Measurement of the photodissociation of the deuteron at energies relevant to Big Bang nucleosynthesis

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Abstract. The photodissociation of the deuteron is a key reaction in Big Bang nucleosynthesis, but is only sparsely measured in the relevant energy range. To determine the cross section of the $d(\gamma,n)p$ reaction we used pulsed bremsstrahlung and measured the time-of-flight of the neutrons. In this article, we describe how the efficiency of the neutron detectors was experimentally determined and how the modification of the neutron spectrum by parts of the experimental setup was simulated and corrected.

1. Introduction, motivation, experimental setup and data analysis

A brief introduction to Big Bang nucleosynthesis, the motivation to measure the photodissociation of the deuteron at energies relevant to it, the experimental setup at the ELBE accelerator at Helmholtz-Zentrum Dresden-Rossendorf and the data analysis are described in ref. [1, 2]. In this article, we discuss two important systematic effects: the neutron detector efficiency and the modification of the neutron spectrum from the $d(\gamma,n)p$ reaction due to interactions with the target and other parts of the experimental setup.

2. Efficiency calibration of the neutron detectors

Neutrons from the $d(\gamma,n)p$ reaction have been detected using a time-of-flight method with 1000 mm long, 42 mm and 11 mm thick plastic scintillators (EJ 200) coupled to high-gain photomultiplier tubes (PMTs) at both ends. To suppress $\gamma$-ray induced events the detectors are surrounded by a 1 cm thick lead shield. The efficiency of unshielded detectors of this type had been determined before [3], but later we observed discrepancies in measurements of shielded detectors relative to a $^{235}$U fission chamber at the neutron time-of-flight facility nELBE [4] as well as in simulations using the NEFF7 code [5], see figure 1.

In 2011 we did a new efficiency calibration of the shielded neutron detectors at Physikalisch-Technische Bundesanstalt (PTB) Braunschweig. A pulsed Van-de-Graaff generator [6] provided charged ions to produce quasi-monoenergetic neutrons in the energy ranges 25 – 565 keV, 1 – 2.5 MeV and around 5 MeV via the reactions $^7$Li(p,n), T(p,n) and D(d,n), respectively. The

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Figure 1. Efficiency $\varepsilon$ of plastic scintillation detectors as a function of kinetic neutron energy $T_n$. Older absolute measurements at PTB Braunschweig (black symbols) [3] and measurements relative to a $^{235}$U fission chamber at nELBE [4] (grey symbols) are compared to NEFF7 simulations [5] with its original, cylindrical geometry (blue line) and with a modified, rectangular geometry (magenta line). The symbols coloured blue, dark green, light green, red and orange are the results of the efficiency calibration of the five neutron detectors at PTB Braunschweig described in this article.

A low-scattering environment reduced the in-scattering of neutrons. We simulated the contribution of neutrons scattered in the target with the TARGET code [7] and found it to be negligible. We used shadow bars made of borated polyethylene, which absorb neutrons on the direct source-detector path, to measure the background of scattered neutrons. Figure 2 shows typical time-of-flight spectra with and without shadow bars. Before the background is subtracted, a time-of-flight dependent dead-time correction as described in ref. [8] is applied, which can differ by up to 1.5% from the integral dead-time correction at high count rates. Finally, the number of detected neutrons $n_{\text{det}}$ is obtained by setting a gate on the neutron distribution in the dead-time corrected, background-subtracted time-of-flight spectra.

Two long counters, a $^3$He Geiger counter and a charge integrator at the target monitored the intensity of the neutron production. To obtain the neutron flux, these monitors were calibrated using a recoil-proton proportional counter, a recoil-proton telescope or a NE213 detector as reference instruments [9]. After taking into account the neutron attenuation in air, the solid angle of the detector and the angular distribution of the neutron-producing reaction, the number of incoming neutrons $n_{\text{inc}}$ can be determined.

Figure 1 shows the efficiency $\varepsilon = n_{\text{det}}/n_{\text{inc}}$ of the five calibrated detectors. While the energy dependence is quite similar among the detectors, the absolute values differ by a factor of two. Scintillator and PMTs are connected optically with silicone grease and mechanically with opaque...
heat shrink tube. We assume that the optical coupling between scintillator and PMTs partly degraded due to ageing or handling, because a comparison of the charge spectra of all PMTs from the calibration measurements with quasi-monoenergetic neutrons shows large differences.

The coincident read-out using high-gain PMTs results in a detection threshold of about 10 keV neutron energy, confirmed by the efficiency of 0.004 measured at 12 keV with one detector.

