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Experimental study of neutron-neutron quasifree scattering in the *nd* breakup reaction at 25 MeV

X. C. Ruan,[*] Z. Y. Zhou, X. Li, J. Jiang, H. X. Huang, Q. P. Zhong, H. Q. Tang, B. J. Qi, J. Bao, and B. Xin
China Institute of Atomic Energy, P.O. Box 275(46), Beijing 102413, People's Republic of China

W. von Witsch
Institut für Strahlen-und Kernphysik, Universität Bonn, D-53115 Bonn, Germany

H. Witała
Institute of Physics, Jagiellonian University, Reymonta 4, PL-30059 Cracow, Poland

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Neutron-neutron quasifree scattering in the *nd* breakup reaction at 25 MeV has been investigated. The absolute cross section was determined with an accuracy of a few percentages, normalized by *np* scattering, which was measured simultaneously. The data were analyzed by detailed Monte Carlo simulations based on rigorous 3N Faddeev-type calculations using the CD-Bonn NN potential. The measured cross-section data in this experiment are (16.0 ± 4.6)% larger than the theoretical predictions.

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Special attention has been paid to three-nucleon ($3N$) systems since the Faddeevv theory could be applied rigorously with realistic NN potentials. They became a useful tool for testing and investigating NN forces. Although in most cases the theoretical calculations and the experimental data are in good agreement, a few striking discrepancies still exist in some kinematical configurations. For instance, space-star (SS) and quasifree scattering (QFS) in the nucleon-deuteron (*Nd*) breakup reactions [1–3] cannot be predicted correctly by the theory. Therefore, new experiments in the above configurations are necessary for testing the NN potentials in the $3N$ system. The neutron-induced breakup of the deuteron is one of the most interesting $3N$ systems. The biggest advantage in using this system is that there is no Coulomb force involved in the process. The situation of quasifree scattering is similar to that of the space star, where the theoretically predicted cross sections are overestimated in comparison to *pd* data and underestimated in comparison to *nd* data [2]. The results of a recent *nn* QFS experiment at 26 MeV [4] tell us that the measured yield exceeds the theoretical prediction by about 18%. In this Brief Report we report a new experiment of *nn* QFS at 25 MeV, performed with the *nd* breakup reaction at the China Institute of Atomic Energy (CIAE).

The experiment was performed at the HI-13 tandem accelerator in CIAE. It was basically very similar to the ones performed in Bonn [4]; therefore, only the main experimental differences are described here. Figure 1 shows the experimental setup. The 25 MeV neutrons were produced by the $T(d,n)^4$He reaction. Compared to the $D(d,n)^3$He reaction, the advantage of this neutron source is that the energy of the breakup neutrons from reactions such as $T(d,np)^3$H, $T(d,2n)^3$He, or $T(d,n)^4$ He* are much lower than those of the $D(d,n)$ reaction. The highest energies of the breakup neutrons from $T(d,n)$ and $D(d,n)$ are about 20 and 6 MeV lower than the energy of the monoenergetic neutrons, respectively. The accelerator was operated in pulse mode and the repetition rate of the pulsed deuteron beam was 4 MHz. The average beam current was about 800 nA. A ϕ10 mm × 75 mm gas target filled with tritium gas at a pressure of 2.2 bar was used to produce the neutrons. Another gas cell with ϕ10 mm × 30 mm filled with 0.3 bar helium gas at the upstream end of the tritium gas cell was employed to ensure the safe operation of the tritium gas target. This means that the tritium gas target has two entrance foils and a helium gas cell as a cushion. It can effectively prevent the leakage of tritium gas into the accelerator. The source neutrons were shielded and collimated at zero degrees to form a beam with constant intensity with the size of 30 × 40 mm^2 at the end of the collimator, which was then used to irradiate a cylindrical ϕ20 × 20 mm CD_2 sample. Two BC501A neutron detectors (ϕ180 × 100 mm) were positioned symmetrically at $\theta_n = \pm 42.2^\circ$ with respect to the neutron beam and 80 cm from the CD_2 sample to detect the two neutrons from QFS. The absolute neutron beam fluence was determined by *np* scattering from a thin polyethylene foil of 36.9 mg/cm^2 located between the gas cell and the CD_2 sample. The recoiled protons were detected at 30° by a silicon surface barrier detector △E-E telescope operated in air. The distance between the polyethylene foil and the E detector (center to center) was 30 cm. Thus the absolute cross sections of QFS could be normalized by *np* scattering. Another ST-451 liquid scintillator was positioned at 60° and 2.5 m from the CD_2 sample to detect the elastic scattered neutrons from C and D of the CD_2. Thereby, the absolute cross sections also could be normalized by *n*C elastic scattering. The results from these two normalizations were checked for consistency as a means of assessing the systematic error in the normalization procedure. The particle identification spectrum of energy loss versus the energy deposition in the △E-E telescope is shown in Fig. 2. The recoiled protons from *np* scattering are indicated in the figure. The results of the two normalizations agree with their experimental uncertainties. However, it is more reliable to use np scattering for the normalization than using

