

Stellar neutron spectra at 28 keV thermal temperature

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Abstract. To calculate the reaction rate in the neutron capture processes it is common to work with the Maxwellian Average Cross Section (MACS), defined as the reaction rate scaled by the most probable neutron velocity of the Maxwell-Boltzmann distribution. For MACS determination with lower uncertainties, the need of a neutron spectrum as similar as possible to the stellar one motivates this work. At the CN Van der Graaff accelerator of the LNL-INFN laboratories, an experimental measurement is performed to produce a Maxwell-Boltzmann neutron spectrum with 28 keV of thermal temperature. The neutron time-of-flight spectrometry is implemented to determine 0°-90° integrated neutron spectrum, employing the ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction as neutron source, an initial proton energy of 3.17 MeV and a 51 μm thickness aluminum foil, as proton energy shaper.

1 Introduction

Nuclei from carbon to iron were found to be produced by charged particle reactions during the evolutionary phases from stellar He to Si burning. Nucleosynthesis of elements beyond Fe ($B=8.8$ MeV/A) is produced in stars by successive (n,γ) reactions and β -decays. The stellar velocity neutron spectrum is a Maxwell-Boltzmann distribution. Depending on the stellar site and the evolutionary stage of the star the most important temperatures (kT) are in the range of 8-90 keV, being 30 keV the standard temperature of reference [1].

The possibility of reproducing the abundance of the elements in the universe depends on stellar reaction rate calculations. For a given temperature and neutron density and for the s-process mainly, the Maxwellian-Averaged Cross Section (MACS) directly describes the reaction rate inside the stars. The calculated MACS uncertainties of several stable and most of the unstable isotopes are higher than the requested accuracy i.e., for the s-process is 3-5%. Hence, the importance of measuring the MACS with the least possible uncertainty. To achieve this goal it is mandatory to have a neutron beam as similar as possible to the Maxwell-Boltzmann neutron spectrum (MBNS), and this is the main purpose of this work.

2 The method

A possible method to obtain a Maxwell-Boltzmann neutron spectrum (MBNS) at 30 keV was published by Mastinu *et al.* [2], in 2009. The work proposed to modify or shape the neutron energy spectrum by shaping the projectile energy distribution in accelerator-based

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neutron sources. In case the projectiles were protons coming from the ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction, the method is based on the idea that if the proton beam distribution is wider, with protons that cover higher energies, the production of neutrons with higher energies will be obtained. This is done by means of a foil, placed before the neutron producing target, intercepting the projectile beam. This method improves the neutron flux at the sample position and avoid the use of moderators. As proposed by Martín-Hernández *et al.* [3], by choosing different thicknesses, different materials, or combinations of both, different thermal temperatures can be obtained with this method. Figure 1 shows a schematic representation of this method.

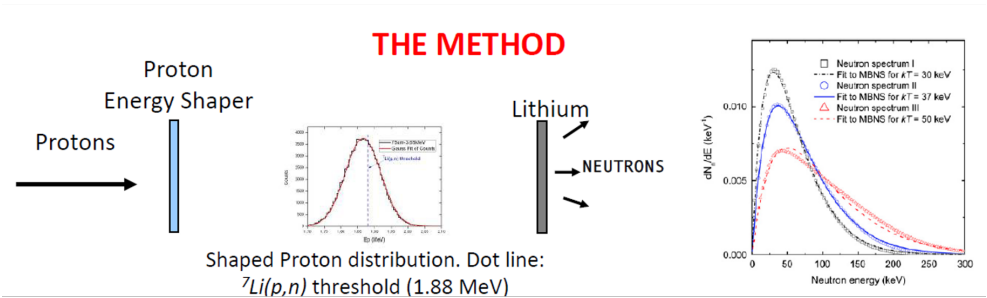


Figure 1. Method to produce a Maxwell-Boltzmann neutron spectrum (MBNS), proposed by Mastinu *et al.* [2].

In the present work, the mentioned method was employed. Different materials and their isotopes were studied as proton energy shaper. The energy threshold for neutron production, the value of the (p,n) cross section, the neutron yield, and the gamma yield were taken into consideration for the analysis. The software SRIM 2013 [4] was employed to obtain the proton energy distributions for various incident monochromatic proton energies impinging on different thicknesses of the studied materials. The theoretical integral neutron spectrum was obtained using the kinematics of the reaction and then fitted to a Maxwell-Boltzmann distribution, determining the kT and the R-square coefficient of determination for that fit. The neutron spectrum that fits best the Maxwell-Boltzmann distribution with $kT = 30$ keV was determined with a fitting code that was developed employing as parameters the proton energy and the FWHM of the proton beam after passing the shaper. After the best fit program calculations, an aluminum foil of $51\text{ }\mu\text{m}$ thickness as proton shaper and an initial proton energy of 3.17 MeV were found to be the best set of parameters to obtain a MBNS with a $kT=28\text{ keV}$.

