Measurements of neutron-induced light-charged particle emission reactions

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Abstract. In the past two decades cooperating with Frank Laboratory of Neutron Physics (FLNP), Joint Institute for Nuclear Research (JINR) measurements of (n, α) reaction cross sections for ${}^6\text{Li}$, ${}^{10}\text{B}$, ${}^{25}\text{Mg}$, ${}^{39}\text{K}$, ${}^{40}\text{Ca}$, ${}^{54,56,57}\text{Fe}$, ${}^{58}\text{Ni}$, ${}^{63}\text{Cu}$, ${}^{64,67}\text{Zn}$, ${}^{95}\text{Mo}$, ${}^{143}\text{Nd}$ and ${}^{147,149}\text{Sm}$ nuclei were performed in the MeV neutron energy region based on the 4.5 MV Van de Graaff accelerator at Peking University. In recent years, our measurements were extended in three aspects. Firstly, measurements were expanded from two-body reactions to three-body reactions such as ${}^{10}\text{B}(n, t2\alpha)$. Secondly, the neutron energy region was extended from below 8 MeV to 8 - 11 MeV by using the HI-13 tandem accelerator of China Institute of Atomic Energy (CIAE), with which cross sections of ${}^{54,56}\text{Fe}(n, \alpha){}^{53,51}\text{Cr}$ reactions were measured. Thirdly, based on the newly-built China Spallation Neutron Source (CSNS) Back-n WNS (White Neutron Source), differential and angle-integrated cross sections for ${}^6\text{Li}(n, t)$ and ${}^{10}\text{B}(n, \alpha)$ reactions were measured in the neutron energy region from 1 eV to 3 MeV.

1 Introduction

Neutron-induced light-charged particle emission reactions $[(n, lcp)$ reactions] are important in nuclear engineering (such as the neutron standards, fusion reactors, and accelerator driven system) and basic research (such as the study of nuclear reaction mechanism, and the synthesis of isotopes in early universe). However, measurement data are scarce with large uncertainties (except for the results at thermal energies) because the measurements of these reactions are rather difficult. The main challenges for the measurement are as follows: a) the cross sections are often

small, b) the intensity of the neutron sources are limited, c) highly enriched isotopic materials are needed, d) thicknesses of the samples are limited by the short ranges of the charged ejectiles, and e) the backgrounds are strong. By applying the techniques solving the problems above, we have been measuring the (n, lcp) reactions for years based on different neutron sources.

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Table 1. The measured (n, α) reactions based on the 4.5 MV Van de Graaff accelerator at Peking University.

Reaction	E_n (MeV)	Reference
${}^6\text{Li}(n, t)$	1.05, 1.54, 1.85, 2.25, 2.67, 3.67, 4.42	[1–4]
${}^{10}\text{B}(n, \alpha)$	4.0, 5.0	[5, 6]
${}^{10}\text{B}(n, t2\alpha)(n, \alpha)$	4.0, 4.5, 5.0	[7, 8]
${}^{25}\text{Mg}(n, \alpha)(n, \alpha_0)$	4.0, 4.5, 5.0, 5.5, 6.0	[9]
${}^{39}\text{K}/{}^{40}\text{Ca}(n, \alpha)$	4.5, 5.5, 6.5 / 5.0, 6.0	[10, 11]
${}^{40}\text{Ca}(n, \alpha_0)(n, \alpha_{12})(n, \alpha_{345})$	4.0, 4.5, 5.0, 5.5, 6.0, 6.5	[12]
${}^{54}\text{Fe}/{}^{56}\text{Fe}/{}^{57}\text{Fe}(n, \alpha)$	4.0, 4.5, 5.5, 6.5 / 5.5, 6.5 / 5.0, 5.5, 6.0, 6.5	[13, 14]
${}^{54,56}\text{Fe}(n, \alpha)$	5.5, 7.7	[15]
${}^{58}\text{Ni}(n, \alpha)$	6.0, 7.0	[16]
${}^{63}\text{Cu}(n, \alpha)$	5.0, 5.5, 6.0, 6.5	[14]
${}^{64}\text{Zn}(n, \alpha)$	2.54, 4.00, 5.03, 5.50, 5.95	[17, 18]
${}^{67}\text{Zn}(n, \alpha)(n, \alpha_0)$	4.0, 5.0, 6.0	[19, 20]
${}^{95}\text{Mo}(n, \alpha)$	4.0, 5.0, 6.0	[21]
${}^{143}\text{Nd}(n, \alpha)$	4.0, 5.0, 6.0	[22]
${}^{147}\text{Sm}(n, \alpha)$	5.0, 6.0	[22, 23]
${}^{149}\text{Sm}(n, \alpha)$	4.5, 5.0, 5.5, 6.0, 6.5	[24, 25]

