Reconstruction of the GANIL-NFS spectral neutron flux with Medley using elastically scattered protons

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Abstract. The experimental setup called Medley, has been installed at the Neutrons For Science (NFS) facility at GANIL to study the production of light-ions in neutron-induced reactions. The setup was first used to measure the neutron spectral flux from neutron-proton elastic scattering, allowing both an assessment of its performance, and providing an independent measurement of the neutron flux of the facility. The experimental setup, its performance, and the challenges encountered are presented and discussed. The deduced neutron flux is compared to the one obtained from a monitor based on position-sensitive parallel plate avalanche counters (PS-PPACs).

1 Introduction

The Medley setup, developed and built at Uppsala University, contributed to the nuclear data community by measuring light-ion production cross sections for neutron-induced reactions, using quasi-mono energetic neutron beams with energies up to 175 MeV [1, 2]. In 2020, it was installed at the recently inaugurated Neutrons For Science facility (NFS) at GANIL, in France [3].

The new facility provides a white neutron beam with energies from ≈1 MeV to 40 MeV [4]. The advantage of conducting new light-charged particle production experiments at NFS relies on its intense neutron flux over a wide energy range, together with suitable background and gamma-flash characteristics.

To assess the performance of Medley in its new configuration, the facility's neutron spectral flux was reconstructed from H(n,p) elastic scattering data applying the Time-of-Flight (TOF) technique, using 25 mm diameter CH_2 and C targets. Our results were compared with those obtained with a position-sensitive parallel plates avalanche counter (PS-PPACs) beam monitor detector installed in the same beam line.

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2 Experimental Setup

2.1 Neutrons for Science (NFS) facility

Neutrons for Science is one of the three experimental areas at the SPIRAL-2 facility in GANIL [5], and is specially dedicated to neutron studies. It provides a neutron beam using the d(40 MeV)+Be reaction. It is a 28 m long (and 6 m wide) experimental hall that allows the possibility of conducting neutron experiments with competitive energy resolution. Irradiation experiments can also be conducted on the site using an irradiation station coupled with a pneumatic transfer system of the sample.

2.2 Medley setup

The Medley setup consists of a 800 mm diameter chamber with eight three-elements telescopes covering angular positions from 20° to 160°, as shown in Fig.1. Each telescope has two silicon surface barrier depletion (SSBD) detectors followed by a CsI(Tl) scintillation detector, allowing to identify particles using the ΔE-ΔE-E technique. The telescopes are installed on a rotating table and equally divided into two groups, placed in forward and backward directions. By rotating the table, the positions of both groups can be interchanged. The first group, comprising telescopes 1 to 4, has 50 µm and 1000 µm thickness silicon detectors, whereas the second group has 20 µm and 500 µm thicknesses. The setup includes also an interchangeable three-target holder, allowing for the use of one target at a time without disrupting the vacuum.

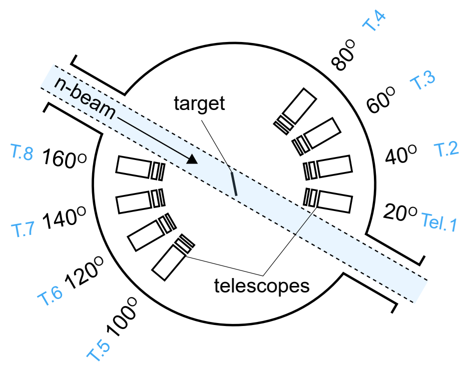

Figure 1. Scheme of Medley chamber showing the disposition of the target and the three elements telescopes. As in the real case, the target is smaller than the beam spot. The distance between the telescopes and the target is approximately 15 cm. Figure adapted from [6].

