MEASUREMENT OF NEUTRON SPECTRA FROM THICK Be TARGET BOMBARDED WITH DEUTERONS

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ABSTRACT

Neutron spectra of Be(d,n) reaction were measured for deuteron energies from 13.5 to 22 MeV by using a stilbene scintillator detector and flight time technique. A special calibration method of neutron detector efficiency for higher energy portion was adopted. The spectral neutron yield per unit beam charge on the Be target at 0° was determined. The fluence-averaged mean neutron energies of the neutron spectra are given as a function of the incident energy for several thresholds. The measured neutron spectra have an almost same shape at different incident deuteron energies. High energy portion (E_n>1.8MeV) and low energy portion (E_n<2.0MeV) of the neutron spectra were separately measured and they were concerned with each other by normalization. The energy range of whole neutron spectra is 0.7 MeV to 30 MeV.

Keywords Neutron spectrum, Be target, Deuterons

1 INTRODUCTION

During the past years, considerable attention was paid to various properties of intense neutron sources produced by deuteron bombardment on thick light element targets[1−4]. Technical and economic reasons favored the deuteron incident reactions on thick Be targets as powerful neutron sources. Information on outgoing neutrons is important for their applications in radiobiology, radiotherapy and material research. The standard neutron spectra can be used for testing neutron integral data measurement. It also provides a simple and effective method to test neutron detector efficiency in wide energy range.

The neutron spectra at 0° from a thick Be target hit with deuterons were measured in present work at E_d=13.5, 15, 17, 20, and 22 MeV. For discriminating γ rays from neutrons, a special technique was developed, so that the neutron energy threshold can be set as low as 0.5 MeV, which is equivalent to an electron energy about 40 keV(1/12 Cs) in our detector. The neutron detector efficiency below 20 MeV was calculated by Monte Carlo method and confirmed experimentally, and one above 18 MeV was got by measuring the neutron angular distribution of T(d,n)^{4}He reaction at E_d=10 MeV. The

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full neutron spectra were obtained by treating high energy (E_n>1.8 MeV) and low energy (E_n<2.0 MeV) portion respectively and then connecting them in a small overlap energy range from 1.8 to 2.0 MeV. The experimental arrangement is described in section 2. The response and efficiency of the neutron detector are dealt with in section 3. The data acquisition, treatment and result are presented in section 4 with discussions and comparison with other data.

2 EXPERIMENTAL ARRANGEMENT

The measurement has been performed with the neutron time-of-flight(TOF) spectrometer at the HI-13 tandem accelerator facility of China Institute of Atomic Energy. The neutron TOF spectrometer is described in detail in Ref.[5]. The detector was positioned at 0° with respect to the beam direction. In order to achieve a time interval of 1 μs corresponding to a neutron energy range from 0.5 to 30 MeV for the flight path of 6.76m, the beam pulse frequency of the accelerator must be chosen as 1 MHz.

The charged particle beam was centered on the Be target by means of the beam scanners and apertures. Apertures number should be minimized to reduce the neutrons

