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AN EXPERIMENTAL TEST OF TIME-REVERSAL INVARIANCE IN THE PHOTODISINTEGRATION OF THE DEUTERON[*]

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We present data from a measurement of angular distributions of the reaction $n + p \rightarrow \gamma + d$ (1a) for neutrons with energies between 300 and 700 MeV. These data are compared with recent data for the inverse reaction $\gamma + d \rightarrow n + p$ (1b). Time-reversal invariance implies that apart from a normalization factor the angular distributions should be the same. We find an intriguing discrepancy in the vicinity of the well-known peak in the total cross section of reaction (1b) and apparent agreement elsewhere. The discrepancy occurs in the shape of the angular distributions and

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does not depend on the normalization of our data or those of the inverse reaction experiments.

Bernstein, Feinberg, and Lee(1) noted the absence of experimental evidence to exclude the possibility that the violation of CP in $K_L^0 \rightarrow \pi^+ + \pi^-$ (2) decay was due to a possible failure of C and T in the electromagnetic interactions of hadrons. A number of possible experimental(1, 3) tests appear now to be expected to yield only relatively small effects even if there is a maximal violation. Other tests, such as reciprocity in photopion production from nucleons are complicated by the neutron, $\gamma + \begin{pmatrix} P \\ N \end{pmatrix} \leftrightarrows \begin{pmatrix} N \\ P \end{pmatrix} + \pi^{(\pm)}$ (2), involved in the comparison. However, Christ and Lee(3) concluded from their study of reaction (2) that a failure of C and T should manifest itself most likely near a pion-nucleon resonance and only for processes which actually correspond to a photopion production with the pion subsequently reabsorbed for reaction (1). Reaction (1) has a peak in the cross section near k_L = 300 MeV as shown in Fig. 1, which is attributed to the excitation of a nucleon to the N^*(1236) in an intermediate state. It is then worth while to test reciprocity in the vicinity of this peak.

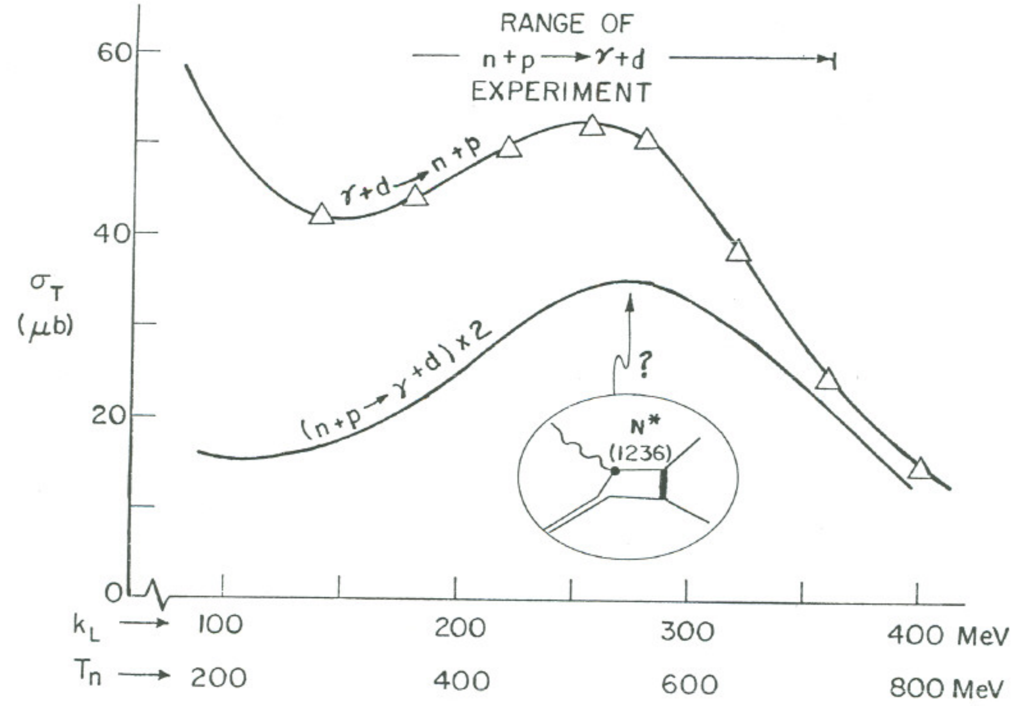

Fig. 1. Total cross section of $\gamma + d \rightarrow n + p$ and $n + p \rightarrow \gamma + d$ as a function of lab kinetic energy of the incident photon and neutron, respectively.

