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Towards a precision measurement of the photodissociation of the deuteron at energies relevant to Big Bang nucleosynthesis

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Experimental data for the reaction p(n,γ)d are scarce at energies relevant to Big Bang nucleosynthesis. In network calculations, the reaction rate used relies on theoretical models constrained by nucleon-nucleon scattering data, the capture cross section for thermal neutrons and experimental data of the inverse reaction d(γ,n)p. The latter reaction - the photodissociation of the deuteron - is also sparsely investigated at Big-Bang energies. A comparison of measurements with precise calculations is difficult due to large experimental uncertainties.

To address the need for precise experimental data we started to measure the cross section of the reaction d(γ,n)p. We use high-intensity bremsstrahlung with an endpoint energy of 5.0 MeV generated at the superconducting electron accelerator ELBE at Forschungszentrum Dresden-Rossendorf. The incoming photon flux is determined by photon scattering at ^{27}Al by measuring the well known transitions at 2.2 and 3.0 MeV with high-purity germanium detectors. With a pulse length of a few ps and an adjustable repetition rate, ELBE offers ideal conditions for precise time-of-flight experiments. For neutron detection we use plastic scintillators read out on two sides by high-gain photomultipliers. With this setup we can measure neutrons between 20 keV and 1.4 MeV with an energy resolution of about 4 %. The statistical uncertainty reached so far is about 5 %, the analysis of systematic effects is ongoing.

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1. Introduction

The expansion of the universe can be traced back to the Big Bang $13.7 \cdot 10^9$ years ago. Protons and neutrons were formed a few seconds after the Big Bang and at temperatures of 10^9 Kelvin they had enough energy to produce isotopes of hydrogen, helium and lithium in the first nuclear reactions. This process is called Big Bang Nucleosynthesis (BBN) and took place in the first three minutes of the universe. The abundances of the nuclei depend on the baryon-to-photon ratio η, on the neutron lifetime and on the cross sections of the involved nuclear reactions. Comparisons between results of nuclear network calculations and astronomic observations offer a unique probe of the early universe. At present, BBN calculations predict three to four times more ^{7}Li than observed and there are hints that results of BBN are sensitive to extensions of the standard models [1].
For the reaction p(n,γ)d, to which the ^{7}Li abundance is most sensitive [2], experimental data are scarce in the relevant energy region. In network calculations the reaction rate used relies on theoretical models (with theoretical uncertainties of about 1 %) constrained by nucleon-nucleon scattering data, the capture cross section for thermal neutrons and experimental data of the inverse reaction d(γ,n)p [3]. The latter reaction - the photodissociation of the deuteron - is also sparsely investigated at Big-Bang energies ($T_{\mathrm{CM}} = 10 - 300$ keV, kinetic energy in center-of-mass frame) and has experimental uncertainties larger than 10 %. A review of experiments between 1950 and 1990 can be found in ref. [4]. In recent years, the reaction d(γ,n)p, especially the M1 contribution to its cross section, was studied (see ref. [5] and ref. therein) using quasi-monochromatic gamma rays from laser-Compton scattering (AIST Tsukuba/Japan, HIγS Durham/USA), charge-exchange spin-flip reactions (RCNP Osaka/Japan) or electrodisintegration (S-DALINAC Darmstadt/Germany).

2. Experimental Setup

To address the need for precise experimental data we started studying the reaction d(γ,n)p at the radiation source ELBE (acronym for *Electron Linac for beams with high Brilliance and low Emittance*) at Forschungszentrum Dresden-Rossendorf [6]. At ELBE, an electron beam with energies up to 40 MeV, with a bunch charge of 77 pC and with a bunch length of less than 10 ps is delivered by a superconducting continous-wave linear accelerator with variable frequencies of