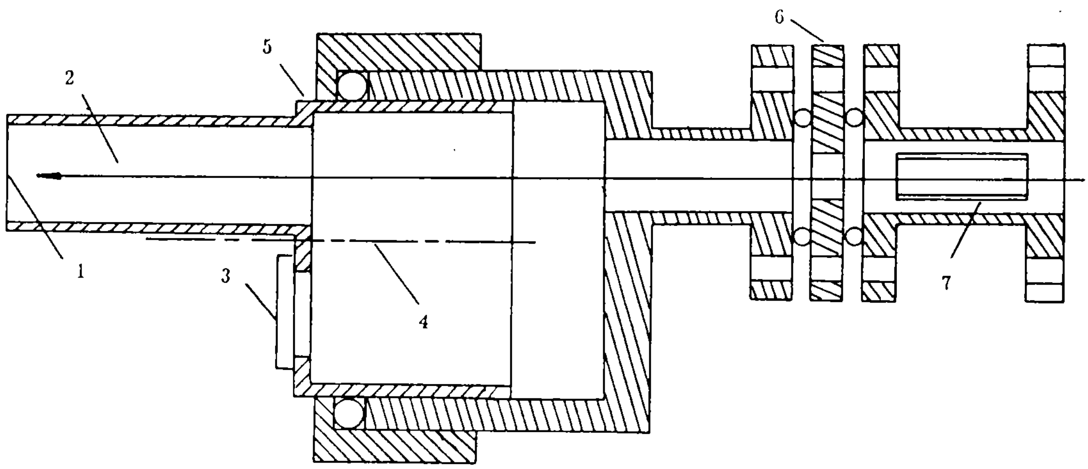

Fig.1 Schematic illustratioh of target arrangement
1) Be disk target 2) Beam line 3) Quartz glass 4) Rotation axis line
5) Rotational casing 6) Negative voltage cycle 7) Capacity pickup pipe

coming from break up reaction and clipping reaction of the deuteron beam on aperture material. To stop all deuterons with the highest incident energy (E_d=22 MeV), it is necessary to take the target thickness of about 3mm. Fig.1 shows some details of the target arrangement. The target with diameter of 25mm was composed of Be(99.2 %), O(0.49 %), Fe(0.115 %), Al(0.056 %), C(0.059 %), Si(0.018 %) and others (0.062 %). A capacity beam pickup system was installed to draw timing signals of the pulsed beam for TOF measurements. A steel ring next to the Be target chamber was supplied with a negative voltage to suppress secondary electrons emitted from the target. There exists a special monitoring window with combining a quartz glass in the target chamber, which can substitute for the Be target by rotating the chamber for 180° in keeping vacuum condition. The beam properties (beam position, size and shape) can be monitored before and after using the Be target. A stilbene scintillator 1' in thickness and diameter covered with a cylindrical aluminum container was coupled to a fast photomultiplier XP-2020 as neutron detector. A block diagram of electronics is shown in Fig.2.

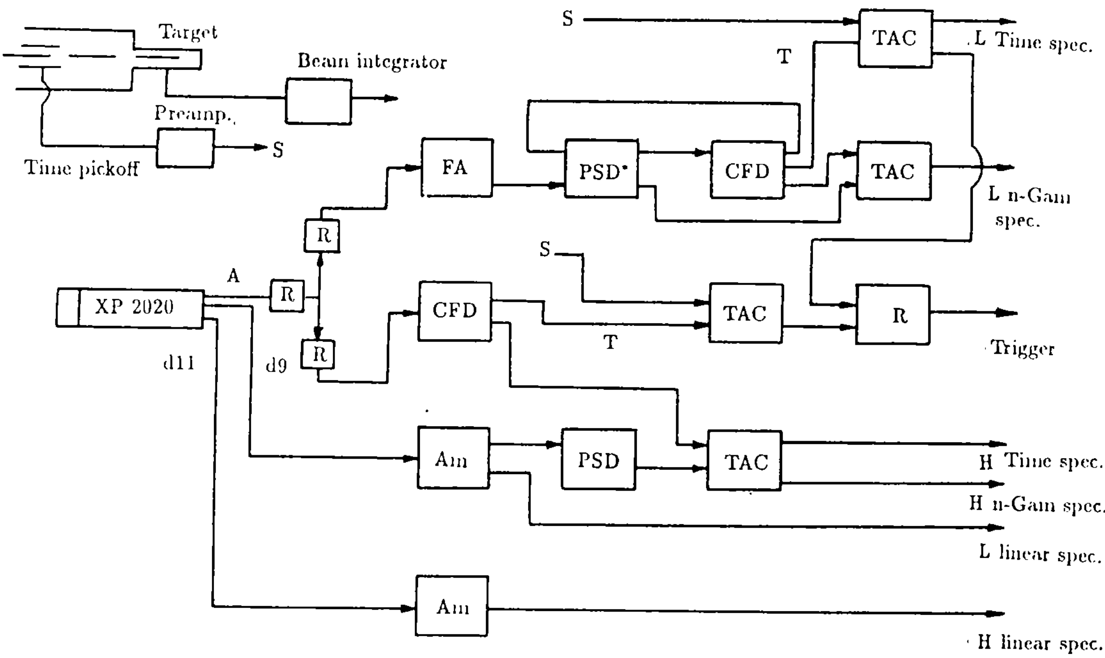

Fig.2 Block diagram of the electronics

FA–Fast amplifier, CFD–Constant fraction discriminator, PSD–Pulse shape discriminator ("*"–Canberra 2160, ORTEC 552), R–Resistance, Am–Amplifier, TAC–Time amplitude converter

