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Deuteron stripping on beryllium target in the 100–2300 MeV energy range

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Abstract. Cross sections for stripping and dissociation of deuterons interacting with Be targets in the 100-2300 MeV energy range have been measured. Comparisons with model calculations suggest a dominant contribution of the stripping process. It is also shown that the deuteron break-up cross section exhibits the same energy dependence as the nucleon-nucleon cross section.

1 Introduction

Neutron beams are generally produced in $^7Li(p,n)^7Be$ reactions. They show two contributions in the momentum distribution: A quasi monoenergetic peak due to the charge-exchange mechanism and a large spectrum due to the inelastic process. The use of such beams has therefore some drawbacks in the study of neutron-nucleus interactions due to a lack of precise information on the incident momentum of the neutrons.

Neutrons obtained by the dissociation of deuterons show some advantages: Small momentum dispersion, high focussing of the beam and a weak contamination due to inelastic processes. To make use of a fast neutron beam facility, it is usefull to know the rate of neutrons and thus the cross section for stripping and dissociation of deuterons which are the dominant mechanisms producing spectator nucleons (neutrons or protons). The stripping process is defined as a breaking of the deuteron due to the interaction between one of the nucleons with the target nucleus, the other nucleon being spectator in this interaction. Nuclear and Coulomb dissociation is the break-up of the deuteron in its two constituents due to the nuclear or Coulomb field of the target. At high energy ($T_d \geq 650 MeV$), some measurements of break-up deuteron cross sections on various targets have been performed twenty years ago [1–4]. Experimental data did not depend, within experimental errors, on the deuteron energy. This is probably due to the weak energy dependence of the total nucleon-nucleon cross section in this energy range.

Good agreement of the data [1] with the predictions of a model [5] in which the total break-up cross section was considered in the framework of the Glauber theory was obtained.

The differential cross section which allows to calculate the neutron beam intensity is given by [1]:

$$\frac{d\sigma_{s+d}}{d\Omega}(0^0) = \sigma_{s+d}\frac{P_n^2}{2\pi\alpha^2\hbar^2} \qquad (1)$$

where σ_{s+d} is the total cross section for stripping plus dissociation, $P_n \simeq P_d/2$ is the central value of the momentum distribution in the neutron beam, and $\alpha\hbar = 46$ MeV/c. With a Beryllium target, the cross section for stripping and dissociation is taken as $\sigma_{s+d} = 172 \pm 34 mb$ [6]. In the $50 - 100$ MeV energy range, the nucleon-nucleon elastic cross sections increases rapidly with decreasing energy and a corresponding increase of σ_{s+d} in the $100-200$ MeV deuteron energy range is expected.

In this paper, new measurements of deuteron break-up on Be targets are reported as well as a comparison with model calculations.

Table 1. Cross sections for the reaction $^9Be(d,n)$ at $T_d \leq 200 MeV$ using the ToF technique

$T_d(MeV)$	$d\sigma_{s+d}/d\Omega(0^0)(b/st)$	$\sigma_{s+d}(mb)$
100	2.10 ± 0.21	$290. \pm 29.$
150	3.13 ± 0.32	$284. \pm 29.$
200	3.73 ± 0.34	$251. \pm 23.$

2 Experimental procedure

The experimental apparatus is similar to the one used for the measurement of neutron spectra in spallation processes [7,8]. Two different experimental techniques were used according to the neutron energy: Low energy neutrons were measured using a time-of-flight technique while high energy neutrons were detected using a liquid hydrogen as a converter followed by a magnetic analysis with help of a spectrometer.

2.1 Measurement of low energy neutrons

The method is based on a time-of-flight technique between the tagged incident deuterons and a liquid $NE213$ scintillator DEMON [12] to measure neutron energy spectra from 2 to 400 MeV at the synchrotron SATURNE at Saclay. The neutrons pass through a cylindrical collimator with a diameter larger than the diameter of the DEMON scintillator with a solid angle of $0.2816 msr$ at 0^0 corresponding to a distance between the Be target and a DEMON cell of $8.45m$. Deuterons that did not interact with the Be target and protons emitted in the forward direction are swept away by a magnet. More, a 3mm thick plastic scintillator was placed in front of the DEMON detector to reject charged particles produced in the collimator. For such measurements, deuteron beams with energies of $100, 150, 200 MeV$ were used with 3mm beryllium thick targets.

