Measurements of Neutron Emission Spectra for Neutron Induced Reactions on ^{9}Be and ^{6,7}Li *

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Abstract The neutron emission double-differential cross sections(DDXs) of n+^{9}Be and ^{6,7}Li were measured at incident neutron energies of 8.17 and 10.27MeV. At 10.27MeV, the influence of breakup source neutrons from D(d, np) reactions was eliminated by using the combination of abnormal and normal fast neutron TOF spectrometers. The measured TOF spectra were analyzed by detailed Monte-Carlo simulation and the DDXs were determined by comparing the measured TOF spectra with simulated ones. The cross sections were normalized to n-p(normal geometry measurement) or n-C(abnormal geometry measurement) scattering measurement. The measured results were compared with the evaluations and the other measurements. A theoretical model based on the Hauser-Feshbach and exciton model for light nuclei was used to describe the double-differential cross sections of n+^{6,7}Li. Good agreement between theoretical calculation and measurement has been obtained.

Key words secondary neutron, double differential cross section, abnormal fast neutron TOF spectrometer, breakup neutron

1 Introduction

DDX is one of the most important nuclear data used in nuclear engineering, particularly in design of nuclear device and neutron shielding. However, the evaluations and measurements of DDX are very sparse. Up to now, most of DDX measurements performed are at around 14MeV and below 8MeV, while the DDX measurements are very scarce from 8 to 13MeV due to the lack of mono-energetic neutron source. On the other hand, the results of theoretical calculation are discrepant from each other with different light nuclei reaction models. Therefore, the DDX measurements for light nuclei are necessary for checking and improving nuclear reaction models and nuclear data evaluations.

In this work, the DDXs of n+^{9}Be and ^{6,7}Li have been measured at 8.17 and 10.27MeV incident neutron energies. Up to now, no measured DDX data for ^{6,7}Li in the energy region of 8 to 13MeV were reported in the literature. For beryllium, the situation is similar to that of ^{6,7}Li. Most published data in this energy region are the differential cross section(DX). Only two DDX data at 8.03MeV measured by Dekempeneer et al.[1] and 10.1MeV measured by Drake et al.[2] were reported. At 8.03MeV, the unfolding technique was used to measure the neutron energy spectra. Thus the energy resolution is very poor. At 10.1MeV, the p(t,n) reaction was used to produce the 10.1MeV mono-energetic neutrons. To produce this neutron source, the radioactive triton beam must be accelerated. The cost for performing

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such an experiment is quite high. The energy resolution is also not so good because the flight path is only 4m, and only 6 angles of DDX data were measured. The aim of this work is to fill the data blankness between 8 and 13MeV region using a convenient and economic D(d,n) reaction source with high energy resolution.

2 Experiment

The experiment was performed with normal fast neutron TOF spectrometer[3] on HI-13 Tandem Accelerator in China Institute of Atomic Energy(CIAE) for 8.17MeV. The diagram of the spectrometer is shown in Fig. 1. For 10.27MeV, because the D(d,n) neutron source is not monoenergetic, the low energy part(e.g. below 4MeV) of DDXs will be contaminated by the neutrons induced by breakup source neutrons. To solve this problem, an abnormal fast neutron TOF spectrometer[4] was constructed and used beside the normal fast neutron TOF spectrometer. In the abnormal setup, the neutron beam was shielded and collimated at 0 degree and the distance between source and sample was 220cm instead of 18cm in the normal TOF case while the distance between sample and detector was reduced from about 600cm to 70cm (Fig. 2). In this setup, the secondary neutrons induced by monoenergetic neutrons and breakup neutrons can be separated well by their TOFs at 1MeV neutron detection threshold. Thus, the DDXs at 10.27MeV can be measured successfully using the combination of normal and abnormal fast neutron TOF spectrometers. The DDXs data above 4MeV can be taken from normal geometry measurement because the energy resolution is better due to the long flight path while the DDXs data below 4MeV can be measured by abnormal geometry setup because it eliminates the influence of breakup neutrons and the energy resolution is also acceptable for low energy part. More details can be found in Ref. [4—7]. The parameters for 10.27MeV measurement are listed in Table 1 and the parameters for 8.17MeV measurement are nearly the same as those in the normal geometry measurement for 10.27MeV. Only the beam repetition rate was changed from 4MHz to 2MHz to fulfill the measurement for the whole neutron emission energy region above the threshold, and the ST-451 neutron detectors were replaced by the larger(BC501A, ϕ7×4 inch) ones. The incident deuteron energy was 5.8MeV to produce 8.17MeV neutrons.