Barshay$^{(4)}$ has used a specific model due to Austern$^{(5)}$ to estimate the possible magnitude of the effect to the expected. The matrix element for the excitation of $J = I = 3/2$ isobar by absorption of a magnetic dipole (M1) photon leading to a $^1D_2$ state with $I = 1$ for the final two-nucleon system is calculated by evaluating Feynman graphs like that shown in Fig. 1. The hypothetical failure of T invariance is introduced by giving the γ-N-N* vertex a phase, $e^{i\Delta}$, different from 0 or π. The matrix element for the reverse reaction is shown to have a phase $e^{-i\Delta}$. If, e.g., $\Delta = \pi/2$ and we are at resonance so that the resonance-energy denominator of the matrix element is purely imaginary, then $M(1a) = - M(1b)$. And if there is another relatively real amplitude with which the isobar amplitude interferes, reciprocity may be grossly violated. The $M1 \rightarrow {}^1S_0$ transition that exists at lower energy can interfere while the $E1 \rightarrow {}^3P_0$ transition cannot. After an estimate of the relative weights of each amplitude, the angular distributions for reactions (1a) and (1b) at $k \approx 290$ MeV are given as

$$\frac{d\sigma}{d\Omega}\begin{pmatrix}1a\\1b\end{pmatrix} \propto 10.66 - 2\, P_2(\cos\theta)\,[\,1 + 0.94 \cos(\delta_r \mp \Delta)]$$

$$= A_0 + A_2\, P_2(\cos\theta),$$

where P_2 is the second-order Legendre polynomial, θ is the CMS angle between photon and neutron, and δ_r is the phase of the resonance denominator which may at resonance be unequal to $\pi/2$ because of the deuteron's internal momentum. The essential features are that the total cross sections of reactions (1a, b) are equal, and that the effect of a T violation is expected to show up only in the normalization-free ratio A_2/A_0. A complete description of the experimental data requires addition of odd-order Legendre polynomials to account for the fore-aft asymmetry attributed to interference between E1-E2 transitions. An estimate of the failure of reciprocity at resonance may be expressed as $A_2/A_0(1b) - A_2/A_0(1a) \approx \sin\Delta/3$.

The coefficient of $\sin\Delta$ is proportional to the imaginary part of the $M(1) \rightarrow {}^1D_2$ amplitude and should vanish at lower and higher energies at least as fast as δ_r, which is scaled by $\gamma^* \approx 120$ MeV, the isobar width.

The neutron's lab kinetic energy, T_N equals $2\, k_L$, the photon's lab energy at the same CMS total energy as shown in Fig. 1. So neutrons with energies up to 700 MeV could test the energy dependence of any possible failure of reciprocity. We decided a test (to $\Delta \approx \pm 15°$) by using the UCLRL 184" Synchrocyclotron was reasonable. A similar test has been made by Bartlett et al.$^{(6)}$ at PPA. The inverse reaction (1b) has recently been remeasured at Cornell,$^{(7)}$ Orsay,$^{(8)}$ and Stanford.$^{(9)}$

A presumably unpolarized neutron beam was produced at 0° from a Be target in the internal cyclotron beam at an energy of