The neutron energy range to be measured is corresponding to a dynamic range of about 150:1. Because of the limited dynamic, range of some electronics modules, it is difficult to get good condition of n-γ discrimination (specially in low energy portion) during measurement, whole neutron TOF spectra had to be divided into two portion, which were measured separately and simultaneously. The high energy portion above 1.8 MeV is measured with three thresholds of E_e=1/2Cs, 1 Cs and 2Cs respectively, which are corresponding to E_p=1.6 MeV, 2.15 MeV and 4.4 MeV respectively. A regular electronics configuration was used in the measurement. The low energy portion under 2.0 MeV was measured with low threshold of E_e=40 keV(1/12 Cs). In this case, the timing signals from the neutron detector must be amplified with an extra fast amplifier

ORTEC 574 (FA) before they were fed into a constant-fraction discriminator ORTEC 583 (CFD), then some high amplitude signals in FA were seriously saturated, so that the upper level threshold of the CFD must be set up to cut the saturated pulses. For the low energy portion, it is important that the resistance chain of the photomultiplier must be adjusted carefully for good signal-to-noise ratio. Two pulse shape discriminators were used for two portion respectively, the typical n-γ discrimination spectra obtained are shown in Fig.3.

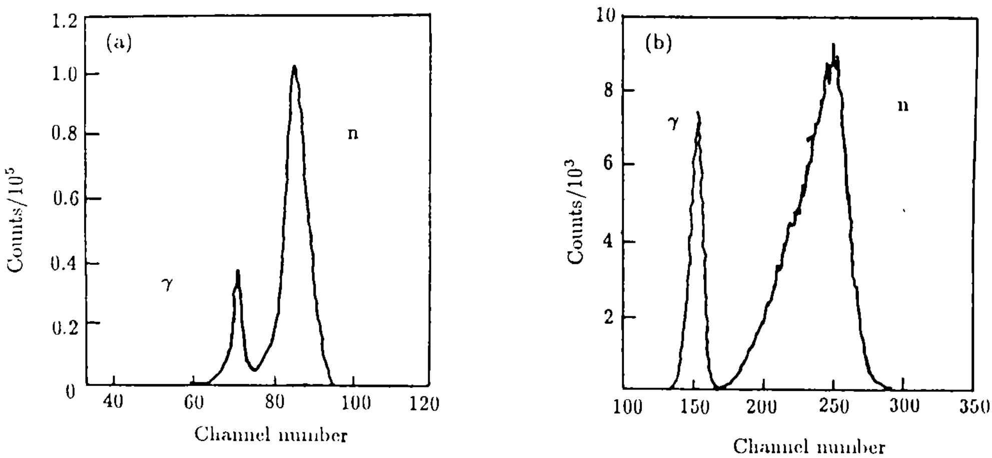

Fig.3 Typical n-γ discrimination spectra a) for low energy portion with lower (E_{th}=1/12 Cs) and upper (E_{th}=1 Cs) threshold, b) for high energy portion with a lower threshold (E_{th}=1/2 Cs)

3 RESPONSE AND EFFICIENCY OF THE NEUTRON DETECTOR

In neutron spectrum measurements, the uncertainty of neutron detector efficiency is one of main error sources. Due to the difference in volume, configuration and composition of neutron detectors, the efficiency of each detector must be determined individually. In the energy range below 20 MeV, the efficiency curves of the neutron detector were determined by combining Monte-Carlo calculations using a standard code NEFF7 provided by C.Wen[4] with experimental calibration measurement using a miniature ^{252}Cf ionization chamber. The fission chamber was specially designed for accurate measurement of the prompt neutron TOF spectrum of ^{252}Cf spontaneous fission, it has a fast time response, good time resolution and excellent discrimination between fission fragments and α particles. The experimental calibration of the detection efficiency was described in detail in Ref.[6].

The input parameters used in the code include light response functions of various monoenergetic neutrons in the detector, which can be given by measuring two dimensional spectra of neutron energy i.e. recoil proton energy and light yields of protons with different energies. Normally, the light yield is represented by electron energy unite, and the correlation between recoil proton energy and electron energy is given in a polynomial with several coefficients.

