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Forward- and Backward-Angle Differential Cross Section for Neutron-Proton Capture at 72 MeV

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The neutron-proton capture differential cross section has been measured at extreme forward and backward angles for 72-MeV neutron energy corresponding to a γ-ray energy of 38.2 MeV in the inverse reaction. The results agree well with recent photodisintegration data at forward angles, but only partially with potential model calculations.

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A basic process in the nucleon-nucleon (N-N) field, the deuteron photodisintegration, has recently received much attention, from both the experimental and the theoretical sides. A measurement by Hughes *et al.*[1] of the 0° differential cross section in the γ-ray energy range 20–120 MeV was found to be in disagreement with the Partovi[2] calculation which, it is believed, should be accurate within a few percent if conventional ideas about the two-nucleon interaction are at all correct. A series of calculations were initiated by this discrepancy. Lomon[3] found a moderate sensitivity to the D-state percentage of the deuteron, with a Hamada-Johnston or Feshbach-Lomon N-N interaction. Rustgi, Sandhu, and Rustgi,[4] using supersoft core potentials, somewhat reduced the discrepancy with the data of Hughes *et al.* Arenhövel and Fabian[5] checked the influence of the tensor force in a Holinde-Machleidt potential. Finally, a modification of Siegert's theorem as well as new constraints on the N-N interaction at short distance were discussed.[6] No calculation was really able to reproduce the data of Hughes *et al.* An extensive reference list for this problem can be found in a recent review paper.[7]

In this Letter we report on a measurement of the neutron-proton radiative-capture differential cross section at extreme forward and backward center-of-mass angles, at a laboratory neutron energy $E_n = 72$ MeV, corresponding to $E_\gamma = 38.2$ MeV, and thus close to a measurement of Ref. 1. The goal of this work was to get a deeper insight into the process by a combination of forward and backward cross-section data, in a new experimental approach which, under the assumption of time reversal, is equivalent to photodisintegration, but is subject to different normalization, corrections, and errors.

The experimental setup is depicted in Fig. 1. A 7-μA, 75-MeV proton beam from the Louvain-la-Neuve isochronous cyclotron was focused on a 6-mm-thick Li target and then bent over 20° into a heavily shielded Faraday cup. Neutrons from the Li(p,n) reaction were collimated at 0° by a 1.5-m-long iron collimator defining a 4.5-cm-diam field at 4 m from the target. At that distance, neutrons interacted with a thin liquid-hydrogen target, 7 mm thick and 7 cm in diameter. The hydrogen volume and vacuum vessel were bounded by 12-μm-thick Havar windows upstream, and by Mylar windows downstream of the neutron beam.[8] The high-energy part of the spectrum was selected by time of flight (TOF) between a capacitive beam pickoff located in front of the Li target, and a thin (0.2 mm) plastic scintillator (START). This spectrum is dominated by a monokinetic (72 ± 1 MeV) neutron peak, of intensity 2×10^6 sec^{-1}. Charged particles contaminating the neutron beam were vetoed in front of the hydrogen target by a thin scintillator and two gas proportional counters. Charged particles from the hydrogen target were identified, and their energy selected by (i) TOF between the START scintillator and a second scintillator (STOP), 0.6 mm thick, 1.8 m apart and (ii) a range telescope consisting of seventeen plastic scintillators of increasing thickness ranging from 0.4 to 0.8 mm. Deuterons from radiative capture at 0° and 180° c.m. angles were stopped in the range telescope. Two sets of multiwire proportional counters (MWPC) were used to measure the X and Y deuteron coordinates in order to reconstruct the neutron-deuteron angle. The first one (6×6 cm^2) triggered on charged particles from the target region only, and the second (18×18 cm^2) was located just in front of the STOP scintillator; the wires are 2 mm apart. The MWPC efficiency was measured with low-intensity deuteron and proton beams from the cyclotron. The range telescope was calibrated and its efficiency measured with deuteron beams. The setup was designed in order to minimize multiple scattering of charged particles from the target. The mean multiple-scattering angle measured with 25- and 40-MeV deuteron beams was found to be 9 and 6 mrad, respectively. Three monitors were used during data acquisition: the Faraday-cup current integrator, the detection of protons from n-p elastic scattering at 177° c.m. in a 2-mm-thick scintillator behind the range telescope, and a neutron-beam monitor.