3 Experimental measurement

The experimental measurement of the Maxwell-Boltzmann neutron spectrum was carried out at the CN Van de Graaff accelerator of the National Laboratories of Legnaro of the Italian National Institute for Nuclear Physics (LNL-INFN), in Padua, Italy. The experimental setup employed in the experiment is shown in Figure 2. The neutron time-of-flight spectrometry (nTOF) was implemented to determine the neutron spectrum, using the ${}^7\text{Li}(p,n){}^7\text{Be}$ nuclear reaction as neutron source and a 600 kHz proton pulsed beam. In the experiment, a proton energy of 3.17 MeV was set in the accelerator and, the $51\text{ }\mu\text{m}$ thickness Al foil was placed before the Li target.

A natural lithium metallic target of $100\text{ }\mu\text{m}$ thickness in a $300\text{ }\mu\text{m}$ copper backing was produced and placed at the end of the accelerator beamline. Three ${}^6\text{Li}$ -glass detectors

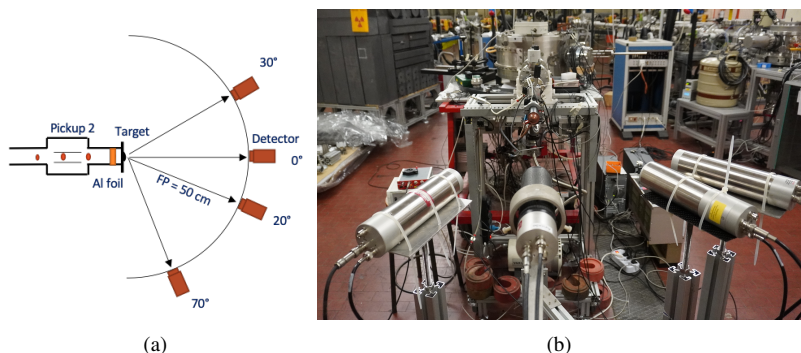


Figure 2. a) Schematic representation of the experimental setup. b) Experimental setup. Detectors were located at 50 cm from the target at different angles to measure the neutron time-of-flight.

purchased from the Scionix company were used for TOF measurements. Two one inch thick detectors and one half inch thick were used. A fourth 3 mm thick Li-glass detector was also used, but as neutron counter monitor for normalization. This detector was also employed to check the target and beam stability. The four Li-glass detectors were placed precisely at 50 cm from the lithium target (flight path) with a low mass designed goniometer. Differential angular neutron TOF distributions from 0 to 90 degrees in steps of 10° were measured in order to obtain the 0° - 90° integrated neutron spectra.

4 Results and discussion

The angle-integrated neutron time-of-flight (nTOF) spectrum is shown in Figure 3 a) and was obtained by summing the weighted TOF spectra from 10 up to 90 degrees for each detector. The differences in the spectrum are due to differences in the efficiency of each detector. A new approach to transform TOF spectrum into energy spectrum was also implemented, using the detector response matrix. This method is long and complex and deserves a separate paper that it is being written. The proposed conversion method considers not only the mean moderation time of neutrons in the detector but also its distribution in time, making an exact deconvolution of the time spectra. This detector response matrix was calculated with the MCNPX [5] simulation code, including the detector geometry and materials composition and determining the neutron time distribution inside the detector for monoenergetic neutron sources. It is important to know precisely the geometry and materials of the detector since the conversion method relies on the response matrix. The geometry and materials composition of each type of detector were directly provided by the Scionix company.

The FWHM of the Gaussian fit for the gamma flash distribution gave a value of 3.43 ± 0.05 ns ($\sigma = 1.46 \pm 0.02$ ns). Because of this, 4 ns was taken as the time resolution of the beam. To mimic the beam time structure in the MCNPX simulation, the source was sampled as a Gaussian-shaped time-dependent distribution with FWHM=4 ns.

Even in the case of monoenergetic neutron beams, different glass thickness in the detectors means different moderation times, and therefore different TOFs. Because of this, two separated analyses were done: one for the half inch thickness detector and the other for the one inch thickness detectors. Figure 3 b) shows the angle-integrated neutron energy spectrum after the new conversion method was applied to the nTOF spectrum for each detector type. As expected, the emitted neutron spectrum is the same even when it was measured with different detectors.