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[*] Electronic address: ntof@ciae.ac.cn

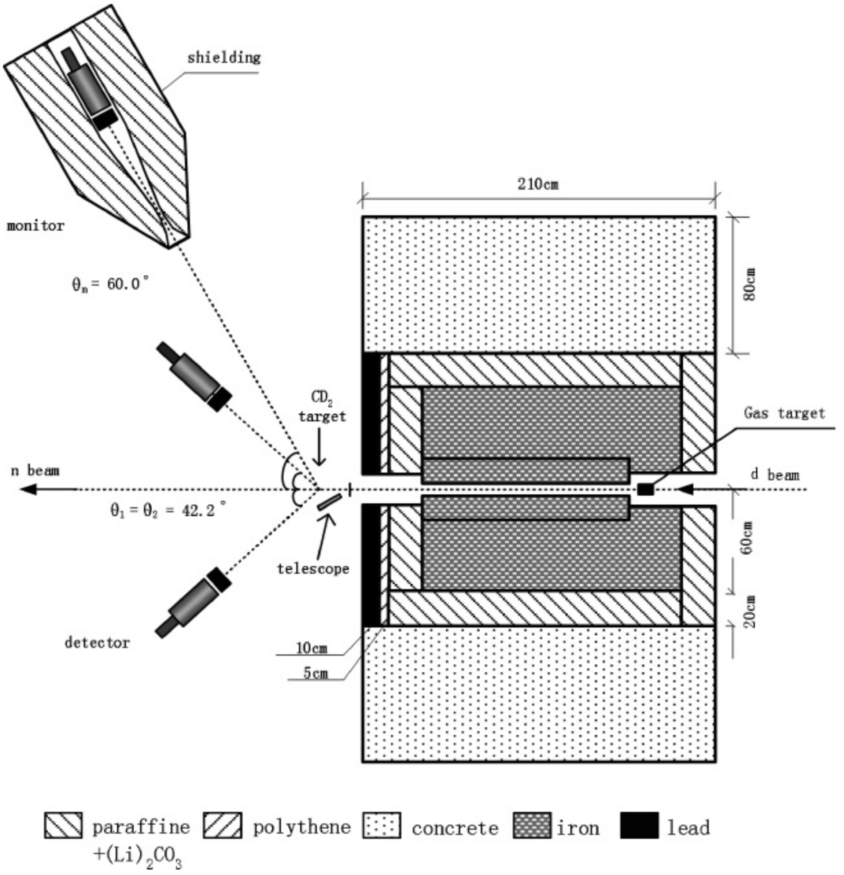

FIG. 1. Schematic view of the experimental setup.

*n*C scattering because the *np* cross section is more accurately known than that of *n*C and also the background in the *np* scattering measurement is much lower than in the *n*C scattering measurement.

