EPJ Web of Conferences **113**, 04010 (2016)
DOI: 10.1051/epjconf/201611304010
© Owned by the authors, published by EDP Sciences, 2016

Neutron-neutron quasifree scattering in *nd* breakup at 10 MeV

R.C. Malone[1,a], B. Crowe[2], A.S.Crowell[1], L.C. Cumberbatch[1], J.H. Esterline[1], B.A. Fallin[1], F.Q.L. Friesen[1], Z. Han[1], C.R. Howell[1], D. Markoff[2], D. Ticehurst[1], W. Tornow[1], and H. Witała[3]

[1] *Department of Physics, Duke University and Triangle Universities Nuclear Laboratory, Durham, NC, USA*
[2] *Department of Physics, North Carolina Central University and Triangle Universities Nuclear Laboratory, Durham, NC, USA*
[3] *M. Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland*

Abstract.
The neutron-deuteron (*nd*) breakup reaction provides a rich environment for testing theoretical models of the neutron-neutron (*nn*) interaction. Current theoretical predictions based on rigorous ab-initio calculations agree well with most experimental data for this system, but there remain a few notable discrepancies. The cross section for *nn* quasifree (QFS) scattering is one such anomaly. Two recent experiments reported cross sections for this particular *nd* breakup configuration that exceed theoretical calculations by almost 20% at incident neutron energies of 26 and 25 MeV [1, 2]. The theoretical values can be brought into agreement with these results by increasing the strength of the $^1S_0$ *nn* potential matrix element by roughly 10%. However, this modification of the *nn* effective range parameter and/or the $^1S_0$ scattering length causes substantial charge-symmetry breaking in the nucleon-nucleon force and suggests the possibility of a weakly bound di-neutron state [3].
We are conducting new measurements of the cross section for *nn* QFS in *nd* breakup. The measurements are performed at incident neutron beam energies below 20 MeV. The neutron beam is produced via the ^{2}H$(d,n)^3$He reaction. The target is a deuterated plastic cylinder. Our measurements utilize time-of-flight techniques with a pulsed neutron beam and detection of the two emitted neutrons in coincidence. A description of our initial measurements at 10 MeV for a single scattering angle will be presented along with preliminary results. Also, plans for measurements at other energies with broad angular coverage will be discussed.

1 Introduction

Despite the success of rigorous ab-initio calculations in predicting most three-nucleon (3N) data, a few notable exceptions remain. One discrepancy between theory and data is the neutron-neutron quasifree scattering (*nn* QFS) cross section in neutron-deuteron (*nd*) breakup. In the quasifree configuration, the projectile transfers momentum to only one of the target nucleons. The other nucleon behaves like a spectator, i.e., its momentum is unchanged by the collision. Measurements of the neutron-proton QFS

[a] e-mail: rm216@phy.duke.edu

This is an Open Access article distributed under the terms of the Creative Commons Attribution License 4.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

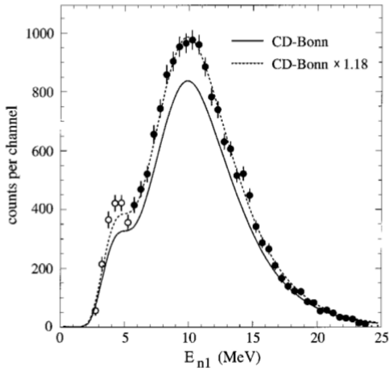

Figure 1. Experimental data (circles) for *nn* QFS scattering in *nd* breakup at 26 MeV. The solid curve is the theoretical prediction from a Monte-Carlo simulation using cross sections calculated with CD-Bonn nucleon-nucleon potential, and the dashed curve represents the simulation scaled by a factor of 1.18. The open circles represent data below the detector energy threshold [1].