3. Modification of the neutron spectrum

The neutron spectrum from the photodissociation of the deuteron measured at the ELBE accelerator contained more low-energy neutrons than expected. To understand this discrepancy, we used the FLUKA Monte Carlo code [10, 11], version 2011.2, to simulate, how neutron scattering on different parts of the experimental setup modifies the neutron spectrum. The simulation included walls, floor and ceiling of the experimental area, the target consisting of alternating layers of aluminium and deuterated polyethylene (PE), all six neutron detectors and their lead shield, lead walls shielding the photon collimator and the beam dump, the lead shield of γ-ray detectors and air. It was not possible to use the incoming photons as primary particles, because the angular distribution of the d(γ,n)p reaction is not properly implemented in the FLUKA code. We calculated a neutron source distribution using the shape of the bremsstrahlung spectrum [12], theoretical values of the E1 and M1 contributions to the total cross section [13, 14] and a parametrisation of the angular distribution (M1: isotropic, E1: dipole). Each neutron started at a random position in the PE layers of the target and its energy and polar angle was randomly sampled from the calculated distribution. It should be noted that the normalisation of the distribution is arbitrary and the results of the simulation do not depend on the absolute value of the cross section, but only on its energy dependence.
Table 1. Relative abundance of events hitting the detector located at 90° depending on their previous interaction place. The relative abundance of events, in which the arriving particles are not neutrons, is given in parentheses, if it is larger than zero.

| prev. interaction place         | rel. abundance | rel. abundance |
|--------------------------------|----------------|----------------|
| no interaction                 | 36.4 %         |                |
| walls, floor and ceiling       | 35.8 %         | (7.5 %)        |
| lead shield γ-ray det.         | 9.8 %          |                |
| target PE                      | 4.9 %          |                |
| lead shield other det.         | 4.4 %          | (0.2 %)        |
| air                            | 3.8 %          | (0.3 %)        |
| target aluminium               | 1.6 %          |                |
| lead shield beam dump          | 1.6 %          |                |
| scintillator other det.        | 0.9 %          |                |
| lead shield collimator         | 0.8 %          |                |

Figure 3. Differential cross section of the d(γ,n)p reaction as a function of total kinetic energy, both in the center-of-momentum (cm) frame. The symbols are preliminary results from the measurement at a neutron angle of 90° in the laboratory system with (black) and without (grey) correction of the modified neutron spectrum. The uncertainties of the data points printed here are due to the bin width (50 keV) and neutron statistics (3 % at 300 keV, 1 % at 1 MeV). For comparison the black line shows a theoretical calculation [15].

Table 1 shows which parts of the setup are the main scatterers for neutrons. Of all simulated particles reaching the detector located at 90°, one third are neutrons from the d(γ,n)p reaction which had no interactions with the setup. Another third of the detector hits had their previous interaction in the walls, the floor or the ceiling. These events are often neutrons slowed down below the detection threshold or capture γ-rays without time-of-flight correlation, which can be subtracted from the experimental time-of-flight spectrum as a constant background. Other major sources of scattered neutrons are the lead shields of the γ-ray detectors, which are close to the target, the deuterated PE in the target, the lead shield of the other detectors and the air. In the analysis of the experiment, the neutron energy is calculated from the time-of-flight assuming they took the direct flight path from the target to the detector. Thus, the energy assigned to scattered neutrons will be wrong and the efficiency correction cannot be applied. To avoid this problem, we apply the efficiency correction to the simulated neutron events, of which the true energy and the time-of-flight are known. By comparing the simulated efficiency-corrected neutron spectrum to the spectrum calculated from the neutron source distribution, we get a correction factor for the experimental neutron spectrum, that includes the experimentally determined detection efficiency and the simulated modification of the neutron spectrum from interactions with the setup. In figure 3 the cross section is plotted with and without the correction of the modified neutron spectrum. At $T_{cm} > 800$ keV the correction results in a realistic description of the cross section whereas at lower energies discrepancies remain.
4. Conclusions
The efficiency of the neutron detectors has been calibrated at PTB Braunschweig in the energy range 25 keV to 5 MeV. The low detection threshold of about 10 keV neutron energy was confirmed experimentally. The large efficiency differences between the detectors require a review of the optical and mechanical coupling of scintillators and PMTs. The successful calibration is very important for the absolute d(\(\gamma\),n)p cross section measurement at the ELBE accelerator at Helmholtz-Zentrum Dresden-Rossendorf, in which the detectors have been used several months before.

The d(\(\gamma\),n)p experiment at ELBE required an investigation of the modification of the neutron spectrum due to interactions of the neutrons with the experimental setup. First results of our FLUKA simulation demonstrated the importance of this correction. Although the correction results in a realistic description of the cross section at \(T_{cm} > 800\) keV, the discrepancies at lower energies are to be investigated. In the next step our simulation will include more parts of the setup, namely further lead shields, the full photon beam dump, the target holder and the \(\gamma\)-ray detectors (high-purity germanium crystals surrounded by an anti-Compton detectors).

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