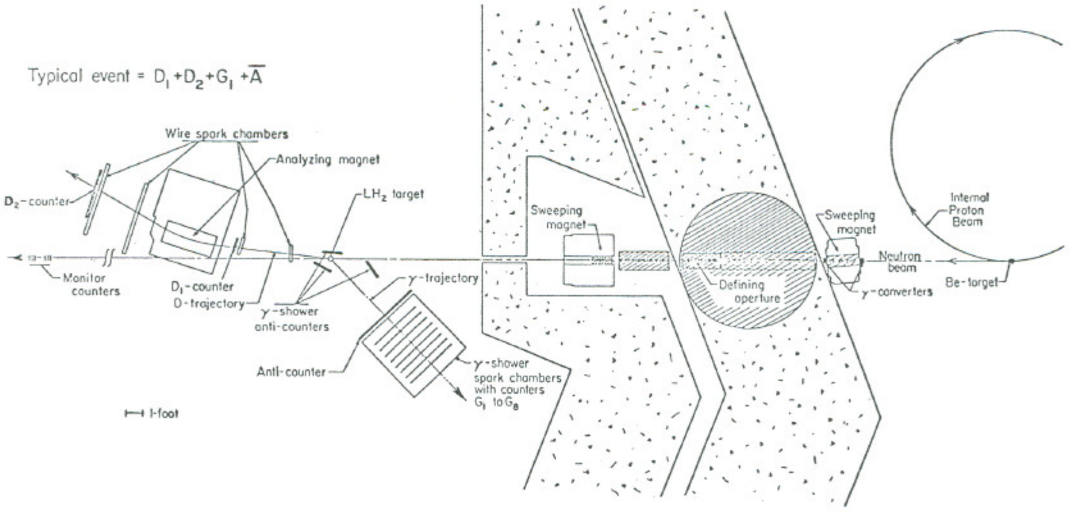

Fig. 2. Experimental arrangement.

≈ 715 MeV (see Fig. 2). The beam passed through a Pb filter to remove γ rays, passed through a sweeping magnet to remove charged particles, then through a carefully constructed collimator, another sweeping magnet, and finally appeared at a 3" diameter by 2" long liquid hydrogen target about 40' from the Be target. At this point the beam had a 2" diameter with very little halo. The neutron flux was estimated to be $\approx 5 \times 10^6$/sec with a peak in the spectrum near 670 MeV due to charge exchange, a flat valley between 500-600 MeV, and a broad hump at lower energies due to pion production. After passing through the target the beam was monitored by three sets of monitor telescopes containing polyethylene converters. These tracked one another to within 0.1% over the time of the data presented. Two side-by-side counters connected to rate meters permitted continuous monitoring of the beam-centering and target setting.

Charged particles were detected by counters D_1 and D_2 before and after passing through a C magnet. Two sets of wire spark chambers before and two sets after the magnet provided the particle's three-momentum. Each set had four planes having 1 mm resolution per plane with magnetostrictive readout. The gammas were converted in an array of ten one-radiation-length 30"×30" optical spark chambers with a total of 40 gaps. A set of 8 counters—G_1, ⋯ G_8—were placed between the first nine chambers to detect the converted pair. These counters were 24" high by 27" wide and established the fiducial area of the chamber. An anti-counter in front of the gamma chambers insured that the incoming particle was neutral. Three lead scintillation sandwich anti-counters were placed near the LH target to reduce the principal source of background due to the reaction $n + p \to d + (\pi^0 \to 2\gamma)$(3), which occurs ≈ 50 times more frequently than reaction (1a).

The spark chambers were triggered by a coincidence between D_1D_2 (with the timing appropriate for a deuteron) and a pulse from any one of the counters, $G_1, \cdots, G_8$, without a pulse from any of antis. Because of the good duty cycle of the cyclotron, accidental rates of all kinds were found to be very low. Those between D_1 and D_2 were always $< 1\%$. Accidental vetos from antis were monitored continuously and were $\leq 7\%$. Scalers recorded singles and coincidences as well as time. Some of these were gated on only during the live time of the equipment.