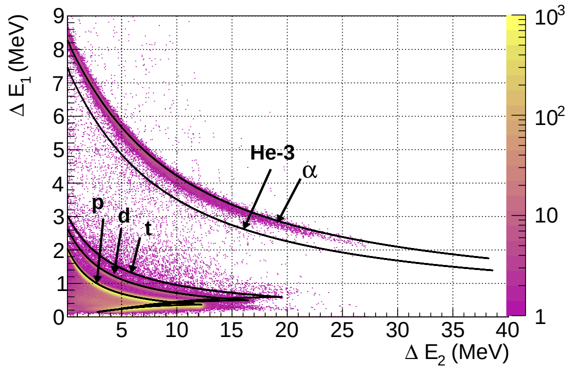

Figure 2. An example of particle identification (PID): showing events for the two first silicon detectors, with the energy loss curves obtained with KaliVeda superposed to the data. The curves for p, d, and t bounce back at the punch-through energy for the second silicon detector. The He isotopes have not enough energy to cross the silicon detectors for this telescope. Experimental data from a CH_2 run, for telescope 1, positioned at 20°.

2.3 Particle identification

The particle identification (PID) is done using the well-known ΔE–ΔE–E method, using the energies deposited in each of the three elements of the telescope. Only particles with energy higher than the first SSBD's punch-through energy can reach the second silicon detector and therefore be unambiguously identified. The setup provides enough resolution for isotopic separation, being able to produce independent measurements for p, d, t, ^{3}He and α particles, as seen in Fig. 2.

The energy calibration for the SSBDs is done using a ^{239}Pu, ^{241}Am, and ^{244}Cm triple-alpha source. This initial calibration is then enhanced with the aid of energy loss calculations performed using the KaliVeda framework [7]. The calibration for the CsI detectors is done for each particle type which punches through the second detector, by reconstructing the remaining energy that a particle has after crossing the silicon detectors, using both the experimental data and the energy loss calculations.

3 TOF measurement

The NFS spectral neutron flux, i.e. the neutron flux as a function of the neutron energy, is obtained by measuring the neutron's TOF, reconstructed from elastically scattered protons detected at the telescopes. At Medley's position, a pulsed beam adjusted to ≈ 1 MHz frequency is required from the facility in order to properly obtain a TOF measurement without overlapping data.

The time measurement starts with an event detection in one of the telescopes and stops with the next radio frequency (RF) signal from the LINAC. Since the thickest silicon detectors are sensitive to gammas, the gamma-flash is detected with 6 ns time resolution in the Medley setup. The time origin (where neutrons are produced) is easily mapped back from the gamma-flash time, as shown in Fig. 3. The acquisition's time response for an individual event remains near 1 ns.

The measured time-of-flight (TOF_{meas} in Eq. 1) is the sum of the neutron TOF from its production point to Medley's target ($TOF_{neutron}$), and the TOF of the outcoming particle traveling from Medley's target to the telescope (TOF_{prod}). The latter is directly obtained from its total deposited energy (E_{prod}). See Eq. 1 and Fig. 3 for details. With this method, neutron energies can be determined with an uncertainty below 2 MeV for 40 MeV neutrons. The total energy lost in the dead layers of the Si detectors for our telescopes is smaller than 13 keV for protons, and therefore we can neglect it in this study.

$$\mathrm{TOF_{meas}} = \mathrm{TOF_{neutron}} + \mathrm{TOF_{prod}}(\mathrm{E_{prod}}) \tag{1}$$

4 Technical challenges

The energy of elastic scattered protons (E_p) depends on the inducing neutron energy (E_n, obtained from neutron's TOF) following Eq. 2 [8]:

$$E_\mathrm{p} = E_\mathrm{n}\frac{4M_pM_ncos^2\theta_\mathrm{LAB}}{(M_p+M_n)^2} \tag{2}$$

where M_p and M_n are the masses of the proton and neutron, respectively, θ_LAB is the outcoming proton angle with respect to the direction of the neutron beam. Our data presented some difference with the expectation, shown in Fig. 4, which can be explained by the difference in the rise-time of a SSBD detector signal for particles with different energies [9]. It causes a residual walk effect in the ToF_{meas} that remains after our constant fraction discrimination (CFD) routine.

A correction for the measured ToF (ToF_{meas}) can be derived as a function of the total energy deposited in the detectors (E_{proton}). This correction is depicted in the inset of Fig. 5, and is calculated by evaluating the difference between ToF_{meas} and its expectation (solid line in Figs. 4 and 5).