The efficiency of the DEMON cells were measured at TSL (Uppsala) with a source of tagged neutrons [13]. Each neutron was tagged by elastic scattering with a proton whose trajectory reconstruction provides according to two-body kinematics, the energy and angle of the tagged neutron.

The ratio of detected neutrons over incoming neutrons gives the detection efficiency with an accuracy less or equal to 1.5%. Efficiencies of $.321, .276, .256$ for respectively $50, 75, 100$ MeV neutron energies were obtained.

The number of detected neutrons at 0^0 divided by the efficiency, the number of incident deuterons, the solid angle and the density of the liquid scintillator allows to derive the differential cross section $d\sigma_{s+d}(0^0)/d\Omega$ and the associated total cross section σ_{s+d} (relation 1). Results are presented in Table 1. The incertainty on σ_{s+d} comes only from the incertainty on $d\sigma_{s+d}(0^0)/d\Omega$. One notices that the relation (1) has been derived [1] assuming that the transverse component of the momentum is limited to very small angles. In our experiment, the solid angle of the DEMON detector gives a maximum value of the transverse momeutum close to $3MeV/c$. This justifies the use of the expression (1) to evaluate the total cross section σ_{s+d} and the associate errors.

Table 2. Cross sections for the reaction $^9Be(d,n)$ using Proton recoil spectrometer ($T_d \geq 400 MeV$)

$T_d(MeV)$	$\frac{d\sigma_{s+d}(0^0)}{d\Omega}(b/st)$	$\sigma_{s+d}(mb)$	
400	6.33 ± 0.95	$202. \pm 30.$	$(np \rightarrow pn)$
800	13.06 ± 1.96	$190. \pm 29.$	$(np \rightarrow pn)$
	15.66 ± 2.30	$228. \pm 34.$	$(np \rightarrow d\pi^0)$
	15.73 ± 2.40	$229. \pm 34.$	$(np \rightarrow d\pi^0)$
1000	15.59 ± 2.34	$174. \pm 26.$	$(np \rightarrow pn)$
	14.65 ± 2.40	$175. \pm 34.$	$(np \rightarrow d\pi^0)$
	16.47 ± 2.49	$184. \pm 26.$	$(np \rightarrow d\pi^0)$
1200	20.76 ± 3.11	$186. \pm 28.$	$(np \rightarrow pn)$
	18.99 ± 2.79	$170. \pm 25.$	$(np \rightarrow d\pi^0)$
	20.81 ± 3.10	$185. \pm 28.$	$(np \rightarrow d\pi^0)$
1400	25.90 ± 3.89	$191. \pm 29.$	$(np \rightarrow pn)$
	28.40 ± 4.19	$209. \pm 31.$	$(np \rightarrow d\pi^0)$
	26.40 ± 4.51	$194. \pm 29.$	$(np \rightarrow d\pi^0)$
1600	32.33 ± 4.85	$200. \pm 30.$	$(np \rightarrow pn)$
	40.48 ± 8.10	$251. \pm 38.$	$(np \rightarrow d\pi^0)$
	35.30 ± 7.04	$219. \pm 32.$	$(np \rightarrow d\pi^0)$
2000	41.71 ± 6.26	$193. \pm 29.$	$(np \rightarrow pn)$
2300	49.17 ± 7.38	$188. \pm 28.$	$(np \rightarrow pn)$

2.2 Measurement of high energy neutrons

The method is based on the detection of particles produced by the interaction of neutrons with an hydrogen converter. Identification and evaluation of the particle momentum are made by using a magnetic spectrometer with a trajectory reconstruction and a time-of-flight measurement. The mass resolution was good enough to allow the identification of protons, deuterons and pions. The absolute calibration of the deuteron flux was performed through an activation measurement of carbon foils irradiated by the deuteron beam [9]. The precision obtained with such a calibration technique was found of the order of ±4%.

