THREE-NUCLEON FORCE EFFECTS IN NEUTRON-INDUCED DEUTERON BREAKUP

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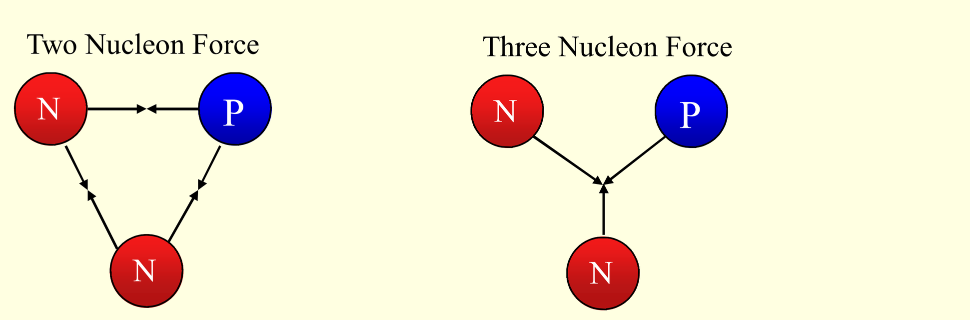
1. Abstract

The differential cross section for the neutron-induced deuteron breakup reaction was measured at the LANSCE/WNR facility at Los Alamos National Laboratory during the summer of 2007. It has been suggested theoretically that the differential cross section for neutron-deuteron scattering may be sensitive to three-nucleon effects for scattering of protons and neutrons in coincidence at small forward angles on the same side of the incident neutron beam. In this experiment, a permanent magnet spectrometer was located at a small forward angle to detect protons and a 'wall' of plastic scintillator neutron detectors was located beyond this spectrometer. The data collected are currently being analyzed.

2. Motivation

Currently, physicists believe there are four fundamental forces that govern the physics of our universe; the gravitational, electromagnetic, strong nuclear and weak nuclear forces. Although some of these forces are well understood, the strong nuclear force is less familiar. The strong nuclear force is the force between nucleons (protons and neutrons) that holds the nucleus of an atom together.

Until recently, the strong force was believed to be a two-nucleon force (2NF), meaning that the total force on a nucleon is the sum of all pairwise interactions (see diagram below). These pairwise interactions can then be used to find, for example, the binding energy of the nucleus[1,2]. It turns out, however, that the 2NF models predict binding energies that are as much as 10% lower than the experimentally determined values[3] for tritium and ^{3}He. A paper[4] by Coon and Glockle in 1981 suggested that this discrepancy in binding energies of light nuclei may be partly due to the neglect of three-body forces. In the case of the three-nucleon isotopes mentioned above, it is possible that there is a three-nucleon force component to the strong force (abbreviated 3NF) which could explain the difference in binding energy.



The easiest way to test the 3NF theory is to create a system which contains only three nucleons. This can be done by causing a neutron to collide with a deuteron (atom with a proton-neutron nucleus). When the incident neutron gets close to the deuteron, a three-nucleon system is created. The process is considered elastic because essentially no energy is lost in the collision. Since the scattering angle depends on the details of the interaction between the three nucleons, the 3NF theoretical prediction for the scattering angle is different than the 2NF theoretical prediction (see Figure 2).

Interest in the 3NF was further motivated by theoretical calculations which predicted the cross section for a neutron-deuteron elastic scattering using a 3NF model. The calculations[2,5] showed for certain kinematics, for example a scattering angle of 120^o for 200 MeV incident neutrons, a dramatic difference between the 2NF and the 3NF predictions exists (see Figure 2).

Up until this time, data obtained regarding the 3NF have come from dp, pd and nd elastic scattering experiments. The goal of the present experiment is to observe 3NF effects through a process called nd breakup. In nd breakup, an incident neutron strikes a deuteron target, separating the deuteron's proton and neutron. There are currently theoretical cross sections for the nd breakup experiment which can be tested. Thus, during the summer of 2007 an experiment was performed to measure the cross section for nd breakup.

