Nuclear Physics in Astrophysics - X

Maxwell–Boltzmann-like neutron spectrum production at kT=28 keV for Maxwellian averaged cross section measurement

Elizabeth Musacchio Gonzalez (a), Pierfrancesco Mastinu (a), Guido Martín Hernández (b), Lisa Centofante (a), Luca Maran (c), Alberto Ruzzon (a), Daniele Lideo (c)

(a) Laboratori Nazionali di Legnaro , Istituto Nazionale di Fisica Nucleare, (LNL-INFN), Viale dell'Università 2, Legnaro, Padova, Italia

(b) Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), 502 Calle 30, Playa, La Habana, Cuba

(c) Università degli Studi di Padova (UNIPD), Via VIII Febbraio, 2, 35122 Padova, Italia

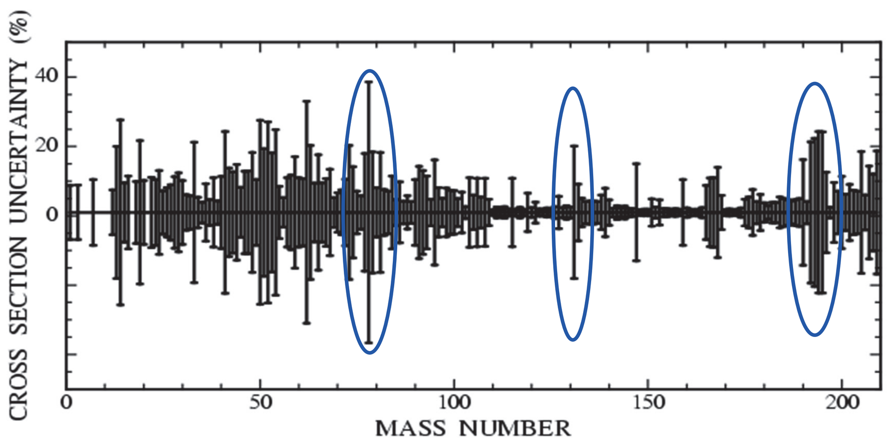
Introduction

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) are 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 8-90 keV, being 30 keV the standard temperature of reference.

The possibility of reproducing the abundance of the elements in the universe depends on stellar reaction rate calculations. For the s-process mainly, the Maxwellian-Averaged Cross Section (MACS) directly describes the reaction rate inside the stars, for a given temperature and neutron density. Hence, the importance of determining the MACS with the least possible uncertainty. Before any MACS measurement, a characterized neutron beam with a stellar spectrum i.e., a Maxwell-Boltzmann neutron spectrum (MBNS) is mandatory.

$$\mathrm{MACS} = \langle\sigma\rangle = \frac{\langle\sigma v\rangle}{v_T} = \frac{2}{\sqrt{\pi}}\frac{1}{(kT)^2}\int_0^\infty \sigma(E)\, E\, \exp\left(-\frac{E}{kT}\right) dE$$

MACS calculated uncertainties of several stable and most of the unstable isotopes are higher than the requested accuracy (for s-process: **3-5%**).

