Measurement of the ${}^6\text{Li}(n,\alpha)t$ neutron standard cross-section at the GELINA facility

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Abstract. The ${}^6\text{Li}(n,\alpha)t$ reaction cross-section is an established standard due to its relatively high cross-section as well as its high Q -value. However, it is only considered a neutron standard up to 1 MeV, because in the neutron energy region 1–3 MeV there exist discrepancies of several per cents between recent measurements [1,2] and evaluated data files [3].

It has been speculated [4] that neglecting of the *particle leaking* effect might be part of the explanation why there is a disagreement in this region. Based on R-matrix calculations, in the region around 2 MeV, one also expects three excitation levels of ${}^7\text{Li}$ to significantly influence the cross section [5].

In order to resolve these discrepancies, we perform measurements at the GELINA facility at JRC-Geel with two Frisch-gridded ionisation chambers. The ${}^6\text{Li}(n,\alpha)t$ cross section is measured relative to the ${}^{235}\text{U}(n,f)$ standard. In order to solve previous encountered problems [6], the setup has been modified and moved to a new flight path station. In this proceeding we show that several problems have been eliminated and discuss possible solutions to newly arisen problems, due to the changed experimental conditions. Preliminary results from new data taken during 2016 with the updated setup are presented.

1. Introduction

The ${}^6\text{Li}(n,\alpha)t$ reaction cross-section is an established standard up to 1 MeV. One reason for that is its relatively high cross section, while another reason is its high Q -value, of almost 5 MeV. A large Q -value enables the reaction products to give large clear signals in many detector setups, e.g. ionisation chambers.

In order to extend and establish ${}^6\text{Li}(n,\alpha)t$ as a neutron standard above 1 MeV some issues must be resolved.

Up to 1 MeV the cross sections from different experiments agree well, but between 1 MeV and 2.5 MeV discrepancies exist. In this region one also expects three broad resonances to affect the cross section [5]. Two recent independent experiments have reported discrepancies [1,2] and got a cross section several percent higher than the ENDF/B-VII evaluation [3].

One possible reason for the evaluation based on previous measurements showing a smaller cross section could be the *Particle Leaking* effect [4]. Due to the incoming neutron momentum there is a possibility of both products (α -particle and triton) being emitted in the forward direction (in the laboratory frame of reference), but with large polar angles ($\theta \lesssim 90^\circ$) for moderate neutron energies. If this is not taken into account, it can lead to an underestimation of the cross section since the pulse height is higher than for a normal α -particle or triton event. Events might be discarded because of that.

The aim of this measurement is to allow for an extension of the standard energy range from 1 MeV up to a few MeV. As a prerequisite any discrepancies in this region must be resolved.

2. Experimental setup

2.1. Facility

The measurement is conducted at the *GEel LINear Accelerator* (GELINA) neutron source which is located at the JRC-Geel. It provides a pulsed continuous neutron energy spectrum that peaks around 1–2 MeV, but extends up to 20 MeV.

Several problems were identified in previous measurements. Solutions proposed in Ref. [6] have now been implemented resulting in a modified setup moved to a new flight path station of 30 m.

2.2. Gridded ionisation chamber

The detector setup consists of two Frisch-grid ionisation chambers which are designed to measure the α -particles and tritons from the ${}^6\text{Li}(n,\alpha)t$ reaction as well as the fission products from the ${}^{235}\text{U}(n,f)$ reference reaction. Previously, only one chamber was used allowing both measurements to share the same gas flow. P-10 is still used as counting gas, but now separate chambers are employed to render a higher pressure in the ${}^6\text{Li}(n,\alpha)t$ chamber. The chamber detecting fission products (FPs) had a 100 kPa pressure, while 200 kPa was used to stop the reaction products of ${}^6\text{Li}(n,\alpha)t$.

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Figure 1. Schematic of the chamber electrodes. The emitted particle will leave a track of liberated electrons. The mean distance from the particle origin of these electrons is denoted $\bar{X}$. The grid-cathode distance, D , is 40 mm and the grid-anode distance, d , is 7 mm.

We paired our four targets in back-to-back positions in order to form two double sided targets that also formed the cathodes in their respective chambers.