An integration over the elastic scattering peak of the proton spectrum in the $0 - 3^0$ angular range gave the number of detected particles. Combined with the elastic cross section [10], it provided the neutron flux. The neutron energy is limited to a minimum energy of $200 MeV$ ($T_d \geq 400 MeV$) due to the energy loss of the recoil proton in the magnetic spectrometer (air and detectors). A similar treatment was applied to the deuteron spectrum. The cross sections of the $np \rightarrow d\pi^0$ [11] reaction is another way to estimate the neutron flux up to 800 MeV neutron energy. Above this energy, it becomes difficult to separate the deuteron produced by the $np \rightarrow d\pi^0$ reaction from those created in $np \rightarrow d\pi^+\pi^-$ processes. The differential cross section $d\sigma_{s+d}/d\Omega(0^0)$ and the associated total cross section derived from equation (1) are presented in Table 2.

Concerning the $np \rightarrow d\pi^0$ channel, two cross sections corresponding to the two kinematical solutions for

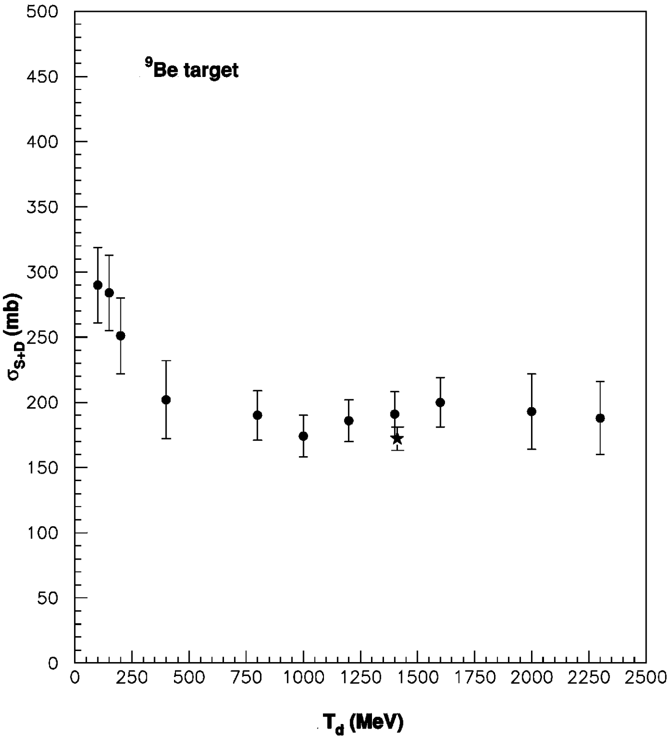

Fig. 1. Energie dependence of the total cross section for stripping and dissociation of deuterons interacting with Be target (($\star$): data from [1])

the deuteron emission angle were derived. The difference between the cross sections obtained by using the $np \rightarrow pn$ cross sections with those obtained in the case of of $np \rightarrow d\pi^0$ reactions does not exceed 15%. Results are compatible with previous data ($\sigma_{s+d} = 172. \pm 34.mb$ at $T_d = 1412 MeV$) [1].

Figure 1 shows the mean value of σ_{s+d} weighted by the inverse of the associated error squared in the $100 - 2300$ MeV deuteron energy range. The general evolution with energy is similar to the behaviour of the total nucleon-nucleon cross section. A weak (within experimental errors) energy dependence of the cross section σ_{s+d} in the $400 - 2300$ MeV deuteron energy range and an increase at lower energies below 400 MeV are observed.

3 Comparison with theories

At high energy, the total break-up cross section has been calculated by Fäldt [5,14]. In the present work, the same model has been used and the energy dependence of the nucleon-nucleon cross section was considered in the formalism. The stripping reaction represents the main part of the break-up cross section ($\geq$ 85%) for light nuclei. The Coulomb dissociation cross section is comparable in magnitude with the one associated with nuclear dissociation. The stripping contribution is related to the so-called generalized nucleon numbers [14] $N_0(\sigma)$, and $\delta N(\sigma)$ defined as:

$$N_0(\sigma) = \frac{1}{\sigma} \int d^2\mathbf{b}(1. - e^{-\sigma T(b)}) \tag{2}$$

$$\delta N(\sigma_p, \sigma_n) = \frac{2\pi}{\sigma R_d^2} \int b_+ d^2 b_+ \int b_- d^2 b_- I_0(\frac{2b_+ b_-}{R_d^2}) \times e^{-\frac{b_+^2 + b_-^2}{R_d^2}} (1 - e^{-\sigma_p T(b_+)})(1 - e^{-\sigma_n T(b_-)}) \tag{3}$$

where $T(b)$ is the two-dimensional nucleus target thickness

$$T(b) = A \int dz \rho(b, z) \tag{4}$$

The integrals were performed with the Gauss method using a Gaussian or a Woods-saxon nuclear density distribution for the target coupled with a Gaussian deuteron wave function.