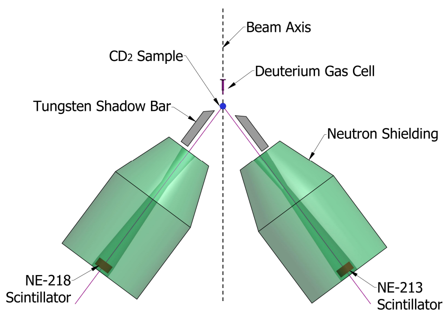

Figure 2. Schematic diagram of the experimental setup for the measurement of the *nn* QFS cross section in *nd* breakup at TUNL (not to scale). The two shielded neutron detectors are placed at equal angles of 36.7° on either side of the beam axis. The two detectors used to monitor the neutron flux are not shown.

cross section are in good agreement with theoretical calculations. However, recent measurements of the *nn* QFS cross section exceed theoretical predictions by almost 20% [1, 2] (see Fig. 1). The theory can be brought into agreement with the data by scaling the $^1S_0$ matrix element by a factor of 1.08. This scaling results in a sign change of the *nn* scattering length, suggesting the existence of a weakly bound di-neutron state. The discrepancy can also be resolved by decreasing the effective range parameter by approximately 10%, implying greater charge-symmetry- and charge-independence-breaking than is expected [3]. Because of the serious implications of this discrepancy, we have undertaken an independent measurement of this cross section.

2 Experimental Setup

Our measurement of the *nn* QFS cross section in *nd* breakup utilized neutron time-of-flight (TOF) techniques. A pulsed neutron beam with a period of 400 ns and pulse width of about 2 ns was used. An uncollimated beam of 10 MeV neutrons produced via the $^2\mathrm{H}(d,n)^3\mathrm{He}$ reaction bombarded a cylindrical deuterated polyethylene target (⌀ = 28.3 mm and h = 36.4 mm). The target was oriented such that its central axis was perpendicular to the incident neutron beam axis. Scattered neutrons were detected by two heavily-shielded liquid scintillators placed at 36.7° on opposite sides of the beam axis (see Fig. 2). Two additional neutron detectors were used to monitor the neutron beam flux.

A minimum detector bias was used to reduce backgrounds from low-energy neutrons and pulse shape discrimination techniques reduced background events from gamma rays. A coincidence between the two neutron detectors was required to identify *nd* breakup events. A two-dimensional coincidence TOF spectrum collected during our measurement is shown in Fig. 3. The raw coicidence

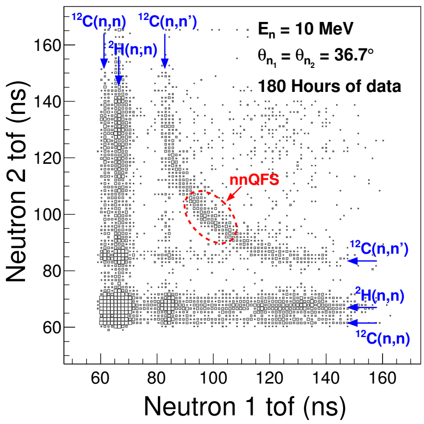

Figure 3. (Color online) Two-dimensional *nd* breakup coincidence spectrum from our measurement. The kinematic locus is clearly visible with the *nn* QFS region circled with a (red) dashed line. Regions with accidental coincidences due to elastic and inelastic scattering are indicated by the (blue) arrows.

TOF spectrum contains both true *nd* breakup events and events due to accidental coincidences. The kinematic locus from breakup events is clearly visible and the quasifree region is well separated from accidental-coincidence backgrounds.

Accidental coincidences are caused by neutrons from two independent events involving neutron scattering from deuterium and carbon. Accidental events were identified using the difference in TOF of the two detected neutrons. The accidental-coincidence backgrounds were measured by forming coincidences of neutrons from two consecutive beam pulses. The net coincidence TOF spectrum is obtained by subtracting the accidental-coincidence spectrum from the raw coincidence spectrum.

3 Preliminary Results

The breakup yields were measured by placing a two-dimensional gate around the experimental kinematic locus and projecting the counts inside this region onto the ideal kinematic locus. The cross section is given by equation 1:

$$\frac{d^5\sigma}{d\Omega_1 d\Omega_2 dS} = \frac{Y_{bu}}{N_n \cdot N_D \cdot \varepsilon(E_1) \cdot \varepsilon(E_2) \cdot \alpha(E_0) \cdot \alpha(E_1) \cdot \alpha(E_2) \cdot d\Omega_1 \cdot d\Omega_2 \cdot dS} \tag{1}$$