The following information was recorded for each trigger. The gamma chamber with its fiducials and the run and event was photographed. A PDP-5 computer recorded the event and run number, and the 16 coordinates from the wire chambers (four planes for each of four chambers. This redundancy allowed us to determine the deuteron's trajectory with high accuracy and an efficiency $>98\%$.) The computer also recorded the D_1-D_2 time-of-flight, the gamma counters that fired, and other less essential information to be used to monitor the experiment on line. In addition, at every twelfth event the scalers were automatically recorded on the magnetic tape.

A total of 10^6 good pictures, of which $\approx 5\%$ are due to reaction 1a (events due to reactions 1a and 3 are called γds and π^0ds respectively), were taken at five angles ranging from $\approx 25°$ to $150°$ in the CMS. Both the magnet and gamma chamber were mounted on rolling carriages to facilitate the changes. The gamma chamber distance was varied to keep the angular interval of accepted events about $\pm 10°$ (CMS). The deuteron spectrometer's position and field were adjusted to accept events corresponding to $200 \lesssim T_N(\text{MeV}) \lesssim 750$ at each angle. Target-full runs were alternated with target-empty runs. The latter showed a negligible background due to target walls.

The data were processed as follows: The gamma chamber film was digitized by a Vidicon scanning system followed by a pattern-recognition program to yield one or more vertices and the corresponding spark count. The efficiency for this process is $\geqslant 99\%$ at all angles. Less than $1/2\%$ of the events with two distinct vertices is rejected from the analysis. Other events where two vertices are found in the same shower are resolved by choosing the vertex closest to the target. Scanning shows this is the correct choice more than 99% of the time. The overall reproducibility of the vertex is accurate to $\pm 1/2$ mm. The vector momentum of the charged particle was determined from the wire chamber data, three-dimensional magnetic field maps, and a particle-tracking program to $\Delta p/p \approx 1\%$. The mass of the particle is then calculated from its momentum and D_1-D_2 time of flight. A small fraction of protons is included in the final analysis to insure that no deuterons are lost even though the separation is quite clean at all angles. The deuteron's direction is projected back to the center plane of the LH target that served as the origin from which the gamma's angle is determined. A χ^2 of the event according to reaction (1a) was calculated. The fit is over determined (a 2C fit) and the χ^2 is essentially a measure of the coplanarity (assuming the neutrons come from the Be target) and the changed particle's missing mass. Figure 3 shows a χ^2 distribution of events binned according to the reconstructed neutron energy for a best and worst case situation, respectively.