In the energy range above 20 MeV, it is difficult to calculate the efficiency curve with any code for lack of cross section data of C(n, α) and C(n, 3α) reactions. They were determined by measuring neutron angular distribution of T(d,n) reaction[7] in present work. In the measurement a Ti-T solid target was utilized and the thickness of the deposited Ti Layer is 3.8 mg/cm^2. The detection efficiency curves with several thresholds are shown in Fig.4.

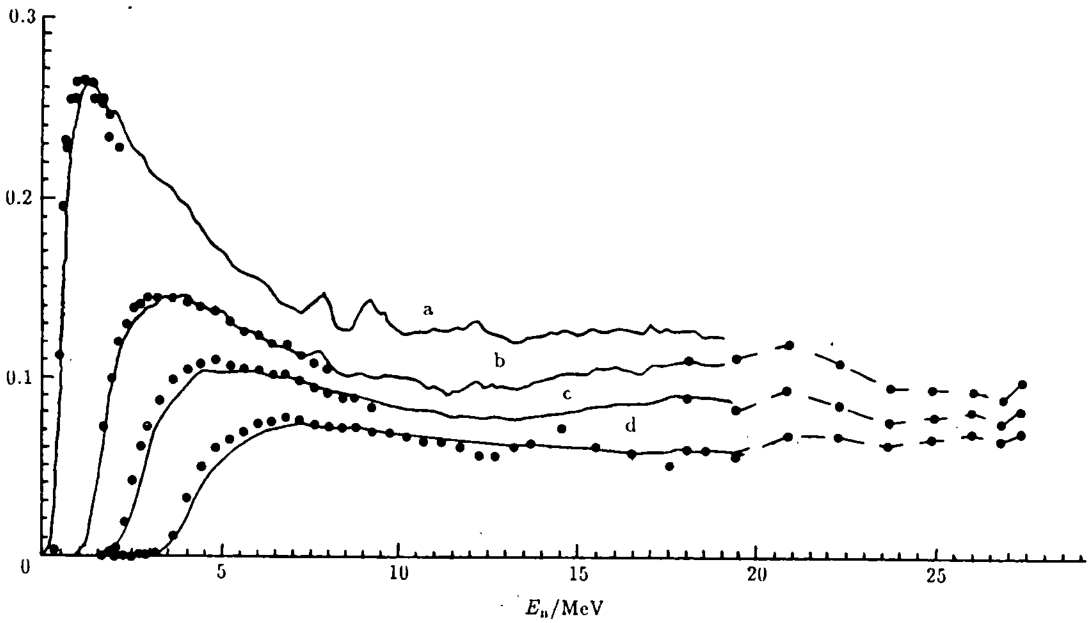

Fig.4 Detection efficiency curves of the neutron detector with various thresholds

Curve a,b,c,d refer to E_{th} of Cs, 1/12 Cs, 1/2 Cs, 1 Cs and 2 Cs respectively, solid lines (E_n=0–20 MeV), –Calculations with NEFF7 code, *–Measured data, Dashed lines only for view

4 DATA ACQUISITION ANALYSES AND RESULT

XSYS multiparameter data acquisition system based on VAX 11/780 computer was used. Neutron TOF spectra, linear spectra of recoil protons, and n-γ discrimination spectra for low and high energy portion were stored event by event into tapes. The events recorded in tapes would be sorted for various thresholds and n-γ discrimination conditions in off-line data analyses. To reduce multi events within a beam pulse period in the detector, the beam intensity should be weak enough. But if the beam intensity was too low, its stability will not be good, the proper beam current intensity is from 20 to 50 nA during our measurement. FWHM of a beam pulse was about 1 ns. The typical n-TOF spectra measured in low and high portion are shown in Fig.5, respectively. The background spectra due to neutrons scattered from surround material were measured by blocking the direct neutrons with a 1.2m long iron bar placed in midway of the flight