where Y_{bu} are the breakup yields, $N_n \cdot N_D$ is the integrated beam-target luminosity, $\varepsilon(E)$ is the neutron detection efficiency, $\alpha(E)$ is the neutron transmission through the sample, and $d\Omega$ is the detector solid angle (the subscript 0 refers to the incoming neutron; the subscripts 1 and 2 refer to the outgoing neutrons). The efficiency factor is for a pulse-height threshold setting of 238.5 keVee ($\frac{1}{2}\times$Cs edge). The luminosity was determined in-situ by normalizing to neutron elastic scattering off of deuterium. Equation 2 was used to calculate the luminosity using the elastic yields (Y_{el}) and the well-established *nd* elastic cross section $\frac{d\sigma}{d\Omega}$ [4]:

$$N_n \cdot N_D = \frac{Y_{el}}{\frac{d\sigma}{d\Omega} \cdot \varepsilon(E_{el}) \cdot \alpha(E_0) \cdot \alpha(E_{el}) \cdot d\Omega} \tag{2}$$

The luminosity measured by the two detectors is then averaged.

The preliminary results of our measurement are shown in Fig. 4, which compares about half of the accumulated experimental data to the theoretical cross section (calculated for a point geometry). There is a systematic uncertainty of ±7% (not shown in the plot) due to uncertainties in the absolute

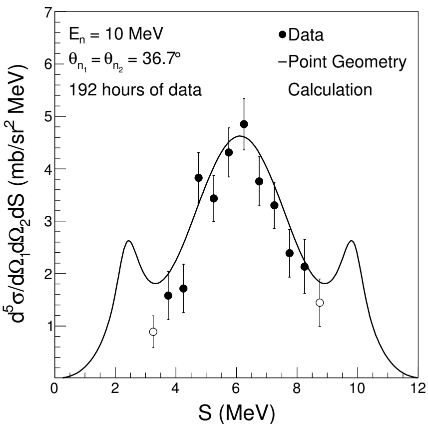

Figure 4. Preliminary results for the *nn* QFS cross section as a function of S (arclength along the kinematic locus). The open circles represent points near the detection energy threshold and have much larger uncertainties than represented on the plot. The theoretical point-geometry cross section was calculated using the CD-Bonn potential. The error bars represent statistical uncertainty only. Systematic uncertainties are discussed in the text.

detector efficiency (5%), the shape of the efficiency curve (3%), neutron attenuation in the sample (2%), and normalization to the *nd* elastic scattering cross section (4%).

A Monte-Carlo simulation is under development to average the theoretical cross section over the finite geometry of the experiment. We do not expect the theoretical prediction to change significantly after implementing the simulation; however, the Monte Carlo will help account for backgrounds associated with the *nd* elastic scattering yields and allow for more accurate determination of the luminosity, which is currently overestimated.

4 Future Work

Data collection at 10 MeV was finished in June. Data analysis is on schedule to be completed by October 2015. A Monte-Carlo simulation is being developed to aid in analysis of current data and to plan future measurements at higher energies. These measurements will be conducted at 13 and 16 MeV at multiple angles using an open detector geometry with a shielded neutron source. Brief tests using the shielded neutron source at TUNL indicate that the signal-to-noise ratio is acceptable to conduct these measurements using this setup. Further tests will be conducted in the fall of 2015.

Acknowledgements

This work is supported in part by the U.S. Department of Energy under grant Nos. DE-FG02-97ER41033 and DE-SC0005367 and by the Polish National Science Center under grant No. DEC-2013/10/M/ST2/00420.

References

[1] A. Siepe, J. Deng, V. Huhn, L. Wätzold, C. Weber, W. von Witsch, H. Witała, W. Glöckle, Phys. Rev. C **65**, 034010 (2002)

[2] X.C. Ruan, Z.Y. Zhou, X. Li, J. Jiang, H.X. Huang, Q.P. Zhong, H.Q. Tang, B.J. Qi, J. Bao, B. Xin et al., Phys. Rev. C **75**, 057001 (2007)

[3] H. Witała, W. Glöckle, Phys. Rev. C **83**, 034004 (2011)

[4] M. Chadwick, M. Herman, P. Obložinský et al., Nuclear Data Sheets **112**, 2887 (2011), special Issue on ENDF/B-VII.1 Library