International Conference on Nuclear Data for Science and Technology 2007
DOI: 10.1051/ndata:07313

Measurement of the D(n,2n)p reaction cross section up to 30 MeV

J.-M. Laborie[1,a], X. Ledoux[1], C. Varignon[1], R. Lazauskas[1,b], B. Morillon[1], G. Bélier[1], D. Doré[2], and N. Arnal[1]

[1] CEA/DAM Île de France – DPTA/SPN, BP. 12, 91680 Bruyères-le-Châtel, France
[2] CEA/Saclay – DAPNIA/SPhN, 91191 Gif-sur-Yvette, France

Abstract. This article presents a running experimental program to measure the neutron-induced deuteron break-up reaction between 5 and 10 MeV, and between 20 and 30 MeV. The measurements are performed with a C_6D_6 detector as deuteron target placed in a beam line of the Tandem 7MV accelerator at Bruyères-le-Châtel, France, dedicated to the use of a 4π neutron detector which allows to measure the two emitted neutrons. This experimental work is done in parallel with an ab initio calculation of the reaction which is sum up in the text. Comparisons to the measured cross section are done together with CENDL2 and ENDF/B-VII evaluations.

1 Introduction

Three nucleon systems are a perfect laboratory to test our understanding of nuclear interactions. One is particularly interested in scattering process, where one is able to test nuclear hamiltonian with different dynamical constraints. Modern theoretical tools now enable an *ab initio* description (exact solution of the problem) of the three-nucleon system for both scattering and bound states. Recently at Bruyères-le-Châtel neutron-deuteron scattering calculations have been performed up to an incident neutron energy of 30 MeV [1]. By solving the three-body Faddeev equations in configuration space, three-nucleon wave functions were obtained and measurable observables were extracted by analyzing wave function asymptotes. In particular one is interested in the total and elastic cross sections, and the break-up cross section with the angular and energy correlations between the three nucleons. To describe the N-N interaction, the Av18 potential [2] that succeeds to reproduce the experimental two-nucleon data was used. Due to the large spatial extension of the deuteron (related to the low binding energy), the three-nucleon force is not expected to manifest in the considered energy range and it was ignored.

In previous theoretical studies of neutron-deuteron scattering [3] it has been demonstrated quasi-perfect ability of realistic interactions to describe experimental data for total cross section and differential elastic cross section. Nevertheless experimental data for differential elastic cross section do not fully cover all angular regions and do not allow to extract the total break-up cross section, for which quality of experimental data does not permit to draw clear conclusions about a full agreement between theory and experiment.

A comparison is done in figure 1 between the calculated cross section and the existing experimental data. Most measurements were made in the 70's and most of the results can be found in the EXFOR database [4]. The data are abundant from the 3.34 MeV reaction threshold up to 15 MeV (full circles in the figure) and the calculation is in agreement within 10-20% whereas the uncertainties rarely undergo 10%. Above

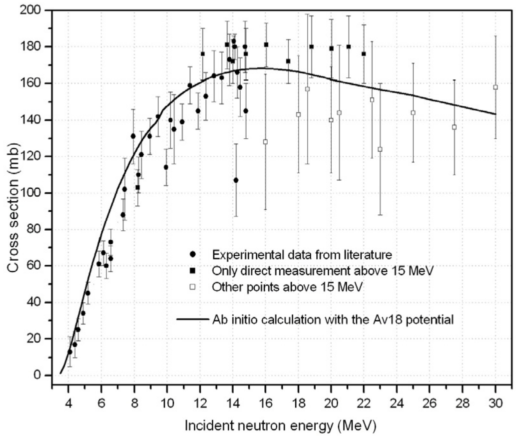

Fig. 1. D(n,2n)p reaction cross section: existing experimental data and the ab initio calculation with the Av18 potential.