For the data analysis, the time bins were chosen to have almost the same counting statistic per bin (about 1% relative error). With the detector acquired statistics, it was possible to obtain the neutron energy spectrum with 34 nonlinear energy bins, from 1 keV to 322 keV. The higher part of the energy spectrum was obtained using 4 ns temporal bins, because of the already mentioned time resolution of the measurement. At lower energies, the spectrum was obtained with energy bins of 2 keV. The energy resolution goes from 2.6% at 1.85 keV to 28.1% at 300 keV.

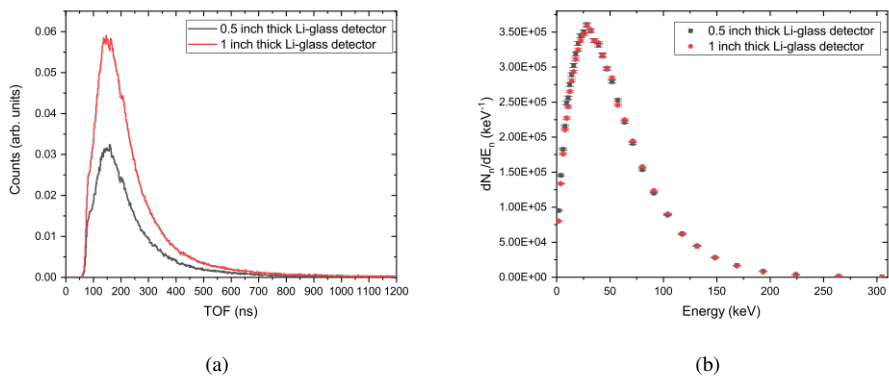


Figure 3. a) Angle-integrated neutron time-of-flight (TOF) spectrum, obtained by summing the weighted TOF spectra from 10 up to 90 degrees for each detector. b) Angle-integrated neutron energy spectrum obtained with the new conversion method.

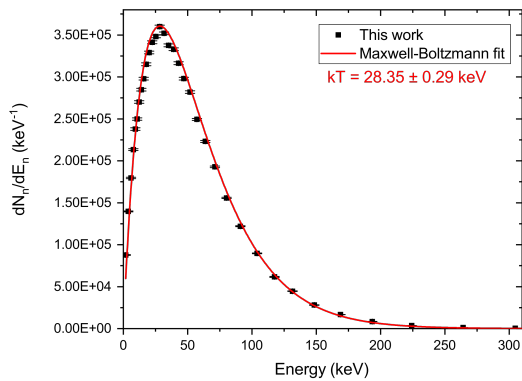


Figure 4. Final angle-integrated, from 0° to 90°, neutron energy spectrum and the least squares fit to a Maxwell-Boltzmann distribution.

The final Maxwell-Boltzmann neutron spectrum (MBNS) is shown in Figure 4, calculated as the average between the values for each energy bin from the two detectors type (Figure 3 b)). The least squares fit to a Maxwell-Boltzmann distribution is also shown, giving a value of thermal temperature of $28.35 \pm 0.29 \text{ keV}$. It is observed in the figure the good agreement

between the experimental data and the Maxwell-Boltzmann fit, even in the high energy part of the spectrum, validating the method proposed by Mastinu *et al.* [2].

5 Conclusions

In the experimental measurement, neutron time-of-flight spectrometry was implemented to determine the neutron spectrum. As source of neutrons, the ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction was employed, using a lithium metallic target and a 600 kHz proton pulsed beam from the Van de Graaff accelerator of the LNL-INFN laboratories, in Legnaro (Padua), Italy. To produce a Maxwell-Boltzmann neutron spectrum, the method of using a proton energy shaper was employed and validated. The most important result of the present work is that a MBNS with a $kT=28$ keV was measured and well reproduced. Irradiating a sample with this neutron field, produced with 3.17 MeV protons and the 51 μm Al foil, a very accurate measurement of the MACS at said thermal temperature can be performed. This is precisely the next experiment to be performed: to measure the "gold standard" for MACS with the activation technique.

References

- [1] P.F. Mastinu, J. Praena, G. Martín Hernández, N. Dzysiuka, G. Prete, R. Capote, M. Pignatarie, A. Ventura, *Physics Procedia* **26**, 261 – 273 (2012).
- [2] P.F. Mastinu, G. Martín Hernández, J. Praena, *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, **601**, 333-338 (2009).
- [3] G. Martín-Hernández, P.F. Mastinu, J. Praena, N. Dzysiuk, R. Capote Noy, M. Pignatari, *Applied Radiation and Isotopes*, **70**(8), 1583–1589 (2012).
- [4] J. F. Ziegler, *SRIM - The Stopping and Range of Ions in Matter*, <http://www.srim.org> (2013).
- [5] D.B. Pelowitz, LA-CP-11-00438, *MCNPX Users Manual Version 2.7.0* (2011).