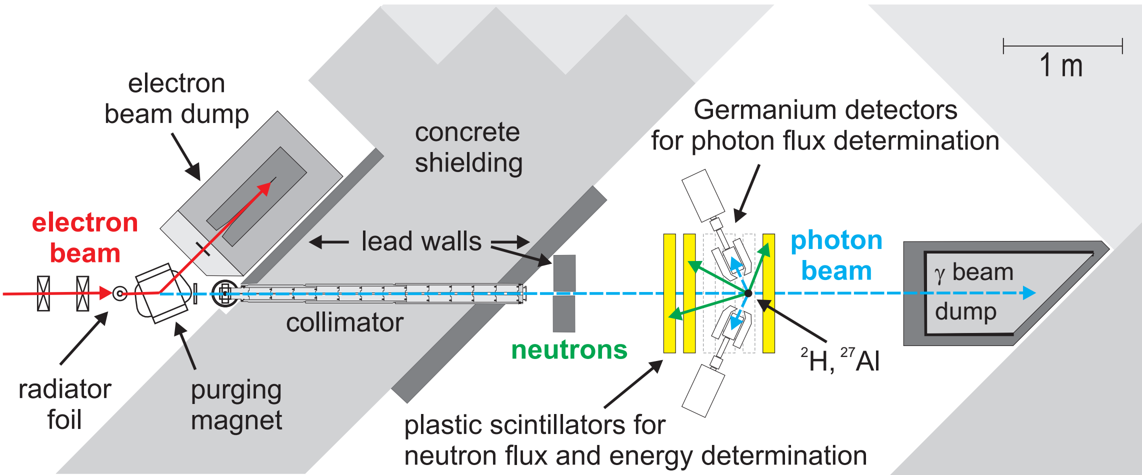

Figure 1: Layout (top view) of the bremsstrahlung facility at ELBE, where the d(γ,n)p reaction is studied.

26 MHz / 2^n ($0 \leq n \leq 8$). The electron beam is used to generate secondary radiation such as coherent infrared radiation from free-electron lasers, quasi-monochromatic X-rays, (unpolarized or partially polarized) bremsstrahlung up to 20 MeV, neutrons or mono-energetic positrons.

At the bremsstrahlung facility [7] at ELBE various experiments related to nuclear physics and its applications, nuclear astrophysics or material science have been performed using methods like nuclear resonance fluorescence (NRF), activation or γ-induced positron spectroscopy, respectively. Its design aimed at minimization of beam-induced background like the production of neutrons or the scattering of photons from surrounding materials. The experimental area of the bremsstrahlung facility is equipped with up to four high-purity n-type germanium (HPGe) detectors with 100 % relative efficiency. The detectors are surrounded by escape-suppression shields consisting of bismuth-germanate scintillation detectors, lead shields and lead collimators.

The experimental setup for studying the reaction d(γ,n)p is shown in figure 1. The electron beam hits a 12.5 μm-thick radiator foil made of niobium, generates bremsstrahlung and is deflected into a beam dump. The bremsstrahlung photons pass through the deflecting magnet and a collimator. The collimated beam enters the experimental area, hits the target and is finally absorbed in a γ beam dump. The cylindrical target consists of alternating layers of aluminum (99.5 % purity) and deuterated polyethylene (CD_2, 98 % enrichment in D) with total masses of 5.0 g and 4.2 g, respectively. An electron energy (endpoint energy of the bremsstrahlung spectrum) of about 5.0 MeV is chosen to stay below the neutron separation energy of ^{13}C which is found in the CD_2 target. The electron energy is measured with a precisely calibrated Browne-Buechner spectrometer to 0.3 % precision (FWHM, see figure 2). By means of NRF on ^{27}Al the photon flux normalization is determined at energies of 2.982 and 2.212 MeV, which is close the d(γ,n)p reaction threshold of 2.225 MeV. ^{27}Al is chosen because its level widths are known with high precision in the relevant energy range [8].