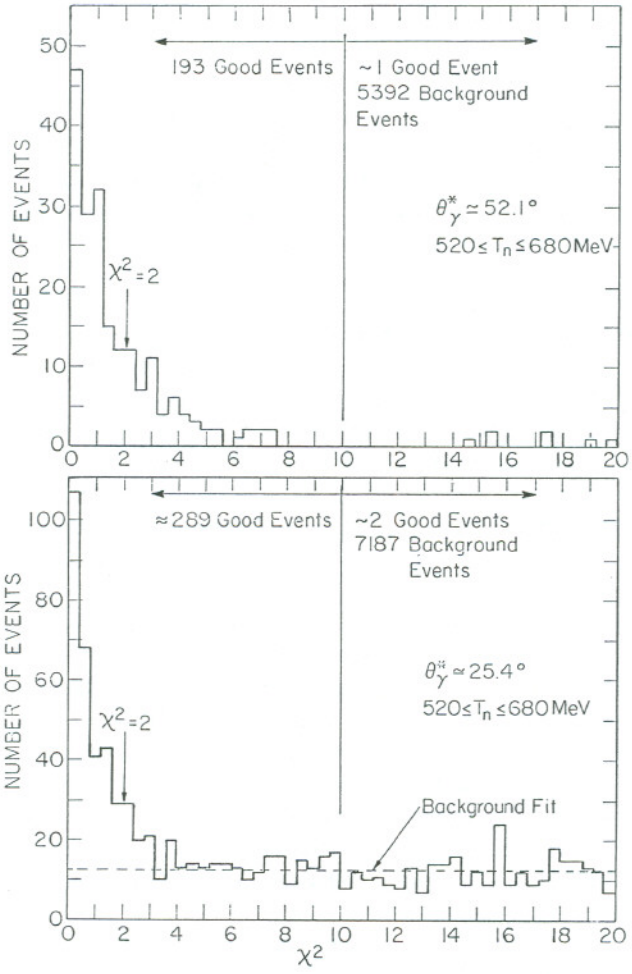

Fig. 3a, b. χ^2 plots of typical best and worst case of background subtraction due to $n + p \rightarrow d + (\pi^0 \rightarrow 2\gamma)$. The χ^2 is calculated according to reaction 1a for each event.

It is seen that there is a nearly complete separation in one case while in the other a significant subtraction of $\pi^0 d$ events must be made. Independent checks on the alignment of the equipment were made by examining the coplanarity and missing-mass plots; e.g., the mass corresponding to the center of the deuteron's peak agreed with the accepted mass of the deuteron to within ± 0.05% for most data points.

A Monte Carlo program was constructed to simulate π^0d and γd events. The purpose of the program is (1) to test the entire data reduction scheme, (2) to check that the experimental and theoretical resolutions agree, (3) to yield the neutron energy resolution of the reconstructed events, (4) to yield the solid angle as a function of T_N for the fiducial areas of the equipment, and (5) to assure that the π^0d background extrapolates smoothly under the γd peak in the χ^2 plots. Good agreement was found between the Monte Carlo and experimental χ^2 plots at small χ^2 for the γd events and at large χ^2 for the π^0d events. This gives us considerable confidence in the background subtraction, which is made by a smooth extrapolation of the χ^2 distribution at high χ^2 under the peak at low χ^2 to obtain the net number of γd events, $N(\theta, \overline{T}_N)$, and the overall statistical error of this method.

The data presented here are based on the final analysis of a sample of 20% of our data. The differential cross section, $d\sigma/d\Omega$, aside from an unknown normalization factor, F, is $d\sigma/d\Omega = F\ N(\theta, T_N)/M\,\Delta\Omega\,\epsilon$, where M is the corresponding number of monitor counts, $\Delta\Omega$ is the CMS solid angle subtended by the system, and ϵ is the efficiency. Our data are divided into four neutron energy bins (300-400, 400-500, 500-600, and 600-700 MeV) for comparison with the inverse data.

Results of three recent measurements of reaction (1b) are shown in Fig. 4. The coefficients A_0, A_1, A_2 are from a least-squares fit of the data to a Legendre polynomial series. Three curves are shown, of which the center one corresponds to average values over the interval of our T_N bins and the outer ones correspond to either the standard deviation of the points or their statistical uncertainty, whichever is larger. The agreement is quite good for the Orsay and Cornell data while the Stanford data (which is statistically more accurate) shows a slight disagreement.

Our angular distributions, $d\sigma(\theta)/\sigma_{\text{total}}$, are shown in Fig. 5. The errors are only statistical and include the uncertainty in background subtraction. The curve is that obtained from the average values of A_1/A_0 and A_2/A_0 obtained from Fig. 4. Agreement is quite good except in the 500-600 MeV bin, where the 26° point is above the line and the 51° and 88° points are below it. The effect of this reversal is most clearly seen in Fig. 6. Good agreement is obtained in the A_1/A_0 ratio but the A_2/A_0 ratios do not agree with the inverse to ≈ 3 standard deviations for the 500±50 MeV bin and ≈ 1 standard deviation for the 450±50 MeV bin. We have had a result of this nature in this data sample for over a