Data were recorded via CAMAC interface on magnetic tape. The monokinetic neutron peak was then selected by software, taking into account the exact TOF of the recoil particle from the hydrogen target to the START scintillator. Deuterons were clearly separated from protons and

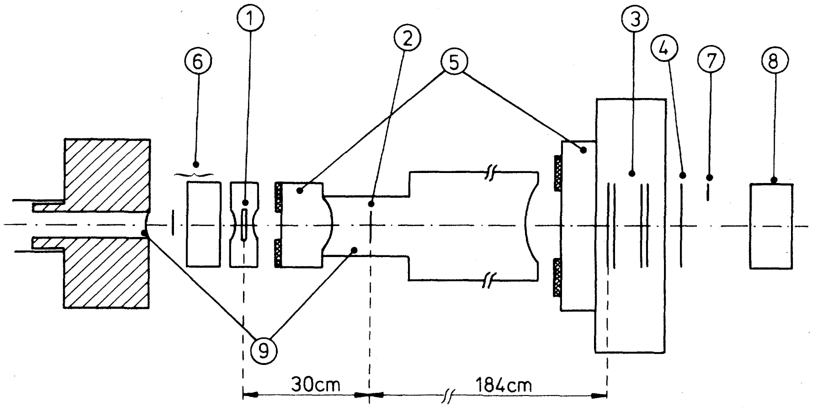

FIG. 1. Experimental setup; 1, liquid-hydrogen target; 2, START detector; 3, STOP detector and range telescope; 4, range limiter; 5, MWPC; 6, veto detectors; 7, proton detector; 8, neutron beam monitor; 9, vacuum chambers.

tritions, by the measurement of their range and TOF (Fig. 2). The contribution of the empty hydrogen target was measured and subtracted. For deuterons, the background versus range was constant, with a signal-to-background ratio of $\frac{1}{2}$. Figure 3 presents a deuteron spectrum showing the deuterons from capture events at forward and backward angles.

The forward and backward differential cross sections were normalized to the total cross section calculated by Partovi. The normalization was done in two steps. First, the forward and backward capture differential cross sections were measured relative to the *n-p* elastic cross section at backward c.m. angle, thus giving

$$\int \frac{d\sigma}{d\Omega}(\theta)\,d\Omega = \frac{N_d}{N_p}\left[\frac{d\sigma}{d\Omega}(177^\circ)\right]_{\mathrm{el}}\Delta\Omega_p, \tag{1}$$

where $[d\sigma/d\Omega(177^\circ)]_{\mathrm{el}}$ is the *n-p* elastic scattering differential cross section at 177° c.m.; $\Delta\Omega_p$ is the proton-detector solid angle in the c.m. system; N_p is the number of protons detected at 177° c.m.; and N_d is the number of deuterons corrected for multiple scattering and reactions (4% and 1.5% at forward and backward angle, respectively), and restricted by the MWPC's to laboratory angles smaller than 32 mrad [corresponding to c.m. limits of 20° (163°) for the forward- (backward-) angle measurements]. $\int d\sigma/d\Omega(\theta)\,d\Omega$ is the capture c.m. differential cross section, integrated over the angular range described above. Second, the capture total cross section was measured relative to the *n-p* elastic cross section. For this, the proton detector was kept at the same position, while the STOP scintillator, range-telescope detector, and second MWPC were brought nearer to the hydrogen target, in order to detect all deuterons from *n-p* capture which are contained in a 6° aperture cone. This second measurement gives

$$\left[\frac{d\sigma}{d\Omega}(177^\circ)\right]_{\mathrm{el}}\Delta\Omega_p = \frac{N_p'}{N_d'}\,\sigma_t, \tag{2}$$

where N_p' (N_d') are the detected numbers of protons (deuterons), and σ_t is the calculated total cross section for radiative capture.[2] From Eqs. (1) and (2) the *n-p* elastic cross section is cancelled out, which makes the present measurement free of experimental error in this quantity.

To extract the differential cross section at 0° and 180° from our integrated measurement, the shape of this cross section has to be known at forward and backward angles. In Partovi's notation, the differential cross section for photodisintegration is written as $d\sigma/d\Omega(\theta) = a + b\sin^2\theta + c\cos\theta + d\sin^2\theta\cos\theta + e\sin^4\theta$. Integrating this expression over our angular limits (c.m.) and assuming Partovi's values for the coefficients b, d, and e at 38.2 MeV, one gets a and c.