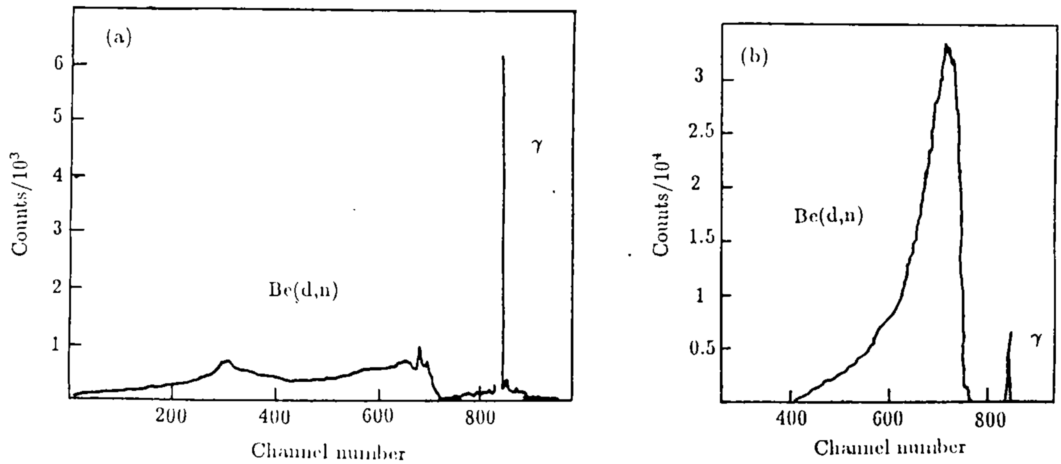

Fig.5 Typical n-TOF spectra measured at E_d=22 MeV

a) Low neutron energy portion with lower (1/12 Cs) and upper (1 Cs) threshold

b) High neutron energy portion with a lower (1/2 Cs) threshold

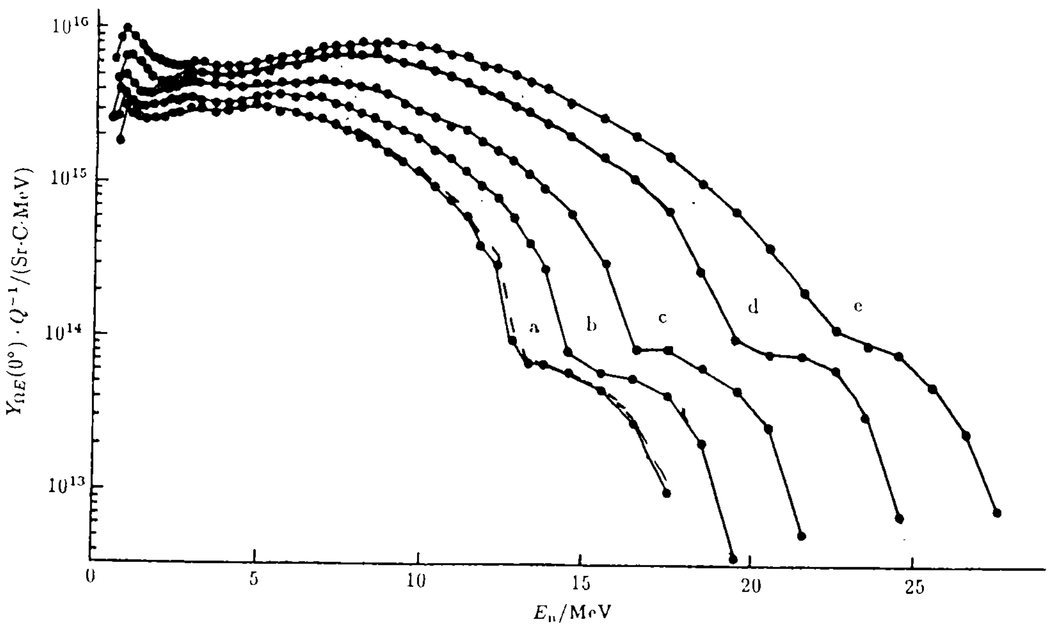

Fig.6 Spectral neutron yield per unit beam charge $Y_{\Omega E}(0°)/Q$ for thick Be target bombarded with deuterons of various energies

Curve a,b,c,d,e correspond to E_d =13.5, 15, 17, 20, 22 MeV; Previous data [4] at E_d =13.54 MeV are also shown here as a dashed line for comparison path. The background is rather smaller in comparison with the effect because several collimators were placed between the target and the heavily shielded detector and scattering neutron seldom reached the detector. Neutron flux attenuation in air and the target and the heavily shielded detector and scattering neutrons material was calculated by using cross section data taken from Refs.[8,9]. Connecting spectra measured with various thresholds after subtracting the background and considering the detection efficiency and