A hollow cylindrical beryllium sample with diameter 25mm and length 40mm was used in the experiment. The hollow diameter is 10mm. The lithium samples were encapsulated in aluminium containers. The size of the containers is ϕ30mm×40mm with a wall thickness of 0.3mm.

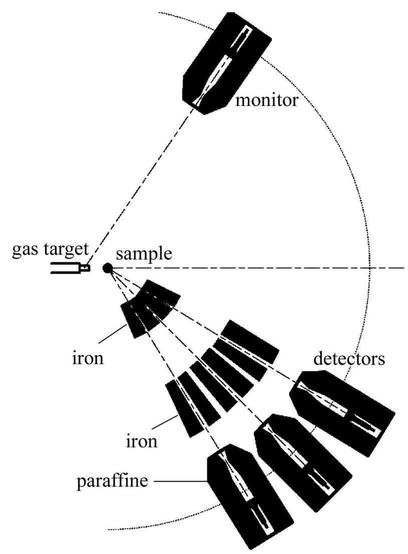

Fig. 1. Schematic view of normal fast neutron TOF spectrometer.

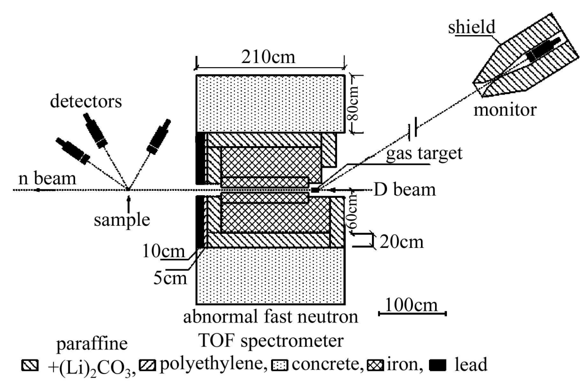

Fig. 2. Schematic view of abnormal fast neutron TOF spectrometer.

Four runs of measurement with gas in (sample in and out) and gas out (sample in and out) were performed for each angle during the experiment. For lithium sample, an empty container was used as sample out measurement. From these foreground and background measurements, we can get the net TOF spectra. All events from the four detectors (three main detectors and one monitor) were recorded by list mode. For each event, there are three parameters which are PH, PSD and TOF. PH and PSD are used for the detection threshold determination and n-γ discrimination.

Table 1. Experimental parameters for 10.27MeV measurement.

	normal	abnormal
projectile		
deuteron energy	7.765MeV	7.765MeV
averaged current	≈1.0μA	≈1.0μA
pulse width(FWHM)	≈1ns	≈1ns
repetition frequency	4MHz	4MHz
deuterium gas target		
length	30mm	30mm
diameter	10mm	10mm
gold backing	0.5mm	0.5mm
molybdenum entrance foil	10μm	10μm
gas pressure	6bar	6bar
neutron energy	10.27MeV	10.27MeV
distance		
target to sample	18cm	220cm
sample to detector	≈6.0m	70cm
neutron detectors		
3 main detectors	ST-451	ST-451
scintillator diameter	10.16cm	10.16cm
scintillator length	5.08cm	5.08cm
angles	30.0°—150.0°	
electron threshold	0.48MeV	0.16MeV
monitor	NE213	NE213
scintillator diameter	2.54cm	2.54cm
scintillator length	2.54cm	2.54cm
flight path	≈6m	≈6m
angle	≈60°	≈160°
electron threshold	0.95MeV	0.48MeV

3 Data analysis

The data analysis was perfermed in the following steps:

1) From the measured raw spectra(gas in, gas out, sample in and sample out), the net spectra were determined including uncertainty propagation. Other relevant data such as gama positions, neutron detection thresholds, monitor count rates, channel width of time-to-amplitude converters(TAC) are also obtained.

2) TOF spectra were calculated by a realistic Monte-Carlo simulation with the code STREUER[8]. The code was developed in PTB Braunschweig/Germany and extensions have been made for CIAE's experiment, especially for our abnormal geometry setup. The cross sections used in the Monte-Carlo simulation are usually taken from an evaluation data (e.g from ENDF/B-VI or JENDL or CENDL). The simulated TOF spectra would be obtained with inclusion of the differential non-linearity of the TACs, the proper detection efficiencies and the proper folding parameters. The folding function is a combination of a Gaussian function and the time response function of the neutron detectors. The time response function is calculated by Monte-Carlo method.