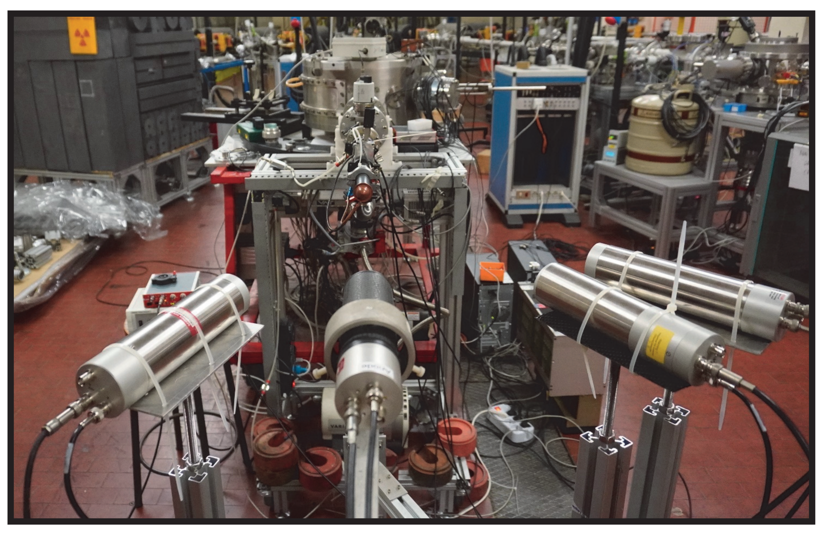


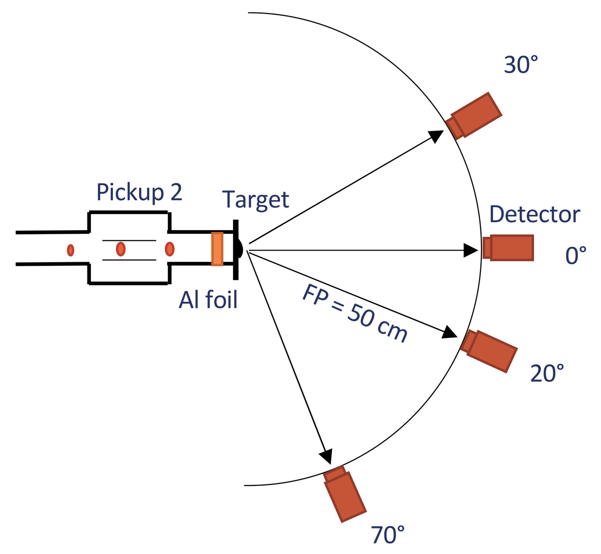
Experiment

- Carried out using the CN Van de Graaff accelerator at LNL-INFN, Padua, Italy.
- The ^{7}Li(p,n)^{7}Be nuclear reaction was employed as neutron source.
- The neutron time-of-flight spectrometry (nTOF) was implemented to determine the neutron spectrum, using a 600 kHz proton pulsed beam.
- A Lithium metallic target was produced and employed.
- Three ^{6}Li-glass detectors 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 beam and the target stability.
- The Li-glass detectors were placed at a 50 cm from the lithium target (flight path).

In the experiment, a proton energy of 3.17 MeV was set in the accelerator and, as proton energy shaper, the 51 µm thickness Al foil was placed before the Li target. Differential angular neutron energy distributions from 0 to 90 degrees in steps of 10° were measured in order to obtain the 0°-90° integrated neutron spectra.