The two targets forming one of the pairs consist of LiF, which was vacuum deposited on an aluminium backing. The deposited layers have similar masses, 2.014 ± 0.023 mg and 2.610 ± 0.040 mg, respectively. The 0.5 mm thick backings make it impossible for any reaction products to traverse through the target to the other side of the cathode (the range of a 5 MeV triton in aluminium is only about 100 μ m [7]).

One of the uranium targets previously used [6] was replaced. The uranium targets now in use have areal densities of 216.0 and 221.5 μ g/cm², respectively. Their aluminium backings of 30 μ m stop any FP emitted in the backing direction.

On each side of both cathodes, the chamber was equipped with an anode and a grid (Fig. 1). Induced signals on the electrodes were recorded by a 100 MHz digitiser. The Frisch grids make the grid pulse height (PH) proportional to $\cos \theta$ and the anode PH proportional to the deposited energy [8].

In order for the electrons to pass through the grid without losses, the field strength between the grid and the anode must be several times higher than the field strength between the cathode and the grid [9]. Accordingly, we have chosen our voltages in both chambers to have a ratio of 5. The actual values of the voltages are different, by a factor of 2, in the two chambers in order to keep a similar field strength.

3. Analysis

A more complete description of the analysis procedure can be found in Ref. [6]. For completeness we still describe the most essential steps here.

3.1. Time-of-flight

The trigger was constructed by combining both cathode signals after they were fed through a CFD module. The recorded timestamp can be turned into a time-of-flight

Figure 2. An example of anode and grid signals from a triton event. The original signals are shown in red while the corrected signals are drawn in black. The dashed blue lines are the fitted functions to the signals.

(ToF) if a reference time is known. The reference time can be found by observing the γ -flash coming from the neutron production target or by identifying resonances.

In order to reduce the magnitude of γ -induced events in our detectors as well as to provide resonances, 2 cm of lead was placed inside the neutron beam. The resonances from the lead appear as a decrease of events at the corresponding energies in the ToF spectrum. The lead resonances, which extend up to the 1 MeV region, are important to the measurement since ²³⁵U mainly provides resonances at quite low neutron energies and the well known resonance of ⁶Li around 240 keV is quite broad.

3.2. Digitised signals

The digital sampling of the signals enables corrections in the post-analysis and has shown to be superior to analogue equipment [10]. Each signal was fitted to a function consisting of line segments to extract the signals features, PH, rise time etc. Most events corresponding to higher neutron energies were piled up with γ -flash induced events. A correction procedure was therefore developed in order to remove the γ -induced part of the digitised signal.

The correction is performed through a peak search in the anode signal's derivative. Once the true signal peak is identified, the regions of other peaks are replaced by zeroes and subsequently the signal is integrated back. The same correction is applied to the corresponding grid signal. In Fig. 2 the anode and grid signal of a γ -piled up triton event can be seen, both before and after the correction. The higher the energy of the neutron, the closer the γ -induced signal comes to the sought signal making the correction increasingly difficult.

3.3. Fission events

Due to the much larger energy deposited in the gas by FPs, a PH threshold separated the FPs unambiguously from the α -particles. Due to the thick backing, only one of the two FPs was detected for each fission event. The neutron energy of interest was no more than a few MeV, so its influence on the fragment kinematics was small.

Figure 3. Grid PH plotted against the anode PH for fission events induced by neutrons of any energy. The lines represent the limits G_0 and G_1 , which defines $\cos \theta = 0$ and $\cos \theta = \pm 1$, respectively.

The basis of the FP analysis is the grid-versus-anode plot shown in Fig. 3. For each anode channel the fission events are projected onto the grid axis. The projection is used to determine for which grid values the distribution drops to half of its maximum. These grid values, G_0 and G_1 , correspond to $\cos \theta = 0$ and $|\cos \theta| = 1$. Since the grid PH is proportional to $\cos \theta$, we can derive the emission angle through,

$$|\cos \theta| = \frac{G - G_0}{G_1 - G_0}, \quad (1)$$

where G denotes the measured grid PH. The value of G_0 is always very close to zero, but the value of G_1 will change with the fragment energy since it is proportional to $\bar{X}$ (see Fig. 1). This in turn depends on the stopping range of the heavy ion in question. G_1 can be well parametrised by two line segments as shown in Fig. 3.