15 MeV, Seagrave et al. [5] and Schwarz et al. [6] deduced respectively three and seven data points by subtracting the elastic cross section to the total one (empty squares) with large uncertainties between 18% and 30%. Only Pauletta and Brooks [7] directly measured the break-up reaction and published six data points – 20% higher than those of Seagrave et al. and Schwarz et al. – between 16 and 22 MeV with uncertainties of 7–9% (full squares).

The dispersion and the uncertainties of the existing experimental data as well as the very low number of points above 15 MeV validate the cross section predictions only to around 20%. To go further, new and more accurate experimental data are necessary. Moreover, in order to test the N-N interaction in the deuteron break-up, several authors have recently asked for accurate and coherent experimental data between 8 and 25 MeV [3, 8].

An experimental program has begun on the Tandem 7MV accelerator at Bruyères-le-Châtel, France, to measure the reaction cross section between 5 and 10 MeV with an accuracy less than 10% (the uncertainties are given at a 68% confidence level) and between 20 and 25 MeV where the lack of data is blatant.

[a] Presenting author, e-mail: jean-marc.laborie@cea.fr
[b] Present address: IPN, CNRS/IN2P3, 15 rue G. Clemenceau, 91406 Orsay, France.

In the paper, the measurement method is first given with a description of the setup. Second, the data analysis is described and the preliminary results are given. A discussion follows with a comparison of the results with the ab initio calculation as well as with evaluations of the cross section.

2 Setup and measurement method

2.1 The neutron beam

A low background and collimated beam line was constructed on the Tandem 7MV accelerator at Bruyères-le-Châtel, France [9, 10]. The beam line specifications were defined in agreement with the operating conditions needed by the Carmen detector, described in the next section. The 5–10 MeV neutrons are produced via the D(d,n)^{3}He and T(p,n)^{3}He reactions, the 20–25 MeV neutrons via the T(d,n)^{4}He reaction. The energy spectrum of the incident neutrons exhibits a monokinetic peak corresponding to the above reactions, and a low-energy component due to the deuteron break-up or to reactions on target impurities. The beam is pulsed with a nominal frequency of 2.5 MHz, and the time-of-flight (tof) technique is used to separate the monokinetic peak from the other components. The typical available monokinetic neutron fluxes are 1 $n \cdot cm^{-2} \cdot s^{-1}$ with a solid TiT target and 1000 $n \cdot cm^{-2} \cdot s^{-1}$ with a gaseous D_2 target.

2.2 CARMEN

A 4π neutron detector called Carmen, recently used to measure differential cross sections of (n,xn) reactions on several heavy nuclei [11, 12], is used to count the number of D(n,2n)p reactions by counting the two outgoing neutrons. A scheme of the setup is given in figure 2.

Carmen is a large spherical neutron detector, constituted of two independent vertical hemispheres, 60 cm outer-radius, 15 cm inner-radius, each one filled with less than 0.5 m^3 of gadolinium-loaded scintillating liquid (BC521). The 15 cm detector inner radius area defines the reaction chamber, located at 3.4 m from the neutron production target. A horizontal channel, 5 cm radius, contains the collimated beam and allows the neutrons to reach the reaction chamber, the beam exit being ensured by a rectangular wide-mouthed channel. Twelve photomultipliers surrounding each hemisphere collect the light produced in the scintillator.

When a neutron enters the scintillating liquid, the neutron is slowed down by loosing its energy by inelastic and mainly elastic scattering on hydrogen and carbon nuclei. Since the neutron slows down to the thermal energy it can be captured by a gadolinium nucleus whose de-excitation produces a delayed light signal. Due to the low gadolinium concentration, 0.5% by weight, 50 μs following the first interaction are necessary to capture 99% of the neutrons total number. Several neutrons emitted simultaneously from the primary nuclear reaction are captured at different times and can be counted independently. For each event, two 50 μs gate signals (separated by 50 μs) are generated to measure the neutron and the background multiplicities respectively.