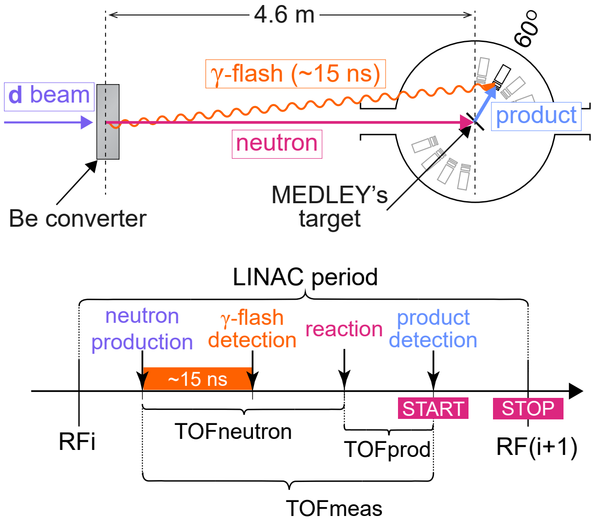

Figure 3. Top: scheme of Medley chamber showing the gamma-flash, the neutron, and the reaction product's paths for a given reaction. Bottom: timeline of events, regarding the radio-frequency (RF) signals coming from the LINAC, for a neutron reaction in Medley, indicating the START and STOP signals of the acquisition setup. Note that the neutron production time is traced back from the gamma-flash, which is synchronized with the RF signals.

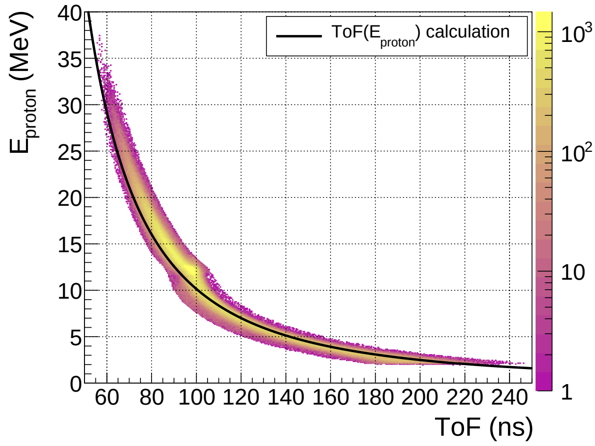

Figure 4. Experimental dependency between proton energy and the neutrons' measured time of flight (ToF_{meas}). The expected value for ToF_{meas} is given by the solid line.

As expected, the deviation for the other H isotopes presented the same structure, so the correction can be carried out for all of them. For He ones, the approach should be slightly different since they do not punch-through (see Fig. 2).

5 Spectral flux reconstruction

5.1 Spectral flux reconstruction using PS-PPACS neutron beam monitor

The NFS' spectral neutron flux was also obtained using a neutron beam monitor consisting of a three position sensitive parallel plate avalanche counter (PS-PPACs) detectors stack alternated with two ^{nat}U targets. The PPACs detect the energy and position of the neutron-induced fission fragments that cross them, and the spectral flux is reconstructed using the ^{238}U(n,f) cross section from ENDF/B-VIII.0 database [10].

Since both fragments are detected, the initial position of the fission event can be tracked, making it possible to obtain the beam profile. Knowing also the beam profile at the collimator outlet, as well as the position of all elements in the beam line with respect to the Be converter, we calculated the beam at the Medley target position to have 27.8(2) mm mm diameter.

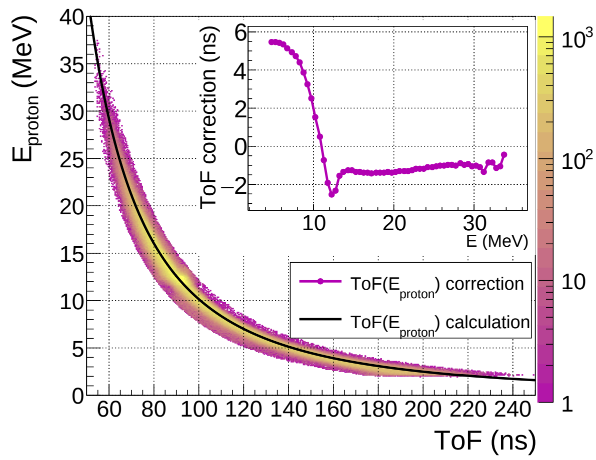

Figure 5. Experimental dependency between proton energy and the neutrons' measured time of flight, after applying the TOF correction, shown in the subplot.