2 Two decades' measurements based on the 4.5 MV Van de Graaff accelerator at Peking University

Cooperating with Frank Laboratory of Neutron Physics (FLNP), Joint Institute for Nuclear Research (JINR), and based on the 4.5 MV Van de Graaff accelerator at Peking University, we have measured a series of (n, α) reactions, including light, medium-mass and heavy nuclei. Twin gridded ionization chambers (GICs) were used as detectors for charged particles with a large solid angle (nearly 4π) and high efficiency ($\sim 100\%$). NIM block electronics and home-made data acquisition system were employed. The neutron energy range was from 1.0 to 7.7 MeV.

Combining measurements with theoretical analysis, systematic results including angular differential cross sections and/or cross sections were obtained. Details of the reaction channels, the energy points and related publications are listed in Table 1.

3 Recent developments

3.1 Measurement of the three-body reaction

Based on the 4.5 MV Van de Graaff accelerator at Peking University, measurement of cross sections of the three-body reaction ${}^{10}\text{B}(n, t2\alpha)$ was performed [7, 8]. A thin-backing ${}^{10}\text{B}$ sample was prepared, and the ${}^{10}\text{B}$ atom number in the sample was measured relative to the ${}^6\text{Li}$ atom number in the standard ${}^6\text{LiF}$ sample using thermal-neutron-induced reactions of ${}^{10}\text{B}$ and ${}^6\text{Li}$. Digital data acquisition system based on wave form digitizers and LABVIEW software were developed. Forward as well as backward signals of grids and anodes of the twin GIC were recorded. Methods of anode-grid and forward-backward coincidences were used to select the valid events. Cross sections of the three-body reaction ${}^{10}\text{B}(n, t2\alpha)$, as well as the two-body reaction ${}^{10}\text{B}(n, \alpha){}^7\text{Li}$ were measured simultaneously at 4.0, 4.5 and 5.0 MeV [7, 8].

3.2 Measurements based on the HI-13 tandem accelerator at CIAE

In addition to the measurements of the ${}^{56,54}\text{Fe}(n, \alpha){}^{53,51}\text{Cr}$ cross sections at the Van de Graaff accelerator at Peking University, neutron energy range was extended to 8 - 11 MeV based on the HI-13 tandem accelerator of China Institute of Atomic Energy (CIAE). Using deuterium gas target and d-d reaction as the neutron source, cross sections of the ${}^{56,54}\text{Fe}(n, \alpha){}^{53,51}\text{Cr}$ reactions were measured at 8.5, 9.5 and 10.5 MeV [15] in which region the measurement results are scarce with big discrepancies among different experiments and evaluations. Since the neutron source was not mono-energetic in this region, the neutron energy spectra were measured using an EJ309 detector by unfolding the measured pulse height spectra [26]. The interference of the low energy neutrons was corrected. A shoulder structure was observed near 10 MeV in both excitation functions of the ${}^{56,54}\text{Fe}(n, \alpha){}^{53,51}\text{Cr}$ reactions [15] and was analyzed.

3.3 Measurements based on CSNS Back-n WNS

China Spallation Neutron Source (CSNS) is the first pulsed spallation neutron source in China and it was put to service in March, 2018. An associated white neutron source (WNS) exploiting the back-streaming neutrons (Back-n) was built for nuclear data measurement [27]. ${}^6\text{Li}(n, t){}^4\text{He}$ and ${}^{10}\text{B}(n, \alpha){}^7\text{Li}$ reactions were selected as the first and the second (n, lcp) reactions to be measured. Measurements were performed at the Endstation 1 (ES#1) along the Back-n beam line. The proton beam power during measurements was ~ 20 kW. The repetition frequency of the proton beam was 25 Hz (double-bunch mode).