Table 1
Spectral neutron per unit beam charge on the Be target $Y_{\Omega E}(0^\circ)/Q[10^{12}/$(Sr· C· MeV)] for various deuteron energies E_d, the values E_n represent the mean neutron energy of the energy bin

E_n	E_d /MeV						E_n	E_d /MeV					
/MeV	13.5	13.54*	15.0	17.0	20.0	22.0	/MeV	13.5	13.54*	15.0	17.0	20.0	22.0
0.5	–	–	–	2636	–	6254	0.7	1809	2775	2712	4018	4678	8560
0.9	3177	3420	3846	4793	6508	9752	1.1	2728	2870	3385	4318	6520	8712
1.3	2614	2625	3111	3812	5921	7551	1.5	2568	2485	3041	3705	5329	6876
1.7	2562	2420	3108	3880	4762	6426	1.9	2612	2445	3256	4032	4469	6118
2.1	2656	2500	3321	4091	4462	5905	2.3	2739	2555	3339	4158	4543	5730
2.5	2693	2630	3354	4238	4657	5621	2.7	2818	2730	3459	4400	4869	5740
2.9	2932	2915	3543	4572	5116	5939	3.2	3006	3063	3416	4577	5167	5923
3.6	2914	2960	3273	4409	5015	5712	4.0	2914	3013	3283	4262	4957	5549
4.4	2984	3098	3431	4249	5146	5712	4.8	3080	3133	3635	4324	5450	6079
5.2	3078	3168	3670	4434	5723	6243	5.6	3009	3098	3718	4537	6000	6552
6.0	2822	2933	3574	4480	6000	6783	6.4	2672	2755	3615	4577	6304	7067
6.8	2569	2595	3536	4713	6607	7650	7.2	2398	2473	3357	4624	6704	7771
7.6	2214	2333	3073	4374	6685	7758	8.0	2042	2165	2848	4288	6630	8133
8.4	1823	1960	2641	4113	6638	8131	8.8	1601	1703	2440	3872	6535	8216
9.25	1378	1498	2194	3362	6093	7888	9.75	1179	1268	1994	3038	5871	7798
10.25	953	1032	1678	2691	5542	7432	10.75	764	854	1443	2417	5039	6958
11.25	613	686	1204	2270	4569	6722	11.75	404	464	994	1938	4135	5908
12.25	300	356	822	1663	3745	5676	12.75	94.0	113	610	1412	3295	5164
13.25	66.7	70.6	422	1174	2959	4649	13.75	65.4	68.4	287	950	2533	4142
14.5	57.4	55.6	79.9	675	2098	3420	15.5	45.0	46.7	58.1	323	1487	2709
16.5	28.0	30.4	53.3	83.5	1081	2072	17.5	10.1	12.6	42.4	83.1	681	1524
18.5	0.6	0.6	21.3	61.8	280	1007	19.5	–	–	3.7	45.4	99.6	683
20.5	–	–	–	26.2	78.6	396	21.5	–	–	–	5.4	77.9	204
22.5	–	–	–	–	62.4	114	23.5	–	–	–	–	31.8	91.6
24.5	–	–	–	–	7.1	78.1	25.5	–	–	–	–	–	48.9
26.5	–	–	–	–	–	24.8	27.5	–	–	–	–	–	7.8
28.5	–	–	–	–	–	0.7							

Note: *: from Ref.[4]

correcting for neutron flux attenuation, the neutron spectra at 0° for all incident energies were obtained. The spectral neutron yields per unit beam charge for a thick Be target were gotten by means of comparing with the yield data in Ref.[4] at E_d=13.54 MeV. The data are listed in Table 1 and shown in Fig.6. The spectra with different incident energies in the figure have almost the same shape. There are two sharp drop tendencies in every spectrum. They are attributed to the $^9Be(d,n_o)^{10}B$ ground state transition with a Q-value of 4.36 MeV and to three transitions n6, n7 and n8 of the excited residual