A ^{252}Cf deposit placed at the location of the target is used to measure the Carmen efficiency. A Si junction is used to trigger on the fission events and allows to measure the associated evaporated neutron multiplicities. Taking the mean number of the evaporated neutrons per fission to 3.8, we deduce the Carmen efficiency which is close to 80%. Since the evaporated neutrons energy spectrum can differ from the D(n,2n) neutrons energy spectrum, a correction is calculated with MCNP [13]. For incident 20–25 MeV neutrons the efficiency decreases to 75%.

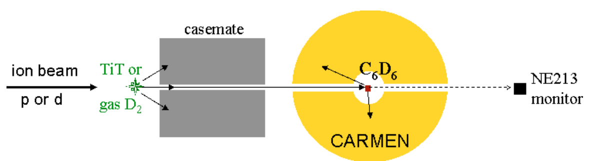

Fig. 2. Setup arrangement.

2.3 The C_6D_6 target

In order to select the monokinetic neutrons and to trigger the experiment, we chose as active deuteron target a 2″ × 2″ C_6D_6 scintillation detector. It is made with the BC537 liquid and sold by Saint-Gobain Crystals&Detectors, associated to a XP2020Q photomultiplier from Photonis. The target is placed inside the reaction chamber of Carmen. The number of target nuclei is $4.06 \cdot 10^{22}$ cm $^{-3}$ and allows to acquire a reasonable statistics of D(n,2n) reactions within some hours to one day.

The trigger signal is induced by the proton recoil from the D(n,2n)p reaction in the target. To avoid a new reaction in the setup the ion beam is deflected with an electric field for the time the detector needs to measure the neutron multiplicity. The number of (n,2n) reactions is then deduced from the number of 2-multiplicity events.

C, Si, O and Al are also present inside or in the close neighbourhood of the target active volume, and the reaction thresholds are 20.3, 8.8, 16.6 and 13.5 MeV for ^{12}C, ^{nat}Si, ^{16}O and Al respectively. To subtract the (n,2n) reactions on these nuclei, a hydrogenated target C_6H_6 is also used. During the experiment, we use alternatively both active targets, and the number of D(n,2n)p reaction is deduced by subtracting the number of (n,2n) reactions per incident neutron measured with the C_6H_6 target to the C_6D_6 one.

The energy threshold on the C_6D_6 and C_6H_6 signal was set at the lowest possible value to minimise the measurement bias. To measure the threshold of the recoil protons in the target, we first calibrated the light response of the detector for electrons: the threshold was put around 10–15 keV electron equivalent (keV ee). The light response to protons and deuterons was measured in a previous experiment in terms of keVee (see figure 3), and a 0.1 MeV threshold was deduced.

2.4 Neutron energy and flux measurement

Two ϕ12.5 cm × 5 cm NE213 scintillation detectors are used to monitor the neutron beam by the ToF technique between

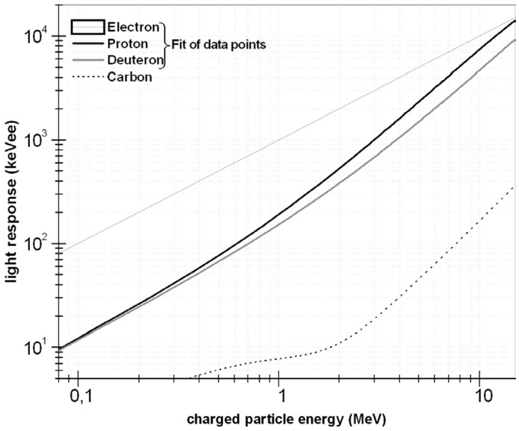

Fig. 3. Light response to charged particles recoil in the C_6D_6 detector.

the production target and the detector. One is placed at the largest distance from the production target (13.4 m) in order to measure the energy of the incident neutrons with the better instrumental resolution. The second one is placed closer to the target in order to measure the neutron flux with a good compromise between statistics and energy resolution. The measured flux is attenuated by the target and must be corrected for: a transmission measurement is made with and without the target in the beam.

The detection efficiency of the NE213 detectors is calculated with the dedicated code SCINFUL [14].