Experimental setup at CN accelerator

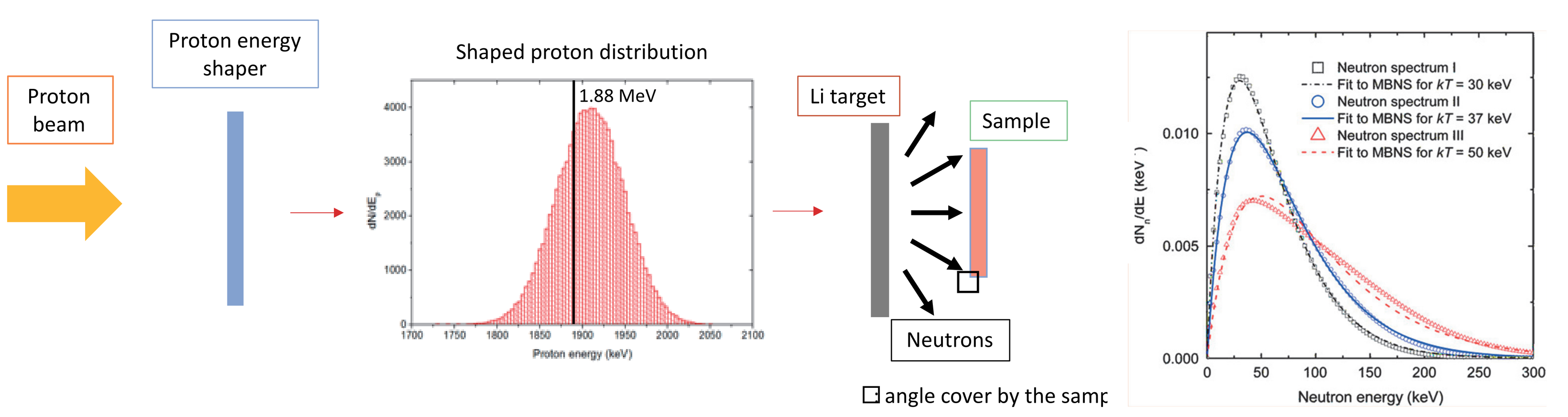




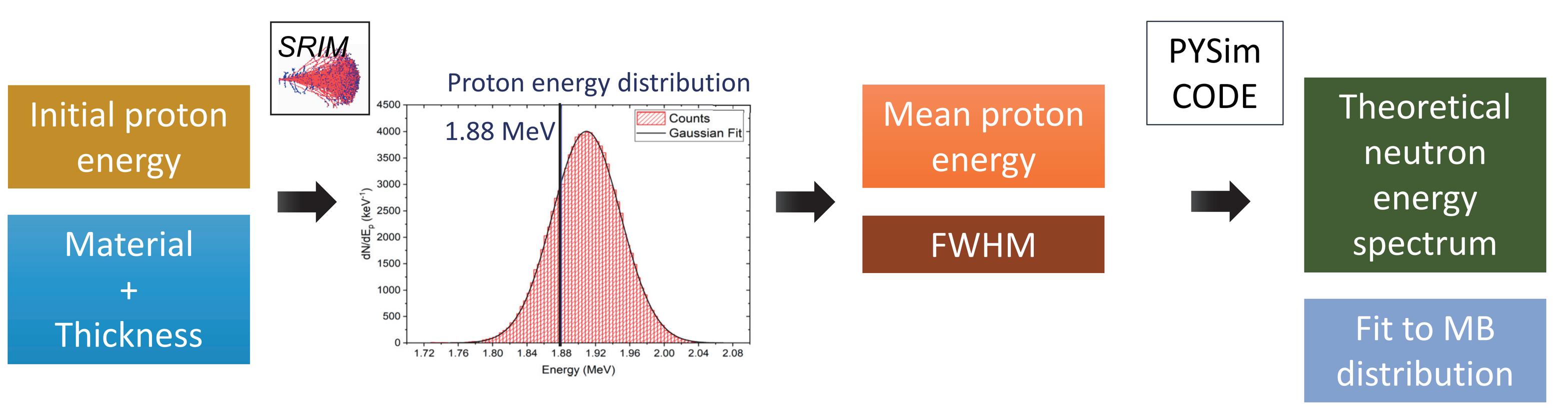
The method

A method to obtain a Maxwell-Boltzmann neutron spectrum (MBNS) at 30 keV was published by Mastinu *et al.* [*Mastinu, P.F., Martín-Hernández, G.,Praena, J., NIM.A 601, 333, 2009*]. This work proposed to modify or shape the neutron energy spectrum by shaping the projectile energy distribution in accelerator-based neutron sources. In case the projectiles were protons coming from the ^{7}Li(p,n)^{7}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 avoid the use of moderators and improve the neutron flux at sample position. By choosing different materials, different thickness, or combinations of both, different kT can be obtained.

Schematic representation of the method



Different materials and their isotopes were studied as proton energy shaper. For the analysis, different aspects were taken in consideration: the energy threshold for neutron production, the value of the (p,n) cross section, the neutron yield and, the gamma yield. A set of calculation were performed using SRIM 2013 software, for various incident monochromatic proton energies impinging on different thicknesses of the studied materials. The theoretical integral neutron spectrum was obtain 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. A second program was developed to find the neutron spectrum that fits best the Maxwell-Boltzmann distribution with kT = 30 keV employing as parameters the proton energy and the FWHM of the proton beam after passing the shaper.



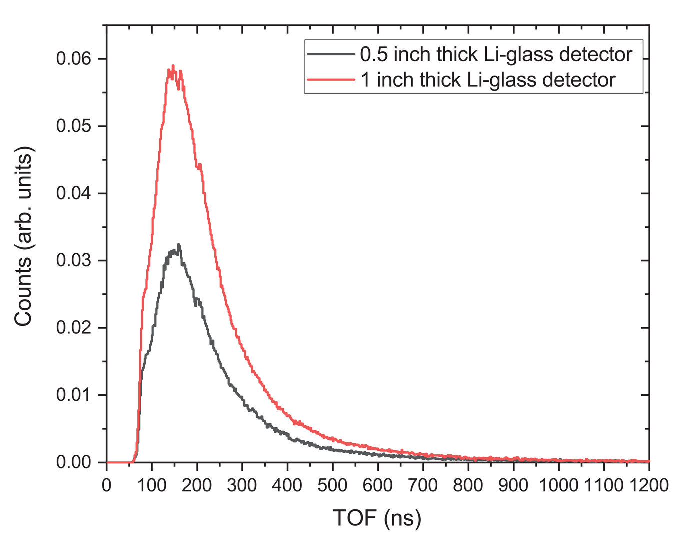
After the SRIM 2013 and the best fit code calculations, an initial proton energy of 3.17 MeV and an aluminium foil of 51 µm thickness as proton shaper were found to be the best set of parameters to obtain a MBNS with a kT=28 keV.

Results

The angle-integrated nTOF spectrum, was obtained by summing the weighted TOF spectra from 10 up to 90 degrees for each detector. A new approach to transform TOF spectra into energy spectra was implemented, using the detector response matrix. The proposed conversion method considers not only the mean moderation time of neutrons in the detector, but also its distribution in time. This detector response matrix is calculated by Monte Carlo simulations, with the MCNPX code, determining the neutron time distribution inside the detector for monoenergetic neutron sources. In the simulations, the detector geometry and materials composition are included. The conversion method relies on the response matrix, hence the importance of knowing precisely the geometry and materials of the detector.