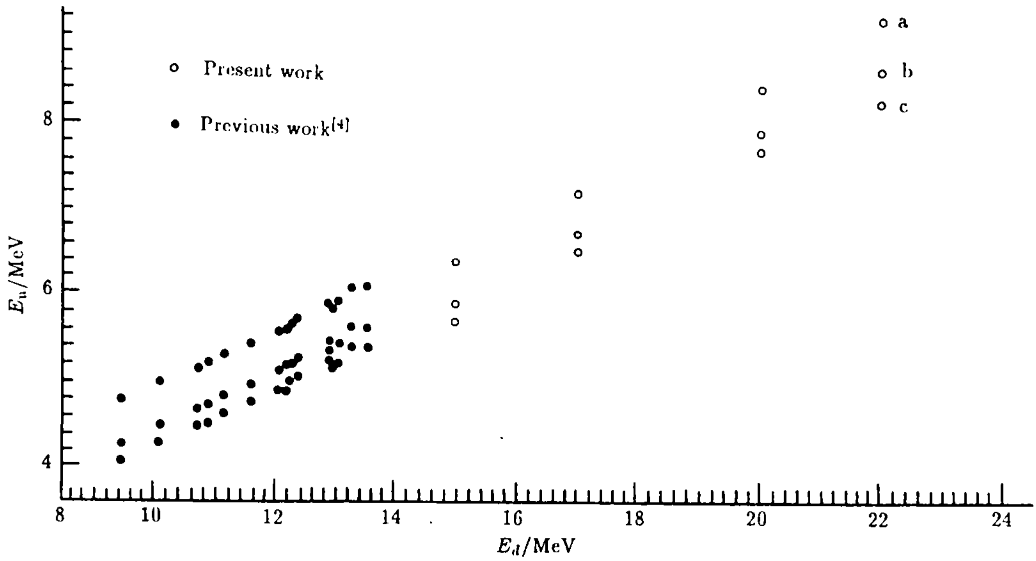

Fig.7 Fluence-averaged neutron energy of the Be+d reaction at 0° for various neutron energy thresholds E_{th}vs deuteron energy E_d

Curve a,b,c refer to E_{th} = 0.7, 1, 2 MeV

Table 2

Fluence-averaged mean neutron energy E_n of the Be+d reaction at 0° for various neutron energy threshold E_{th} vs deuteron energy E_d

E_d/MeV	E_{th}/MeV			E_d/MeV	E_{th}/MeV		
	0.7	1	2		0.7	1	2
9.43*	4.08	4.27	4.78	10.06*	4.29	4.49	4.98
10.68*	4.48	4.68	5.16	10.87*	4.51	4.73	5.23
11.11*	4.63	4.83	5.32	11.58*	4.76	4.96	5.44
12.03*	4.91	5.12	5.59	12.17*	4.88	5.19	5.61
12.23*	5.00	5.19	5.66	12.35*	5.05	5.26	5.73
12.88*	5.24	5.45	5.90	12.92*	5.13	5.37	5.85
13.05*	5.19	5.43	5.92	13.26*	5.41	5.62	6.07
13.5	5.33	5.52	6.01	13.54*	5.39	5.62	6.09
15	5.68	5.88	6.36	17	6.46	6.67	7.15
20	7.65	7.86	8.36	22	8.19	8.57	9.12

Note: * from Ref.[4]

nucleus ^{10}B with Q-values of -0.75, -0.81 and -0.82 MeV, respectively. The positions of these sharp edges for E_d=13.5 MeV are the same as those of E_d=13.54 MeV in Ref.[4]. There is also a small peak at 0.9 MeV in every spectrum. It is correlated with the inelastic scattering on 2.43 MeV excited state of ^9Be. Which mainly decays by neutron emission. i.e. $^9Be(d,d')^9Be^* \rightarrow n+^8Be \rightarrow 2\ \alpha$. In Ref.[4], this small peak is found at E_n=0.8 MeV. The position difference of the peak between two experiments may be due to different energy resolution and energy scale error of neutron detection efficiency.

The fluence-averaged mean neutron energies of the Be+d reaction at 0° for various thresholds as functions of deuteron energies are listed in Table 2 and shown in Fig.7 as well as those previous measurements for comparison. The dependence of mean neutron energy on the incident deuteron energy is similar to Ref.[4].

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