A 2″ × 2″ NE213 detector is used inside the casemate to monitor the instabilities of the neutron beam.

3 Data analysis and results

A first campaign allowed to acquire data at 6.8 and 20.2 MeV. A second campaign have just finished where data were acquired at 5.6, 5.8, 6.3, 6.8 and 9.3 MeV on the one hand, 21.2, 21.8, 22.4, 23.1, 23.6 and 24.6 MeV on the other hand.

3.1 Data reduction

For each energy point, the neutron and background multiplicity distributions are extracted with the selection of the monokinetic peak in the energy spectrum deduced from the tof spectrum between the neutron production target and the active target. The background deconvolution is made to deduce the multiplicity distribution associated to the physics that occurred inside the target. The number of deconvoluted 2-multiplicity events is corrected for the Carmen efficiency, and normalized to the neutron fluence. Then we can make the C_6D_6–C_6H_6 subtraction to get the number of D(n,2n) reactions per incident neutron.

3.2 Monte Carlo simulation

In order to correct the cross section for the finite geometry effect of the target and the loss of D(n,2n)p reactions due to the energy threshold, a Monte Carlo simulation code SIM [15] is used. The energy resolution and the spatial profile of the neutron beam are taken into account, as well as a detailed description of the target. All interactions are simulated. The energy-angle correlations between the two neutrons and the proton are completely taken into account in the simulation of the break-up reaction: the angles and the energies are directly extracted thanks to the break-up amplitudes issued from the resolution of the Faddeev equations. Because of the target thickness, more than one interaction occur in the target with a ~20% chance.

The main target thickness effect is a decrease of the observed number of D(n,2n)p reactions which amounts to 10% and 6% for 5–10 and 20–25 MeV incident neutrons respectively. This effect is mainly attributed to the energy degradation in conjunction with the cross section decrease for energies lower than the incident neutron energy.

To estimate the loss of D(n,2n)p events due to the threshold, the charged particles recoil energy is converted into light response in keVee units with the relations plotted in the figure 3, so that the energy deposits can be summed. With the thresholds mentionned in the paragraph 2.3, the events loss amounts from 2% to 7% depending on the incident neutron energy.

The active volume of the target is surrounded by an expansion chamber with a 10% residual volume in which D(n,2n) reactions can occur and give rise to a trigger signal if one of the two neutrons looses part of its energy in the active volume. The fraction of these extra events is estimated between 3 and 4%.

Then, the measured cross section can be corrected to deduce the experimental microscopic cross section: the total correction factor is close to 1.15 and 1.05 for 5–10 MeV and 20–25 MeV incident neutron energies respectively.

3.3 Uncertainties

The statistical uncertainty on the number of D(n,2n) reactions depends on the counting time as well as on the counting time ratio between the C_6H_6 and C_6D_6 targets related to the (n,2n) count rates ratio. With several hours counting, we obtained in most cases from 3% to 4%.

The other main uncertainties come from the neutron flux measurement and the Carmen detection efficiency. The uncertainty on the neutron flux is dominated by the uncertainty on the detection efficiency of the NE213 monitor and by the uncertainty on the measured transmission of the targets. Today the total uncertainty on normalisation reaches 5–7% and should decrease to 2–4% thanks to the efficiency calibration of the NE213 monitor that we will make at the German primary laboratory of neutron metrology (PTB).

The second major systematic error can come from the Carmen detection efficiency and the uncertainty was evaluated to 3%. Finally the total uncertainty is evaluated from 8.5 to 11%.