The energy of source neutrons from breakup reactions are all below 5 MeV, and they do not affect the measurement of *nn* QFS induced by 25 MeV neutrons when using a detector bias of about 2 MeV neutron energy. The spectator protons are almost at rest during the *nn* QFS process. A twofold coincidence between the two main neutron detectors was used, and the neutron energies E_{n1} and E_{n2} were determined by time-of-flight (TOF) technique using signals from the detectors and from the pulsed-beam pick-off system. In addition, the time difference (TOF_{12}) spectra between the two neutron detectors over three pulsed beam cycles was measured simultaneously. It was used to subtract the accidental background. Figure 3 shows the coincidence logic of the twofold coincidence measurement.

The total effective running time was about 450 h, with 400 h for sample in and 50 h for sample out. The sample-out measurement was realized by replacing the CD_2 sample with a carbon sample (with the same size as the CD_2 sample). The γ positions, the channel width of TACs, and the neutron detection thresholds were also calibrated carefully.

The relative neutron detection efficiency was determined from the calibration of the light output function of the detector with Monte Carlo simulations and corresponding corrections [5]. The absolute efficiency was calibrated at 14.6 MeV using a neutron generator where the neutron fluence at the detector position was determined by counting the associated α particles. The uncertainty of the detection efficiency was about 2%.

First, the raw data were reduced by n/γ discrimination to reduce the γ background. The hardware threshold of the

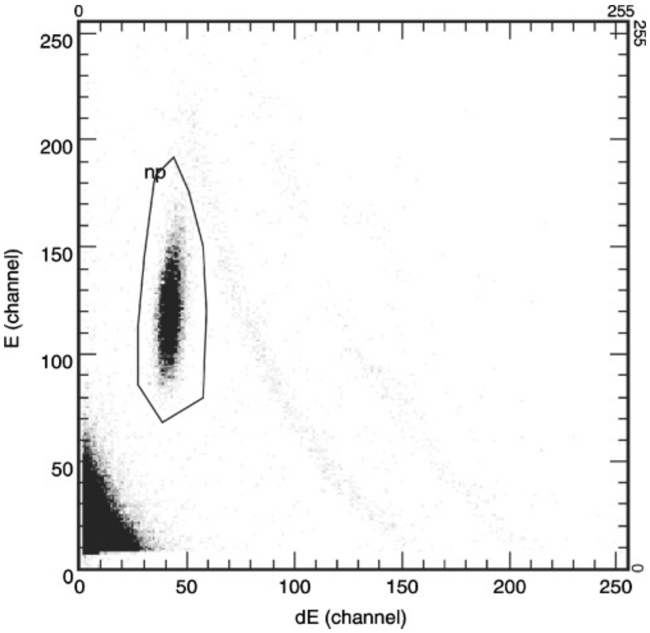

FIG. 2. Recoiled protons measured by the △E-E telescope. The E detector was too thin to stop the protons from elastic *np* scattering.

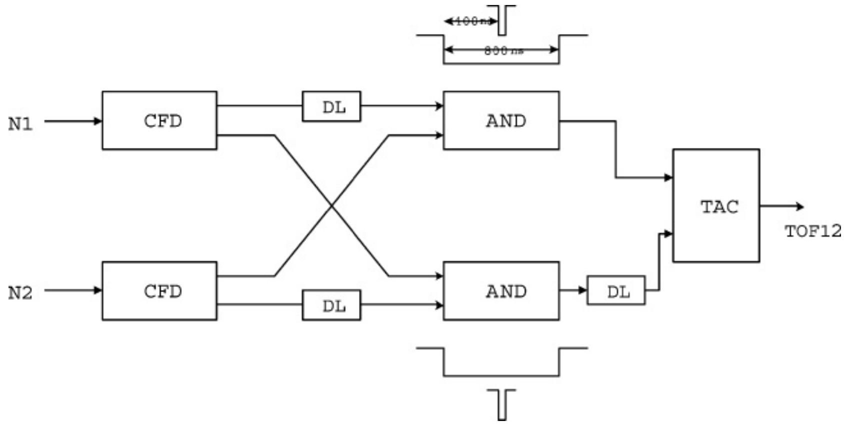

FIG. 3. Coincidence logic of the TOF_{12} measurement.

neutron detection was set at about 0.24 MeVee for the two main detectors and 0.48 MeVee for the monitor, respectively. In the data analysis, the threshold was set accurately by software, with 0.48 MeVee for the main detectors and 0.96 MeVee for the monitor. Then, from the two-dimensional plots of TOF_{12}-TOF_1(or TOF_2) and TOF_1-TOF_2, the true QFS events and the corresponding accidental background could be clearly separated. Figure 4 shows the 2D plot of TOF_{12}-TOF_1.