Joanna Kuroś-Żołnierczuk[6-8] has performed an extensive study of the effects of 3NF in both n-d elastic scattering and the breakup process. For the latter, she has searched the final-state phase space for regions where the sensitivity to the inclusion of 3NF is large (see Figure 3). Not unexpectedly, these regions are very non-quasifree, e.g. kinematics in which the two fast nucleons come out at close to the same angle on the same side of the beam. Another example is where one nucleon is emitted at a small angle and the other nucleon at a large (backward) angle.

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[5] M. Chtageev, Master's Thesis, MIT (2005).
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[7] J. Kuroś-Żołnierczuk *et al., Phys. Rev. C* ***66*, *024004 (2002).***
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3. History

In 2000, nd elastic scattering was studied at the Los Alamos Neutron Science Center (LANSCE). In this reaction, incident neutrons with energies up to 800 MeV were scattered from a liquid deuterium target (see Figure 1). Scattered neutrons and deuterons were detected in coincidence, so that 3NF effects could be studied. The results from this experiment are shown in Figure 2.

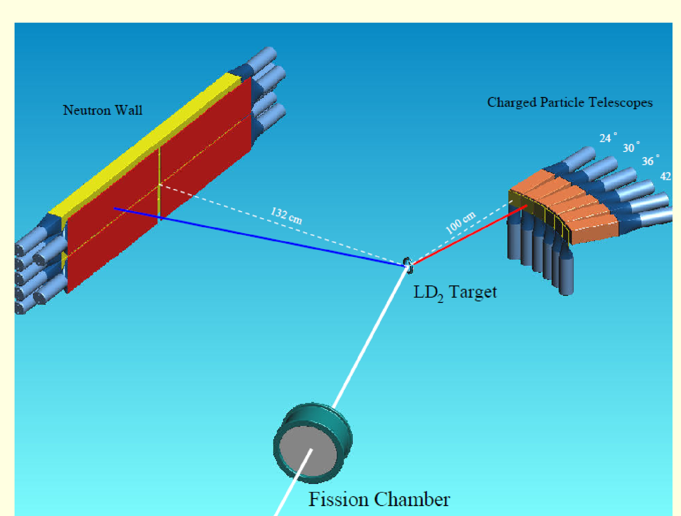

Figure 1. The nd scattering experiment performed at LANSCE from 2000-2002. The neutron beam passed through a fission chamber and struck the LD_2 target. The neutrons (n) and deuterons (d) were then scattered from the target; the scattered deuterons are detected by CsI detectors and the neutrons by plastic scintillator neutron bars.

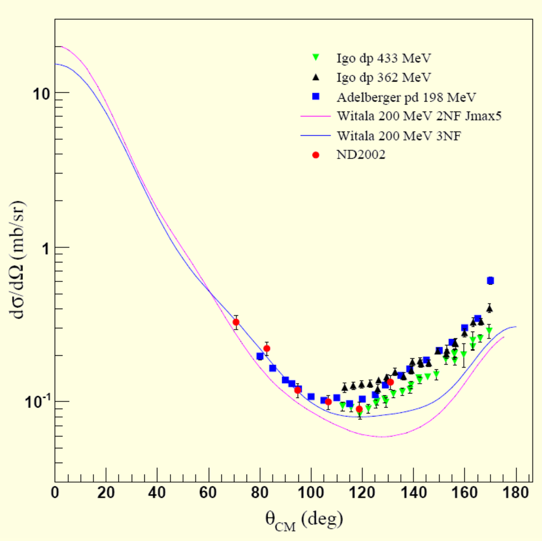

Figure 2. The cross section for nd elastic scattering as a function of center of momentum deuteron scattering. The blue line is the theoretical prediction of the 3NF and the purple line is the theoretical prediction of the 2NF. Shown are experimental results of pd and dp cross sections at energies between 198 and 433 MeV as well results from our experiment (ND2002). [5]

Since these data were consistent with the presence of a 3NF effect in nd elastic scattering, it was decided that investigating the nd breakup reaction would be useful. Thus, the nd breakup reaction experiment was performed the summer of 2007. In this experiment, the outgoing protons and neutrons were detected at non-quasifree kinematics, that is, at small scattering angles on the same side of the beam line (see Figure 4).

