-backward asymmetry is defined as

$$A_{fb} = \left(\int_0^{\frac{1}{2}\pi} \sigma d\Omega - \int_{\frac{1}{2}\pi}^{\pi} \sigma d\Omega\right) \Big/ \int_0^{\pi} \sigma d\Omega$$

and is shown in fig. 4. It has been shown that the real part of the ratio of the isospin-violating to isospin-conserving amplitudes is proportional to A_{fb}[3].

$$A_{fb} = K \mathrm{Re} \frac{\langle 1,0|S|0,0\rangle}{\langle 1,0|S|1,0\rangle}$$

where S is the scattering matrix and K ranges from 0.25 to 2.45 depending on the particular violating transition assumed in the model.

A fit to the function

$$\sigma(\theta) \propto A + \cos^2\theta$$

generally gives a much larger χ^2 than for eq. (1). Thus the B coefficient is necessary for a fit to this experiment.

Conclusions. There are a number of tests of isotopic spin invariance in reactions involving pions and light nuclei. (see ref. [6] for a short summary.) These tests show that isospin invariance holds to at least 5%. The recent experiment at Princeton [3] results in a forward-backward asymmetry of 1.0 ± 3.0% in the angular distribution of the reaction $n+p \rightarrow d+\pi^0$. Our results show an average asymmetry of -0.36 ± 0.66% in the same reaction.

Our angular distribution agrees well with all other N+N⇌d+π experiments. In fitting the cross section to the formula.

$$\sigma(\theta) \propto A + \cos^2\theta + B\cos^4\theta$$

we and CERN find consistently values for B with a sharp negative drop above 600 MeV. The A and B coefficients for these two experiments are the same within an uncertainty ranging from ~4% to ~9% (for a 90% confidence level). Evidence from the forward-backward asymmetry shows that transitions which do not conserve total isospin are zero to within ~1% accuracy - the level at which electromagnetic violations might be expected to occur.

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