After background subtraction, the measured neutron spectrum from QFS was analyzed by detailed Monte Carlo simulations based on rigorous three-body calculations with realistic NN potentials. The simulation starts from the incident deuteron. The energy loss of the deuterons in the entrance foil and gas, the neutron production, the QFS process, and neutron detection were simulated in a realistic manner. At the same time, the np and nC scattering processes were also simulated. This simulation yields the neutron energy spectrum from QFS precess with theoretical cross-section data as input of the Monte Carlo code, as well as the number of the recoiled protons and the elastic scattered neutrons by nC scattering, normalized to 1 mC incident deuterons. The corrections due to the flux attenuation, multiple scattering, and finite geometry were included in the simulation. The neutron detection efficiency, the time response function of the neutron detectors and the time resolution of the TOF measurement were also included. Then, the simulated neutron energy spectrum can be compared with the measured one directly after normalizing the the number of simulated recoiled protons or nC scattered neutrons to the measured ones. In our Monte Carlo simulation, the total cross section and differential elastic-scattering cross section for the deuteron were taken from $3N$ theoretical calculations based on CD-Bonn; the cross sections for carbon were taken from ENDF/B-VI, including the total cross section, differential elastic, and first inelastic scattering cross sections.

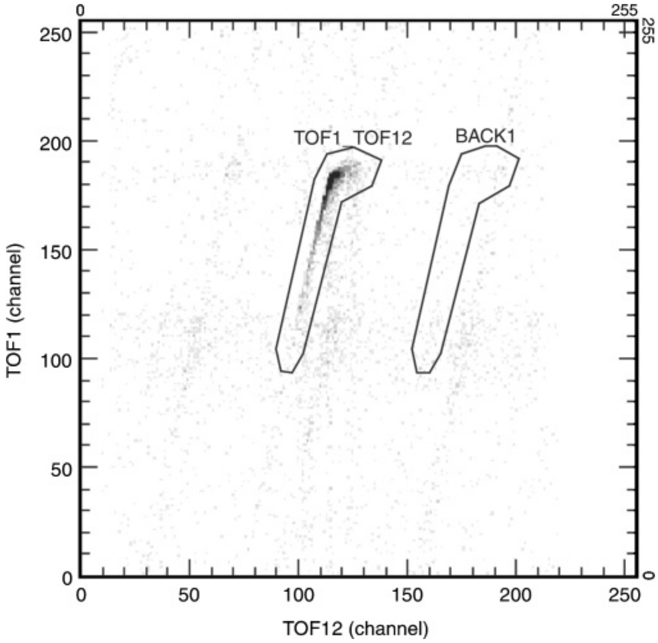

FIG. 4. 2D plot of TOF_{12}-TOF_1. The left window selects the QFS events and the right window the corresponding accidental background in another beam cycle.

Figure 5 shows our measured neutron energy spectrum of QFS compared with the theoretical prediction by Monte Carlo simulation using CD-Bonn, normalized via np scattering. The neutron energy spectrum was deduced from the TOF12-TOF1