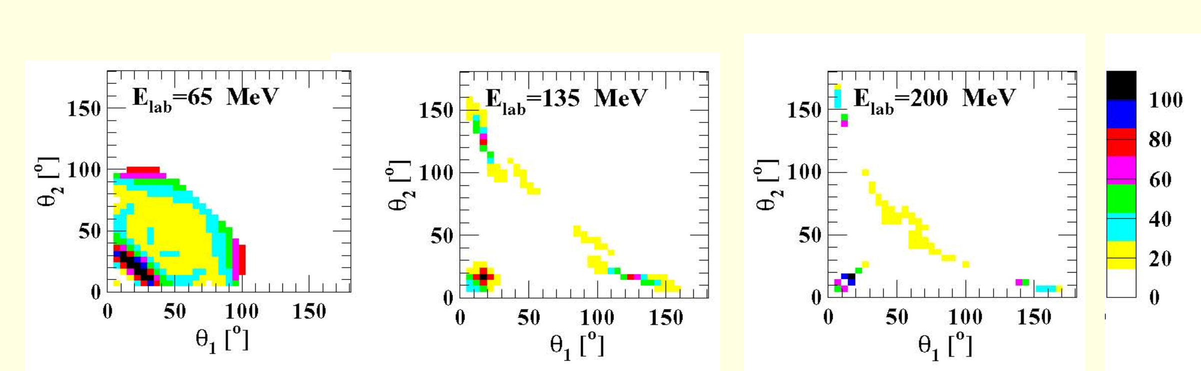

Figure 3. The 3NF theoretical calculations [5] for nd breakup. The coloring represents the difference in cross section between the 2NF [5] and 3NF [5] predictions. The angles θ_1 and θ_2 are the scattered proton and neutron angles. Darker regions are places that are best for studying the 3NF. [6-8]

5. Conclusion

During the summer of 2007 data were collected for nd breakup. Data analysis is currently underway and the expected completion of the analysis is June 2009. Due to the fact that the incident pulsed neutron beam had a much lower repetition rate than originally planned, it is unlikely that a statistically meaningful conclusion will be reached. However, if the results are consistent with the 3NF model, this experiment may be continued and more statistics collected.

4.Apparatus

The experiment was performed at the WNR facility at LANSCE. As seen in Figures 4 and 5, a pulsed neutron beam created by the Clinton P. Anderson linear accelerator passed through a fission chamber. The purpose of the fission chamber was to monitor the neutron flux. The neutron beam was then incident upon a liquid deuterium target. These collisions between the neutrons and deuterons can cause the deuterons to break up.