The neutron stripping cross section is expressed as:

$$\sigma_{n,strip} = \sigma_p N_0(\sigma_p) - (\sigma_p + \sigma_n)\delta N(\sigma_p, \sigma_n) \tag{5}$$

in which:

$$\sigma_n = \frac{Z}{A}\sigma_{np} + \frac{N}{A}\sigma_{pp} \tag{6}$$

and

$$\sigma_p = \frac{N}{A}\sigma_{np} + \frac{Z}{A}\sigma_{pp} \tag{7}$$

Total cross sections σ_{np} and σ_{pp} were calculated using simple parametrizations proposed in [15].

Nuclear and Coulomb dissociation cross-sections, whose expressions may be found in the original paper [5], have been evaluated neglecting the Coulomb-nuclear interference term. For light nuclei this contribution is very small.

The energy dependence of $d\sigma_{s+d}/d\Omega(0^0)$ versus the neutron momentum P_n is shown in Fig. 2. The curve (labelled c) corresponds to a constant break-up cross section $\sigma_{s+d} = 172 \pm 9 mb$ [6]. The curves (labelled a and b) are the results of the calculation with two different nuclear density distributions (respectively Woods-Saxon and Gaussian). The observed differences are due essentially to the energy dependence of the nucleon-nucleon cross section.

Another way to evaluate the differential cross section $d\sigma_{s+d}/d\Omega(0^0)$ is to calculate the amplitude corresponding to the diagram displayed in Fig. 3. The non-relativistic limit of the deuteron vertex function dpn [16] is related to the deuteron wave function $\Phi(\mid \boldsymbol{P_n} - \boldsymbol{P_d}/2 \mid)$ and the sub-process pA (the interaction of the proton with the target) is factorized. Then, the double differential cross section corresponding to the spectrum of the neutron in the laboratory system writes:

$$\frac{d^2\sigma}{dp_n d\Omega_n} = KS\Phi(\mid \boldsymbol{P_n} - \boldsymbol{P_d}/2 \mid) \int \mid T_{pA} \mid^2 d\Omega_{cm} \tag{8}$$

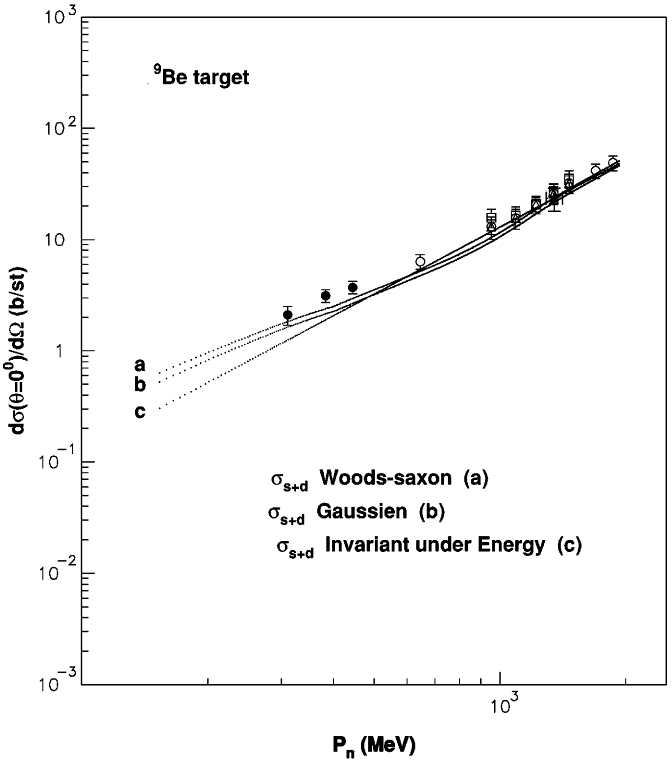

Fig. 2. Stripping and dissociation differential cross section at zero degree laboratory angle as a function of the neutron momentum (($\star$): data from [1]). The solid curves are the results of calculations using the Fäldt model (see text)