3.4 Discussion

Eight among thirteen energy points have been preliminarily analysed. They agree with the old measurements within the

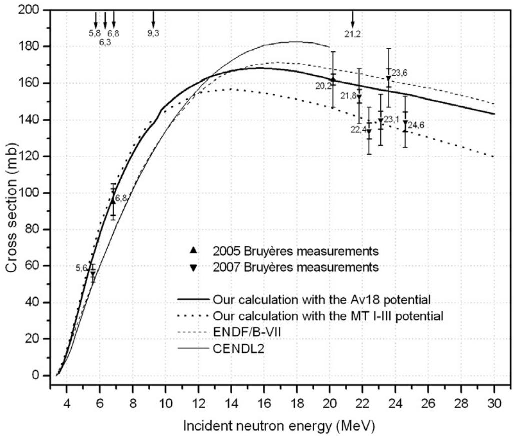

Fig. 4. Measured, calculated and evaluated cross section. The total and the statistical uncertainties are exhibited.

uncertainties. Nevertheless we observe a dispersion in the 20–25 MeV six points: the standard deviation relative to a linear fit is 7% and may be partly explained by the statistics. We see in the figure 4 that the calculated cross section agrees too with most of these new points, the mean discrepancy being 7%.

We have also plotted a previous calculation made with the Malfliet&Tjon I-III potential [16], based on the Yukawa potential. It is worthwhile to observe that despite its simplicity, this potential succeeds to give a result quite close to that obtained with the realistic and much more elaborated Av18 potential. The discrepancy is lower than 10% from the threshold up to 20 MeV and reaches 15% at 25–30 MeV.

The CENDL2 evaluation [17] is plotted in the figure 4. The double differential cross sections are said to be based on the Faddeev equations resolution with the Malfliet&Tjon potential, but the total break-up cross section was adjusted in order to better reproduce the experimental data. Between 5 and 10 MeV, it is found up to 20% lower than our calculation. Above 16 MeV, this evaluated cross section is up to 10% higher than the calculated one, and it agrees better with the old data points of Pauletta&Brooks rather than with ours.

We have also plotted the ENDF-BVII evaluated cross section [18], based on experimental data. It agrees well with the CENDL2 at low energy, but is closer to our calculation at high energy.

Some of the data points remain to be analysed; they are indicated in the upper part of the figure by arrows. Moreover, we plan to make new measurements with long counting times in order to reduce the statistical uncertainty. It should helps to better know the neutron-induced break-up reaction and to appreciate the Av18 potential relevance for the deuteron break-up.

We are very grateful to Dr Jaume Carbonnel who helped us for the ab initio calculations with the Faddeev equations.

References

1. R. Lazauskas, B. Morillon (2005) (private communication).
2. R.B. Wiringa et al., Phys. Rev. C **51**, 38 (1995).
3. W. Glöckle et al., Phys. Rep. **274**, 107 (1996).
4. EXFOR nuclear data library: www.nea.fr.
5. J.D. Seagrave et al., Ann. Phys. **74**, 250 (1972).
6. P. Schwarz et al., Nucl. Phys. A **398**, 1 (1983).
7. G. Pauletta, F.D. Brooks, Nucl. Phys. A **255**, 267 (1975).
8. C.R. Howell, Nucl. Phys. A **689**, 298 (2001).
9. C. Varignon et al., Nucl. Instrum. Meth. B **248**, 329 (2006).
10. I. Lantuéjoul et al., CEA-R-6073 Report, 2005.
11. I. Lantuéjoul, Ph.D. thesis, Université of Caen, décembre 2004.
12. X. Ledoux et al, *Proceedings of the* 2006 *International Workshop on Fast Neutron Detectors and Applications*, http://pos.sissa.it.
13. J.F. Briesmeister (ed.), MCNP – A General Monte-Carlo N-Particle Transport Code, Version 4B, LA 12625-M, Los Alamos National Laboratory, Los Alamos, New Mexico (1997).
14. J.K. Dickens, ORNL-6462 and ORNL-6463, April 1988.
15. B. Morillon, CEA-R-2805, CEA/DEN/Serma, 1996.
16. G.L. Payne, J.L. Friar, B.F. Gibson, Phys. Rev. C **26**, 1385 (1982).
17. CENDL2, dist. october 1995, revision 1.
18. ENDF/B-VII, dist. december 2006.