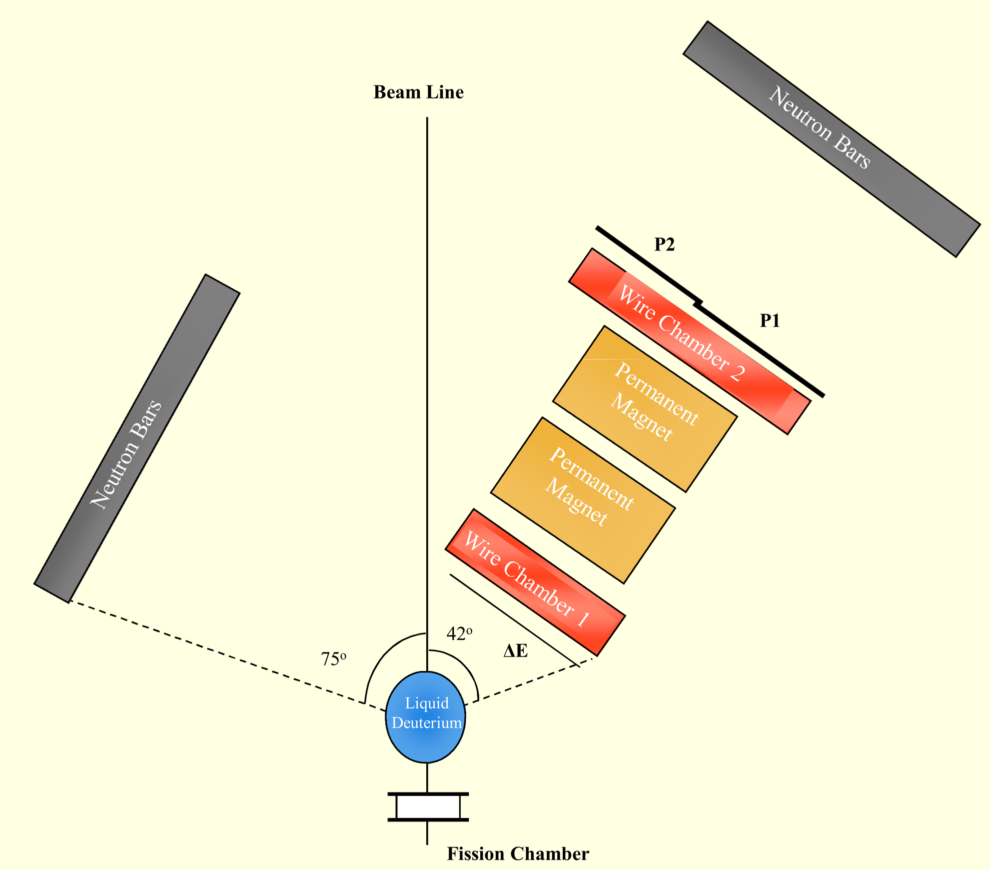

Figure 4. The nd breakup experimental apparatus in the WNR facility at LANSCE.

In order to determine the cross-section, detectors were set up at angles ranging from 5 to 42 degrees on beam right. Protons were detected first by a 2.5 mm thick plastic ΔE scintillator. Once the protons passed through the ΔE scintillator, they traveled through a permanent magnet spectrometer, consisting of two wire chambers and SmCo permanent magnets. The spectrometer was used to determine the momentum of the particle passing through it. The wire chambers determined the trajectories of protons passing through the magnetic field. The amount of deflection of the trajectory can be used to determine the proton momentum. At the rear of the spectrometer, protons pass through a thin plastic scintillator (P1 and P2). A proton must hit both the P and ΔE scintillators in order for an event to be recorded by the computer. Since neutrons are not charged, they continue along their original path unaffected by the spectrometer until detected by the neutron detectors. These nine bars are plastic scintillators, each two meters high and 10 cm thick.

The thickness of these bars increases the likelihood of neutron-proton collisions in the scintillator and therefore the probability of neutron detection.

The beam left neutron bars are identical to the ones used on the right side of the beam. Their purpose was to detect the neutrons from quasifree scattering; scattering the incident neutron from the deuterons proton or neutron as if it were alone. Data obtained from these neutron bars are used for normalization.

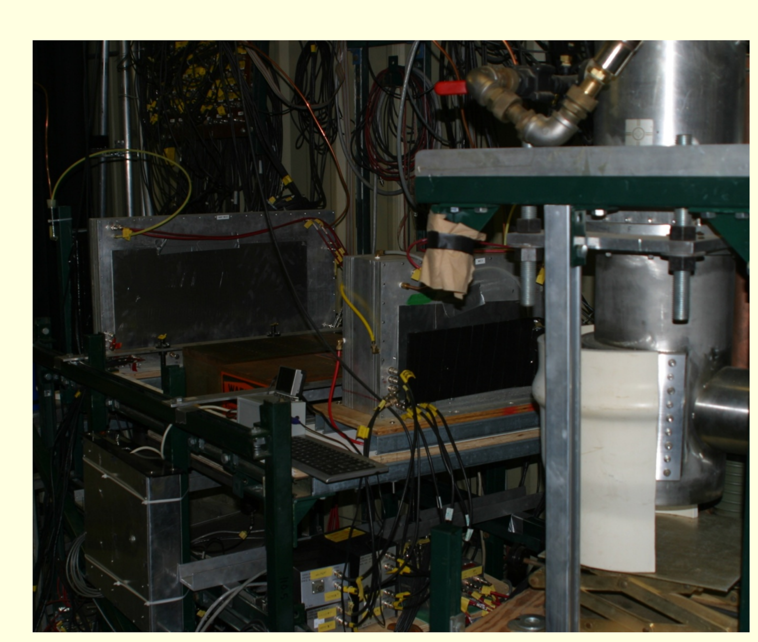

Figure 5. A photograph of the experiment. Nearest to the camera is the liquid deuterium target covered by a white plastic shield. The DE scintillator is in front of the first wire chamber, followed by the magnet (lowered), the rear wire chamber and P1 and P2.