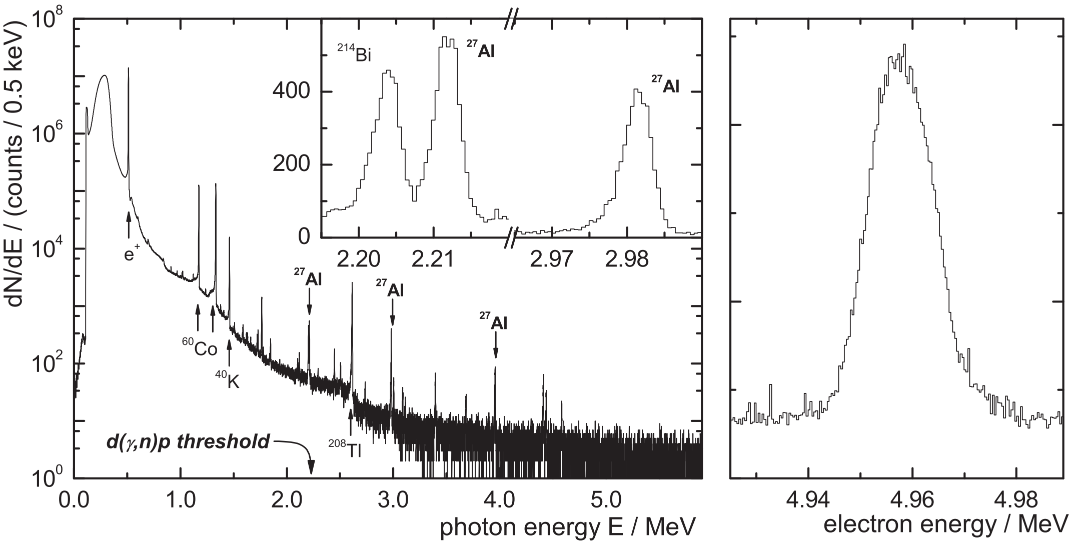

Figure 2: The left panel shows a HPGe spectrum containing the ^{27}Al-transitions that are used for the photon flux determination. Further labeled peaks are related to natural or beam-induced background or to a ^{60}Co-source that was placed next to the detector and that was used for monitoring of dead time and pile-up. The inset shows the same spectrum at the ^{27}Al-transitions at 2.212 MeV and 2.982 MeV. In the right panel a spectrum of the Browne-Buechner electron spectrometer is shown (mean: 4.958 MeV, FWHM: 14 keV). The constant background is related to noise of the camera used to read out the screen of the spectrometer.

The γ-transitions are measured with two HPGe detectors placed at angles of 115° with respect to the incoming beam (see spectrum in figure 2). Absorber plates of copper and lead (each 3 mm thick) are mounted onto the collimator entrance holes of the HPGe detectors in order to attenuate scattered low-energy photons. The detector efficiency is simulated with Geant4 [9] and is normalized to efficiencies measured with calibrated radioactive sources (^{226}Ra, ^{88}Y, ^{137}Cs, ^{60}Co).

The neutrons are detected using a time-of-flight (TOF) method with 1000 mm long, 42 mm wide and 11 mm thick plastic scintillators (EJ-200). Scintillation light is detected on two sides by Hamamatsu R2059-01 high-gain photomultiplier tubes (PMT). By the double-sided read-out, low-amplitude signals stemming from low-energy neutrons can be discriminated from noise by applying a coincidence trigger condition. Thus, the neutron detection threshold is lowered to about 20 keV. On the other hand, the point of interaction within the detector can be obtained from the time difference between the two PMTs with a spatial resolution of $50-55$ mm (FWHM), which is equivalent to a time resolution of $640-700$ ps (FWHM). The spatial information is important to determine the angle and the flight path of the outgoing neutron. The TOF is determined from the PMT time-signals and a reference signal from ELBE recorded with time-to-digital converters (CAEN V1190A) with a dispersion of about 100 ps per channel. The detector efficiency is between 10 % at 24 keV and 20 % at 1.2 MeV and was measured at PTB Braunschweig. Further details about the neutron detectors and their data aquisition system can be found in ref. [10].

In this experiment, six of the neutron detectors are aligned centered one meter above the target at angles between 80° and 125° with respect to the incoming beam (see figure 1). Because overlap of the slowest detectable neutrons with the following pulse has to be avoided, an ELBE pulse frequency of 1.625 MHz is chosen at this detector-target distance. 10 mm-thick lead shieldings are mounted around the neutron detectors in order to attenuate photons scattered from the target. Thus, the contribution of detected photons to the total count rate is decreased to 50 - 90 % (depending on the angle).