The fragments emitted at an angle close to 90° will suffer from larger energy losses in the target. Corrections for these energy losses are made by observing how the mean PH changes with $\frac{1}{\cos \theta}$. For gracing angles energy losses are too big to be fully corrected and some particle losses are unavoidable.

3.4. Lithium events

Due to increased recombination at a higher gas pressure of 200 kPa, the α -particle events are difficult to separate from the background. However, the triton events are much less sensitive to recombination since their stopping power $\frac{dE}{dx}$ is much lower. The larger penetrability of the tritons, unfortunately, also causes problems for forward events of a few hundreds of keV or more. The tritons emitted at small angles are able to pass through the grid which results in distorted grid and anode signals (see Fig. 5). The events can still be separated and counted, but the recorded signals are difficult to correct. Consequently, providing angular distributions at these energies is difficult.

4. Preliminary results

FPs of gracing angles will sometimes not even escape the target. A loss of events at low cosine values is visible in the spectra depicted in Fig. 4. To avoid the cross section being affected by particle losses, only fission events with $|\cos \theta| > 0.3$ are used, since no losses have been observed above that limit. The extrapolation to $\cos \theta = 0$ is made by assuming isotropic emission angles. This introduces an error at neutron energies where angular anisotropy is prominent.

Figure 4. Cosine distributions of the events emerging from the forward and backward facing fission targets respectively. Apart from losses due to the target, the low energy distributions are isotropic, while angular anisotropy can be seen for the 1 MeV events.

Figure 5. Lithium events induced by neutrons in the energy range 300–350 keV. The particle leaking effect manifests itself as a new cluster of events seen in the top left of the plot. The punch-through effect appears as a bent shape for tritons at small forward angles (large grid PH).

However, this is a minor effect and will be taken into account in future analyses.

Contrary to FPs, the two reaction products from ${}^6\text{Li}(n, \alpha)t$ have comparable masses to the neutron's. The kinematics are therefore strongly dependent on both the neutron energy as well as the emission angles in the laboratory frame of reference. The *particle leaking*, where both particles are emitted in the forward direction, must be taken into account in order not to underestimate the cross section. The particle leaking is manifested in the data as a loss of α -particles and tritons at large forward angles, but at the same time a new cluster of events appears at energies corresponding to the sum of both particles' energies. This is shown in Fig. 5.

The energy calibration is not final, but resonances from the lead put in the beam has been found. Our preliminary results reproduces the ${}^6\text{Li}(n, \alpha)t$ cross section (Fig. 6) fairly well from low energies up to the large ${}^6\text{Li}$ resonance. To

Figure 6. Preliminary cross section of the ${}^6\text{Li}(n,\alpha)t$ reaction, the error bars represent statistical uncertainties only. The different data points are based on α -particle counting and triton counting, respectively.

obtain absolute values the ${}^{235}\text{U}$ cross section from the ENDF/B-VII.1 evaluation [3] has been used. The same results is obtained no matter if only α -particles or only tritons are taken into consideration.

5. Conclusion and outlook

The experience gained from the previous measurements [6] allowed us to improve our setup. The higher pressure used now has resulted in a much improved measurement situation since we can also count the tritons instead of only the α -particles. Previously, partly stopped tritons provided a cumbersome background which no longer is present. Still, an even higher pressure would be required to fully stop the tritons at all the neutron energies of interest. Doing that would allow us to measure the angular distributions also for all energies. An alternative would be to change our counting gas from P-10 to a mixture with higher stopping power.

Moving from a moderated beam at 10m to an unmoderated beam at 30m allowed us to reach higher neutron energies. Unfortunately the γ -flash was more problematic than expected. A 2 cm lead plate placed in the beam did not attenuate the γ -flash to a satisfactory degree. However, since we use digital acquisition many signals can be corrected and we are currently trying to extend the

energy range in which this correction works well. More lead or a longer flightpath would alleviate some of these problems.

The preliminary cross section presented here comes from data acquired during the first half of 2016. While improvements are still in progress we can already reproduce the ENDF/B-VII cross section reasonably well using either α -particles or tritons. Extending the energy range, in which we can provide a decent cross section, is our main challenge for the future.

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