3) The measured and simulated TOF spectra were compared for the n-p scattering realized with a polyethylene sample. These ratios deduced from the comparison were used for normalization, i.e. all calculated TOF spectra were normalized to measured ones, it means that the ratios became unity. Thus, the derived cross sections are normalized with the elastic scattering on hydrogen.

4) Measured and calculated TOF spectra of the beryllium and lithium samples were compared with respect to specific scattering fractions, i.e with respect to the elastic peak or to the inelastic peak or to the windows for different neutron emission energies of the continuum. These ratios of measured to calculated fractions are used to obtain differential and double-differential cross sections. Then, the complete angular distribution of the cross sections determined in this way is fitted by a Legendre polynomial expansion.

5) The result of the Legendre polynomial fitting was used to improve the input data of the Monte-Carlo simulation(i.e it replaces the data from evaluation). In this way, the data were iteratively refined so that the measured and calculated TOF spectra were

in agreement with each other within their experimental uncertainties. Thus, the experimental result can be obtained from the last iteration.

The uncertainties due to the statistical uncertainty, the neutron detection efficiency(4%), the scattering angle(0.3 degree), the normalization(1%) and the correction for multiple scattering(5%) have been taken into account, including their correlation.

The sample containers for ^{6,7}Li were also included in the Monte-Carlo simulation to study the sample out background. For beryllium and ^{7}Li, the inelastic scattering of Q=−2.43MeV and Q=−4.63MeV levels overlap with the continuum part from three body reaction precesses such as (n,2n), (n,np), etc. For ^{6}Li, similar situation occurs for the Q=−2.19MeV level. Therefore, to get the correct differential cross sections for these inelastic scattering levels, the continuum part must be subtracted as “background”. By this way, the DX and DDX data can be treated simultaneously in the above iteration procedure.

4　Theoretical calculation of DDXs for ^{6,7}Li

To describe the neutron induced reaction behavior of ^{6,7}Li, especially the particle pre-equilibrium emissions from composite nuclei to the discrete levels of the residual nuclei, the angular momentum dependent exciton model have been used. In this model, the angular momentum coupling effects as well as the accurate kinematics including the recoil effect for all kinds of reaction processes have been taken into account to get the correct energy spectra. If the secondary particle emissions exist, they are all from discrete levels of composite nuclei to discrete levels of the residual nuclei, or through two body breakup such as ^{5}He → n + α and ^{5}Li → p + α, as well as the three-body breakup processes of ^{6}He* → n + n + α. All these processes have been considered in this model. The calculation result shows that the pre-equilibrium mechanism dominate the whole reaction processes, even over 80%. For n+^{6}Li reaction, the direct three-body breakup of n+d+α has been taken into account, and the systematic formula of direct three-body breakup coefficient was established and introduced in this model calculations[9—13]. All of the calculations agree well with measurements.

5　Results

Differential and double-differential cross sections have been obtained at 11 angles in the range between 30 degree and 150 degree for 8.17MeV and at 9 angles in the range between 35 degree and 120 degree for 10.27MeV. For normal geometry measurements, all the energy resolution is better than 5%. For abnormal geometry measurement, the energy resolution is about 18% due to the short flight path.

Figure 3 shows our measured elastic differential cross sections for ^{9}Be at 10.27MeV comparing with evaluations[14] and other measurements[2, 15—17]. The three evaluations give nearly the same result but the measurements deviate from each other between 70 and 110 degrees. In this angle region the differential cross sections are small and the corrections due to multiple scattering will be large. This may result in some larger uncertainties.

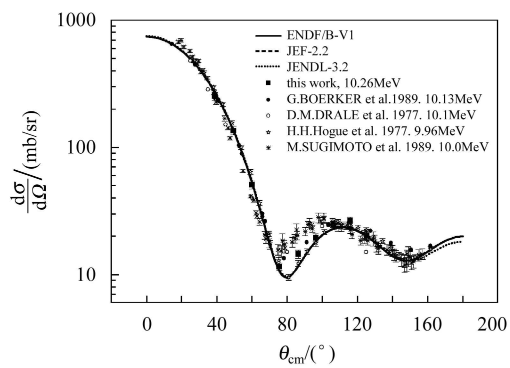

Fig. 3.　Result of elastic scattering differential cross sections for ^{9}Be at 10.27MeV comparing with evaluations and other measurements.