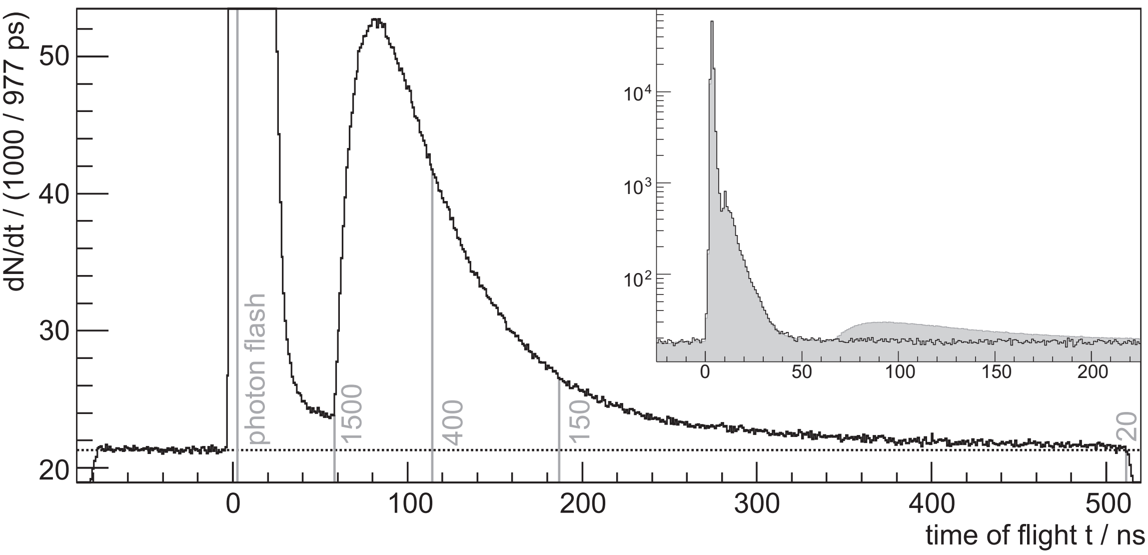

Figure 3: TOF-spectrum measured with the neutron detector at 90° in 127 hours (real time). The gray labels are neutron energies (in keV) caclulated for certain TOFs assuming a flight path of 1.0 m. The inset shows how the TOF-spectrum changes, if a target of CH_2 (black line) is used instead of a CD_2 (shaded gray).

3. Ongoing work

Figure 3 shows a TOF-spectrum measured with the neutron detector at 90° of the setup described above. The TOF-offset of the spectrum is determined from the centroid of the peak stemming from photons scattered at the target ("photon flash"). In the region prior to the photon flash, the flat background originating from random coincidences and natural radioactivity can be obtained by fitting (dotted line). The distribution of neutrons starts at 60 ns (end of bremsstrahlung spectrum) and ends at about 520 ns (low-energy detection threshold). The origin of the tail of the photon flash starting at 40 ns is still investigated in order to prove that this tail will not affect the relevant energy region. Therefore, we measured with a CH_2-target (polyethylene) in the same setup (see figure 3) and we studied the time structure of the photon flash and of its tail using a fast BaF_2 detector.
The ongoing analysis focusses on the proper correction of all systematic effects such as dead time, beam stability, background, absorption in the target, feeding or detector efficiencies. Finally, precise cross sections are to be extracted from the measured data.

4. Conclusions

First experiments studying the reaction d(γ,n)p at energies relevant to Big Bang nucleosynthesis have been performed at the ELBE bremsstrahlung facility at Forschungszentrum Dresden-Rossendorf. From the data of our experiments we estimated statistical and systematic uncertainties of 5 % each for one detector at a neutron energy of 150 keV with an energy uncertainty of 4 %. The latter is dominated by the thicknesses of target and detector and at lower neutron energies by the combination of TOF-channels (in order to reach an appropriate statistical uncertainty).

5. Acknowledgements

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