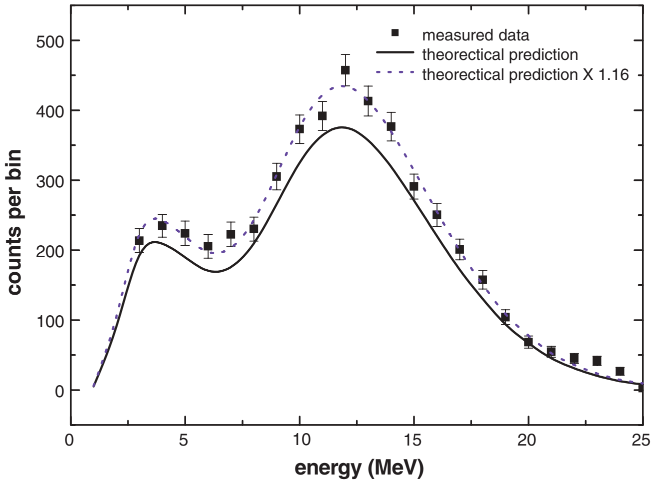

FIG. 5. (Color online) Measured neutron energy spectrum from QFS compared with the theoretical prediction by Monte Carlo simulation based on CD-Bonn. The solid squares show the measured data, and the solid curve is the theoretical prediction, whereas the dotted line gives the theoretical prediction multiplied by a factor of 1.16. The error bars denote the statistical uncertainty only.

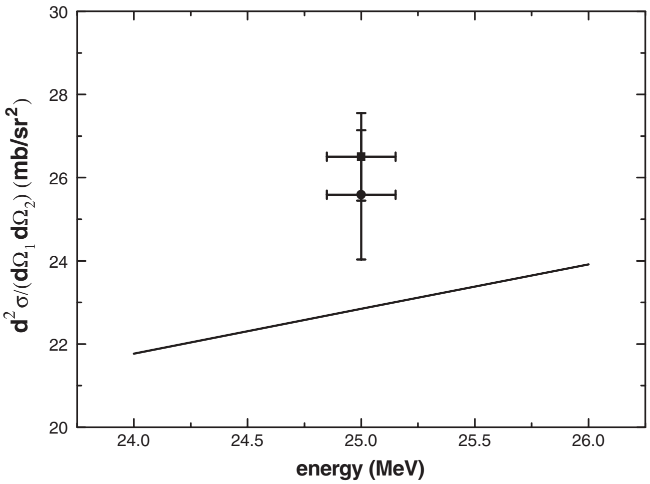

FIG. 6. The measured integral *nn* QFS cross section compared with the theory based on CD-Bonn. The solid square shows the result normalized via *np* scattering, whereas the solid circle is the result normalized by *n*C scattering. Here the energy is the incident neutron energy.

plot by projecting the events in the QFS cut onto TOF1 and then converting the TOF spectrum to energy spectrum after background correction with 1 MeV energy bin. One can immediately see the discrepancy between the measured data and the theoretical prediction. The measured data exceeds the theoretical prediction by (16.0 ± 4.6)%, where the uncertainty includes the statistics over the QFS peak from 8 to 18 MeV (1.72%), the normalization (1%), solid angle of neutron detection (1%), solid angle of recoiled proton detection (0.5%), neutron detection efficiency (2%), Monte Carlo correction (1.5%) and others (we assume 2%). The uncertainty in the Monte Carlo correction mainly comes from the uncertainty of the total cross sections for the deuteron and carbon. Although there is a 16% discrepancy between experiment and theory in the absolute cross section, the shape of the neutron spectra agree with each other very well if the predicted spectrum is multiplied by a factor of 1.16. The fitting χ^2 per degrees of freedom over the QFS peak is 0.73.

The measured result exceeds the theoretical prediction by (12.0 ± 6.8)% if it is normalized by *n*C scattering, assuming an error of 5% for the differential cross section of *n*C elastic scattering. This result, though with larger uncertainty, agrees with the result obtained from *np* scattering within uncertainties.

The integral *nn* QFS cross section of the QFS peak compared with the theoretical one (integrate from 10.5 to 24 MeV along the S curve) based on CD-Bonn was shown in Fig. 6. The result of our experiment agrees with the result obtained in Bonn at 26 MeV [4], where the measured data for *nn* QFS exceed the theory based on CD-Bonn by (17.8 ± 3.2)%, whereas the measured data for *np* QFS agree with the theory very well. Another experiment, at 10.3 MeV [6], also indicated that the measured data exceed the theory by about 13%. From these results, it seems that the discrepancy between experiment and theory in *nn* QFS is real and of similar magnitude as in the space-star anomaly.

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