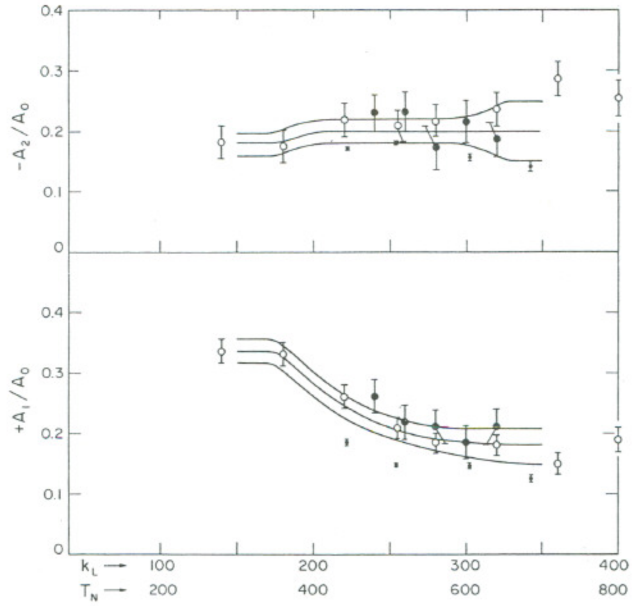

Fig. 4. Results of recent measurements of reaction 1b as a function of photon energy, k_L. The CMS scattering data is θ. The three lines represent the average value and its uncertainty in these ratios.
Legend:
● Stanford-SLAC (≃ 40 MeV wide)
○ Orsay (40 MeV wide)
⬤ Cornell-Ithaca-Princeton (20 MeV wide)

year and have found no systematic errors in our treatment that could lead to this discrepancy. The ratio of wire chamber tracks to triggers was 98% after subtracting randoms. Scattering from the pole-tips is easily rejected in the momentum fitting program. Hence, we trust our estimates of $\overline{\Delta\Omega\epsilon}$ for this part of the system and our Monte Carlo results based on uniform chamber efficiency. Our data do not include a small correction for the efficiency of detecting a gamma. The spark count on low-χ^2 events shows ≥ 15 sparks/event at all angles. This represents 2-3 chambers involved in a detected shower. We estimate the detection efficiency to be > 98% for photon energies > 140 MeV, the lowest energy involved in the $500 < T_N < 600$ MeV data. Furthermore, this correction should be most important for the lower energy neutrons. Its effect will be to increase the discrepancy slightly since our cross sections are high in the region where the γ energy is lowest. We have not found any reason to change the method of background subtraction, which could easily lead to this result. Data over the entire neutron energy spectrum was taken simultaneously to reduce the time-dependent efficiency of the apparatus. Systematic

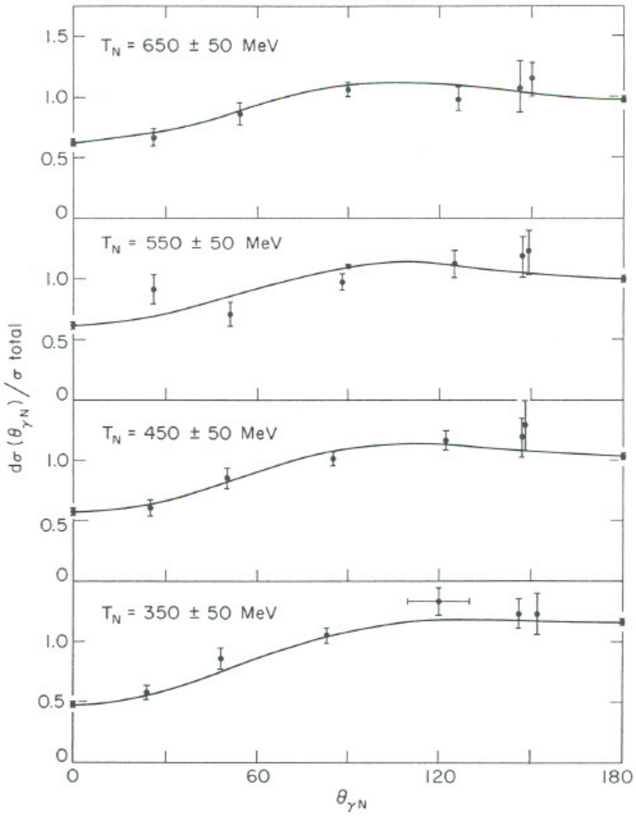

Fig. 5. Angular distributions of our data for four intervals of neutron energy where $\theta_{\gamma N}$ is the CMS angle. The error bars shown at 0° and 180° for all energies and at 90° for T_N = 550 MeV reflect the uncertainty in these curves as shown in Fig. 4.