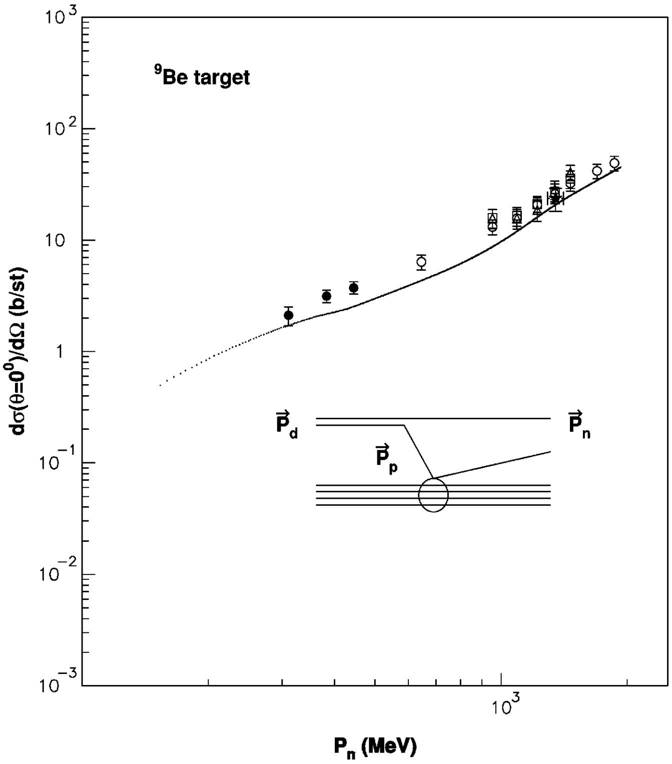

Fig. 3. Stripping and dissociation differential cross section at zero degree laboratory angle as a function of the neutron momentum (($\star$): data from [1]). The solid curve is the result of calculations corresponding to the displayed diagram

where K,S are respectively a numerical constant and the invariant phase space factor. A parametrization of the Reid soft-core wave function [17,18] with only $l = 0$ (S-state) was used for the evaluation of Φ. The integral over the solid angle Ω_{cm} of the proton in the CM frame of the recoiling pA sub-system, is related to the cross section σ_{pA}. Thus, the differential cross section is given by:

$$\frac{d\sigma}{d\Omega_n} = K'S' \int \Phi(\mid \boldsymbol{P_n} - \boldsymbol{P_d}/2 \mid)\sigma_{pA} dp_n \qquad (9)$$

In neutron-stripping reaction, which is the main part of the break-up cross section, the neutron suffers no collision, whereas the proton collides inelastically. Therefore, a parametrization of σ_{pA} of the $p+^9B_e$ non-elastic cross section was used [19]. The result of the calculation is shown in Fig. 3. The general trend is similar to the predictions of the previous model. More, a detailed analysis of the result shows that the effect of the nucleon-nucleon cross sections which increases below 400 MeV is partially counterbalanced by the invariant space phase factor which decreases rapidly with decreasing energy. The calculation underestimates the data by roughly a factor 1.5. This could be due to the following approximations:

– We take into account only the stripping process and not the Nuclear and Coulomb dissociation processes which would require a much more involved model (however, these contributions are not expected to be more than 15% of the total cross section).

– The proton-nucleus interaction is described schematically only by considering the non-elastic process with no contribution from a possible quasi-elastic interaction. More, the parametrization of the non-elastic cross section may be questionable for such a light nucleus as ^9B_e.

4 Conclusions

We have measured the cross section for stripping and dissociation of deuterons on Be in the 100 – 2300 MeV incident energy range. Data have been compared sucessfully with two theoretical models. It has been shown that the break-up deuteron cross section has the same energy dependence as the nucleon-nucleon cross section. The dominant contribution in d-Be reactions is the stripping process in which the proton from the deuteron interacts with the nucleons of the target whereas the neutron is emitted freely at forward angles.

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