Fig. 4 shows the measured DDXs of ^{9}Be at 40 degree of 8.17MeV, comparing with the evaluations and

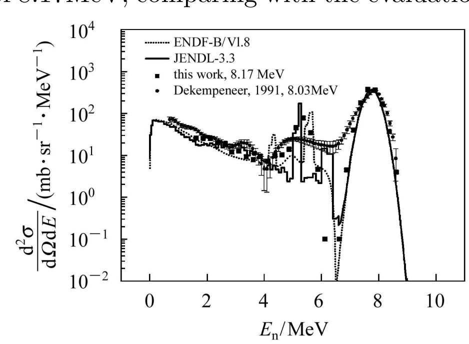

Fig. 4.　DDXs result of ^{9}Be at 40 degree and 8.17MeV.

other measured data. Large differences between ENDF-B/VI.8 and JENDL-3.3 exist for the prominent inelastic levels. Our resolution is better than the data measured by Dekempeneer (data retrieved from EXFOR[1]).

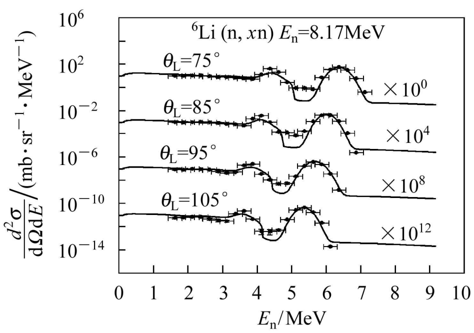

Fig. 5. Measured DDXs for ^{6}Li at 8.17MeV, comparing with theoretical calculation.

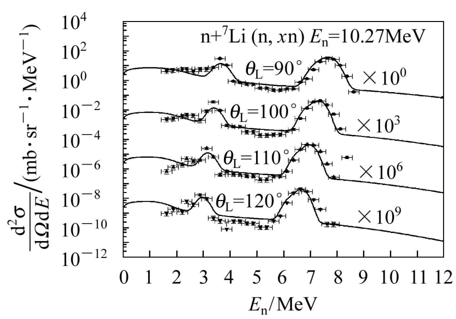

Fig. 6. Same as Fig. 5 but for ^{7}Li at 10.27MeV.

Part of the DDXs for ^{6}Li and ^{7}Li at 8.17MeV and 10.27MeV are shown in Fig. 5 and Fig. 6. It can be seen that the present theoretical calculation can reproduce the experimental data well.

6 Summary

Double-differential neutron emission cross sections were measured for ^{9}Be and ^{6,7}Li at incident neutron energies of 8.17 and 10.27MeV using normal and the combination of normal and abnormal fast neutron TOF spectrometers, respectively. The influence from the D(d,np) breakup reaction on secondary neutron spectra was successfully eliminated. The experimental data were analyzed by detailed Monte-Carlo simulation. The statistical reaction model and angular momentum dependent exciton model were applied to describe neutron induced reaction processes on ^{6,7}Li. The experimental results were compared with the data of evaluations and theoretical calculations. Well agreement between experimental data and calculation result has been obtained.

These measurements fill the blankness of DDX data for ^{6,7}Li in the energy region from 8 to 13MeV. For beryllium, our energy resolution is better than that of other experiments, and DDX data of more angles were measured in this work than others. Based on these measurements and the existing experimental data in the literature at other energy region, the LUNF code has been improved, especially in description of the DDX data for light nuclei.

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中子与 ^{9}Be 和 ^{6,7}Li 反应的次级中子发射谱实验研究*

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摘要　测量了8.17MeV与10.27MeV中子与 ^{9}Be 和 ^{6,7}Li 作用的次级中子双微分截面. 对于10.27MeV, 为了消除从D(d,np)破裂反应来的源破裂中子对双微分截面测量结果的影响, 采用了常规多探测器快中子飞行时间谱仪和非常规多探测器快中子飞行时间谱仪相结合的办法. 用Monte-Carlo方法对实验测量得到的飞行时间谱进行了详细的模拟, 通过测量谱与模拟谱的比较, 得到了实验测量的次级中子双微分截面. 实验测量结果以n-p(常规谱仪)和n-C(非常规谱仪)弹性散射微分截面作为归一. 测量结果与评价数据以及其他测量数据进行了比较. 用一个基于Hauser-Feshbach和激子模型的轻核核反应理论模型对 ^{6,7}Li 的次级中子双微分截面进行了计算, 理论计算结果与实验结果符合得较好.

关键词　次级中子　双微分截面　非常规快中子飞行时间谱仪　破裂中子

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