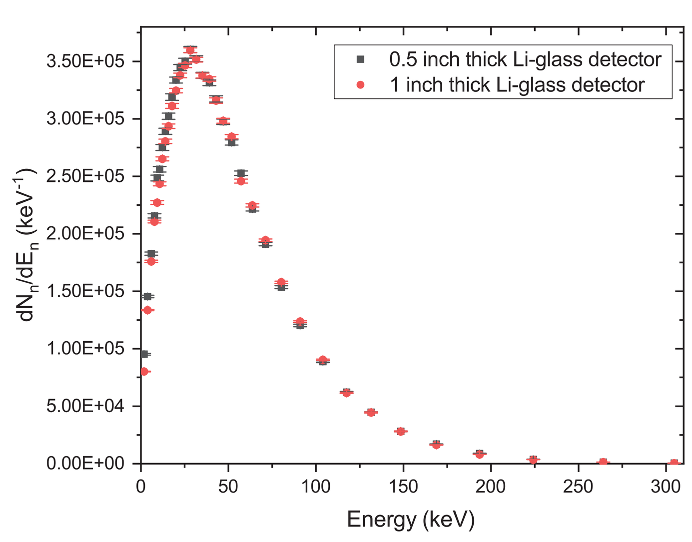
Different glass thickness in the detectors implies different moderation times, and therefore different time-of-flights, even in case of monoenergetic neutron beams. Because of this, two separated analysis were done, one for the half inch thickness detector and the other for the one inch thickness detectors.

nTOF Spectrum

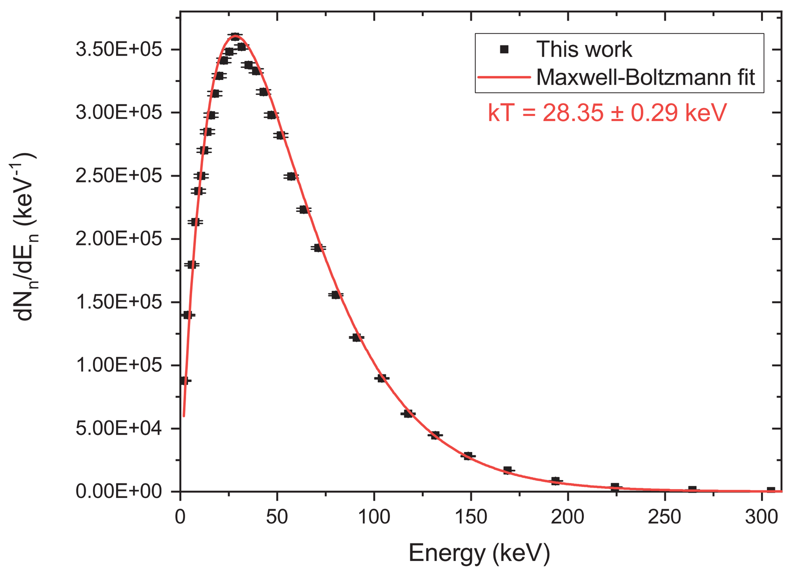


Response matrix method

Neutron Energy Spectrum



The final Maxwell-Boltzmann neutron spectrum is shown in the figure, calculated as the average between the values for each energy bin from the two detectors type. The least squares fit to a Maxwell-Boltzmann distribution is also shown and it is observed the good agreement between the experimental data and the MB fit, even in the high energy part of the spectrum.



$$f(\mathrm{E}) = \frac{dN}{d\mathrm{E}} = a \cdot \mathrm{E} \cdot \exp\left(\frac{-\mathrm{E}}{\mathrm{kT}}\right)$$

$$R^2 = 0.992$$

Well reproduce Maxwell-Boltzmann spectrum

Conclusions

In the experimental measurement, the neutron time-of-flight spectrometry was implemented to determine the neutron spectrum. As source of neutrons the ^{7}Li(p,n)^{7}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 Padua, Italy. To produce a Maxwell-Boltzmann neutron spectrum, the method of using a proton energy shaper was employed and validated. The most important achievement from this work is that a well reproduced MBNS with a thermal temperature of 28 keV was measured. Irradiating a sample with this neutron field, a very accurate measurement of the MACS at said kT can be performed. In a future experiment, setting the same proton energy (3.17 MeV) and using the same Al foil the neutron activation method will be employed to this purpose.