Enriched double ${}^6\text{LiF}$ and double ${}^{10}\text{B}$ samples 50 mm in diameter were prepared. The detector system used for the measurement was the Light charged Particle Detector Array (LPDA), which mainly consisted of 15 silicon detectors ($2.0 \times 2.5 \text{ cm}^2$, with detection angles ranging from 19.2° to 160.8°) in a vacuum chamber. Based on the CSNS

Back-n WNS, and the LPDA system, the ${}^6\text{Li}(n, t){}^4\text{He}$ and ${}^{10}\text{B}(n, \alpha){}^7\text{Li}$ reactions were measured. The beam durations for measurement of the ${}^6\text{Li}(n, t){}^4\text{He}$ and ${}^{10}\text{B}(n, \alpha){}^7\text{Li}$ reactions were 196 h and 357 h, respectively.

Measurement data are under analysis and preliminary results are obtained. For the ${}^6\text{Li}(n, t){}^4\text{He}$ reaction, differential cross sections at 80 neutron energies were measured from 1 eV to 3 MeV (selected preliminary results are presented in Fig.1). For the ${}^{10}\text{B}(n, \alpha){}^7\text{Li}$ reaction, differential cross sections at 67 neutron energies were measured between 1 eV and 2.0 MeV (selected preliminary results are presented in Fig.3). For the ${}^{10}\text{B}(n, \alpha_0){}^7\text{Li}$ and ${}^{10}\text{B}(n, \alpha_1){}^7\text{Li}$ reactions, differential cross sections were measured at 59 neutron energies between 1 eV and 1 MeV (selected preliminary results are presented in Figs.5 and 7, respectively). Moreover, angle-integrated cross sections for the reactions above are also obtained through integration. Preliminary results of the present cross sections for the ${}^6\text{Li}(n, t){}^4\text{He}$, ${}^{10}\text{B}(n, \alpha){}^7\text{Li}$, ${}^{10}\text{B}(n, \alpha_0){}^7\text{Li}$ and ${}^{10}\text{B}(n, \alpha_1){}^7\text{Li}$ reactions compared with those of other measurements and evaluations are shown in Figs.2, 4, 6 and 8, respectively. Present data are subject to further corrections.

Figure 1. Selected preliminary results of differential cross sections for the ${}^6\text{Li}(n, t){}^4\text{He}$ reaction.

Figure 2. Preliminary results of present cross sections for the ${}^6\text{Li}(n, t){}^4\text{He}$ reaction compared with those of other measurements and evaluations.

Figure 3. Selected preliminary results of differential cross sections for the ${}^{10}\text{B}(n, \alpha){}^7\text{Li}$ reaction.

Figure 4. Preliminary results of present cross sections for the $^{10}\text{B}(n, \alpha)^7\text{Li}$ reaction compared with those of other measurements and evaluations.

Figure 6. Preliminary results of present cross sections for the $^{10}\text{B}(n, \alpha_0)^7\text{Li}$ reaction compared with those of other measurements and evaluations.

(a) $E_n = 1.00 \times 10^{-6}$ MeV

(b) $E_n = 0.002$ MeV

(c) $E_n = 0.20$ MeV

(d) $E_n = 0.60$ MeV

(e) $E_n = 0.90$ MeV

Figure 5. Selected preliminary results of differential cross sections for the $^{10}\text{B}(n, \alpha_0)^7\text{Li}$ reaction.

(a) $E_n = 1.00 \times 10^{-6}$ MeV

(b) $E_n = 0.002$ MeV

(c) $E_n = 0.20$ MeV

(d) $E_n = 0.50$ MeV

(e) $E_n = 0.90$ MeV

Figure 7. Selected preliminary results of differential cross sections for the $^{10}\text{B}(n, \alpha_1)^7\text{Li}$ reaction.

Figure 8. Preliminary results of present cross sections for the $^{10}\text{B}(n, \alpha)^7\text{Li}$ reaction compared with those of other measurements and evaluations.

4 Conclusion and outlook

For more than 20 years, we have been engaged in the measurements of the (n, lcp) reactions based on the 4.5 MV Van de Graaff accelerator at Peking University. In recent years, we extended our measurements based on the HI-13 tandem accelerator of CIAE and on CSNS. A series of measurements have been performed and systematical results obtained. Further measurements are planned, such as the $^{58,60,61}\text{Ni}(n, \alpha)$ reactions and the $n-p$ and $n-d$ scattering reactions.

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