The present data are compared in Table I with the Hamada-Johnston and Feschbach-Lomon (5.2% *D* state) calculations at 40 MeV and with two experimental values interpolated linearly at 38.2 MeV: the measurement of Hughes *et al.* at 0°, and a previous photodisintegration experiment[8] analytically extrapolated at 0° and 180° with normalization to the Partovi total cross section.

The errors quoted on our data are purely statistical. Systematic errors which could affect

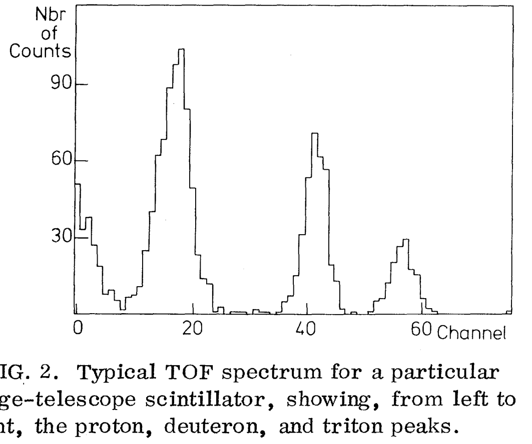

FIG. 2. Typical TOF spectrum for a particular range-telescope scintillator, showing, from left to right, the proton, deuteron, and triton peaks.

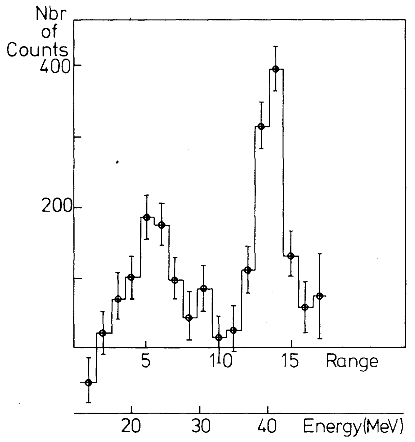

FIG. 3. Range spectrum of the deuterons after background subtraction. The abscissa, labeled "Range," actually represents the range-telescope scintillator number. The two peaks correspond to deuterons at backward and forward angles.

TABLE I. Results of the present experiment, converted into photodisintegration cross section ($E_\gamma = 38.2 \pm 0.5$ MeV), compared with data of Hughes *et al.* and Weissman and Schultz (WS) at the same energy and with calculations using a Hamada-Johnston (HJ) potential, or a Feschbach-Lomon (FL) potential with a 5.2% D-state term ($E_\gamma = 40$ MeV). All numbers are in μb/sr. The quoted experimental errors for the present experimental values are statistical and are obtained from a combination of three independent runs.

	This experiment	Hughes *et al.*[a]	WS[b]	HJ[c]	FL[d]
$d\sigma/d\Omega\,(0°)$	5.7±0.6	5.2±0.3	6.0±0.8	7.2	6.9
$d\sigma/d\Omega\,(180°)$	6.9±0.6		3.4±0.8	5.2	5.1
a	6.30±0.45		4.7±0.5	6.2	6.0
c	-0.60±0.45		1.3±0.5	1.0	0.9

[a] Ref. 1.
[b] Ref. 9.
[c] Ref. 2.
[d] Ref. 3.

our results are as follows. (i) The normalization to the Partovi total cross section: besides the fact that subsequent calculations differed from Partovi's value by at most 3%, it is known that two measurements[9,10] of σ_t around 40 MeV agree with Partovi (while a third one[11] falls 10 ± 5% below). (ii) The b, d, and e coefficients of the angular distribution: we used Partovi's coefficients, for consistency; a ± 10% change of those coefficients should change our a (c) value by less than 2% (10%). (iii) The effect of neutrons scattered in the iron collimator before reaching the hydrogen target ("penumbra effect"): this was estimated with a Monte Carlo calculation, and affects our cross-section data by less than 1%.

Referring to the goals of this work, the following conclusions can be drawn: (i) The present radiative-capture cross section at 0° confirms the data of Hughes *et al.*[1] and is in agreement with an extrapolation at 0° of a (renormalized) previous photodisintegration experiment.[8] (ii) Our backward cross section is in disagreement with the extrapolated photodisintegration data and with potential model calculations.

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