5.2 Spectral flux reconstruction using Medley

For reconstructing the spectral neutron flux, measurements with CH_2 and C targets were used, analyzing only the protons coming from the H(n,p) elastic scattering. These protons are selected by subtracting the C contribution (normalized by its atomic density and relative neutron fluence) from the data obtained with CH_2 target.

The number of protons detected in a given telescope can be determined using Eq. 3:

$$N_p(E_n) = \varphi(E_n) \cdot \frac{1}{D^2} \cdot N_H \cdot \frac{d\sigma}{d\Omega}(E_n, \theta_{LAB}) \cdot \Delta\Omega_{tel} \cdot Q \quad (3)$$

where φ is the spectral neutron flux in units of neutron/sr/μC/MeV, D is the distance between the Be converter and Medley's target, N_H it the number of H nucleus exposed to the beam, $d\sigma/d\Omega$ is the double differential cross section for the H(n,p) reaction, considering given incoming neutron energy E_n and the proton outcome angle θ_{LAB}, $\Delta\Omega_{tel}$ is the solid angle for a given telescope (which is around 20 msr), and Q is the total charge of deuterons incident at the Be converter.

The spectral neutron flux reconstruction was carried out using differential cross sections of the neutron-proton elastic scattering calculated with the partial-wave analysis model [11]. Results obtained with/without applying our TOF correction are presented in Fig. 6, and compared with the preliminary results obtained by the PS-PPACs neutron monitor.

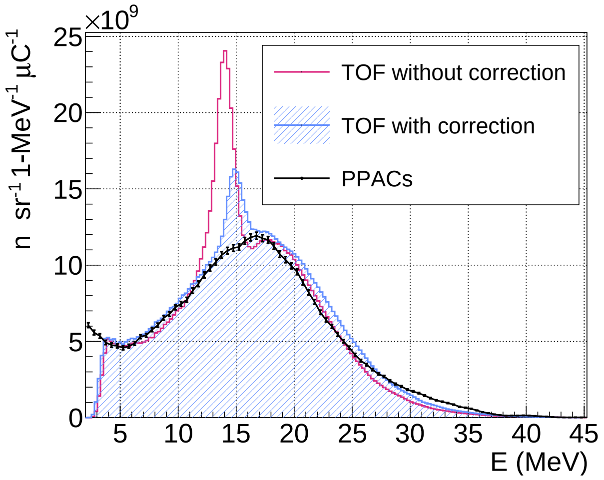

Figure 6. NFS neutron spectral flux reconstructed with Medley from H(n,p), with/without the TOF correction for the electronics acquisition defect, compared with the preliminary result from the PS-PPACs neutron beam monitor.

As shown in Fig. 6, most of the electronic acquisition distortion around 13 MeV, which corresponds to proton punch-through energy for the second silicon detector, was successfully removed after the correction in the TOF data. A reasonable agreement between Medley and PS-PPACs was then obtained, mainly in the range 2 MeV to 25 MeV. The difference observed between Medley and PPACs around 30 MeV is due to the smaller efficiency of the CsI detectors when compared to the SSDBs. On the other hand, the PID threshold poses a limitation for energies smaller than 2 MeV, which does not compromise Medley's energy range of interest.

6 Conclusions and perspectives

The Medley setup has shown its capability to operate with the white neutron beam at NFS, even at the closest possible position. Despite the short flight path of $\approx$ 5 m, the time resolution is enough to cover the whole energy range of the facility.

The time-of-flight (TOF) reconstruction of the neutron spectral flux, based on neutron-proton elastic scattering using the Medley setup, matches the results obtained by a PS-PPAC flux monitor, specially between 2 MeV to 25 MeV, consequently strengthening the overall knowledge of the NFS beam characteristics. A correction factor on the TOF has been used to compensate for the observed time drift, which improves the results. Further work to completely remove the spurious peak in the flux at 13 MeV is ongoing. Additionally, development on the electronics is being done to avoid this problem in future experiments of light-ion production to be done at NFS.

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