errors in the reconstructed neutron energy have been extensively investigated to remove the possibility that the rapidly changing structure of the neutron energy spectrum could produce our result. The resolution of T_N varies from 3% - 1% at low and high energy, respectively. Neutron energy spectra at each angle agree well in shape and to ± 1.5% at the high energy cutoff at ≈ 720 MeV.

The vertical bar in Fig. 6 represents Barshay's estimate of the possible consequence of T violation from no violation ($\Delta = 0°$) to maximal violation ($\Delta = -90°$). The photodisintegration of the deuteron has been studied intently for many years. It is interesting to ask whether there is any direct information which a priori precludes a large T violation and, if not, what the energy dependence of an observed violation might be. The horizontal bar is an estimate of the FWHM of the effect of the isobar amplitude taken from the analysis of Pearlstein and Klein.(10) Also shown is their result for A_2/A_0, which agrees surprisingly well with recent data. They disagree

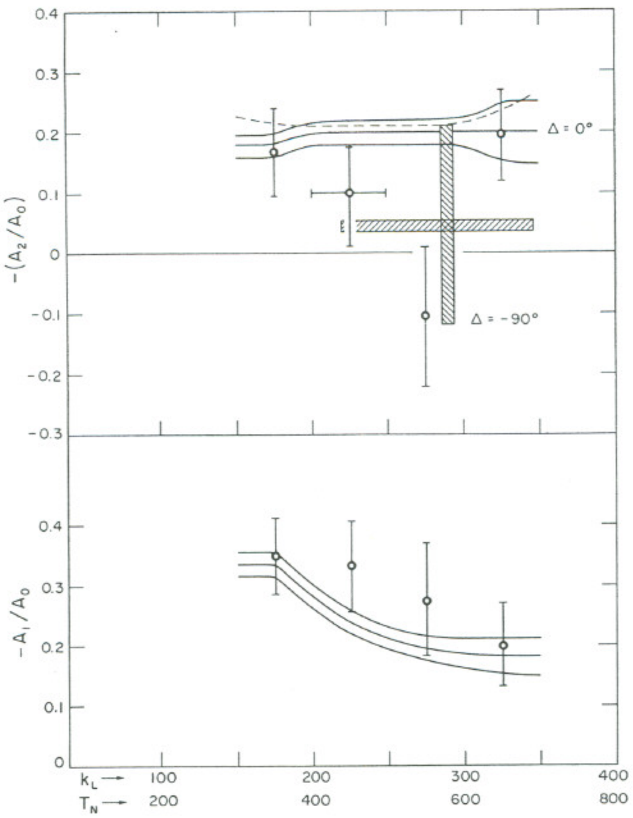

Fig. 6. Comparison of our results with the inverse reaction.
Legend:
○ UCLA-UM-LRL (50 MeV bins)
— — — Theory (Pearlstein and Klein)
▧ Barshay
▨ $\sqrt{\sigma\ (\mathrm{MD})} > 0.5\sqrt{\sigma\ (\mathrm{MD})}_{\mathrm{max}}$

with Barshay as to the contribution of E1, M1 transitions to the total cross section. A possible T violation should show up in the value of $\delta_2 - \delta_0$ (the $^1D_2$ and $^1S_0$ n-p phase shifts) required to obtain a fit to data. They required a value that can be interpreted to be ≈ 90° different from recent analyses of nucleon-nucleon scattering.(11) We interpret this as a restatement of the observation of Ref. 1.

In view of the importance of our results it is essential that further studies be made of reactions (1a) and (1b) to remove the uncertainties in the experimental data and to investigate theoretically the magnitude of a possible violation allowed by all existing data.

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