

A Method to Obtain a Maxwell–Boltzmann Neutron Spectrum at $kT = 30$ keV for Nuclear Astrophysics Studies

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Abstract: A method to shape the neutron energy spectrum at low-energy accelerators is proposed by modification of the initial proton energy distribution. A first application to the superconductive RFQ of the SPES project at Laboratori Nazionali di Legnaro is investigated for the production of a Maxwell–Boltzmann neutron spectrum at $kT = 30$ keV via the ${}^7\text{Li}(p, n){}^7\text{Be}$ reaction. Concept, solutions and calculations for a setup consisting of a proton energy shaper and a lithium target are presented. It is found that a power density of 3 kW cm^{-2} could be sustained by the lithium target and a forward-directed neutron flux higher than 10^{10} s^{-1} at the sample position could be obtained. In the framework of the SPES project the construction of a LEgnaro NeutrOn Source (LENOS) for Astrophysics and for validation of integral nuclear data is proposed, suited for activation studies on stable and unstable isotopes.

Keywords: nuclear astrophysics, Maxwellian averaged cross sections, neutron production

1 Introduction

Neutron-capture reactions play an important role in astrophysics and nuclear energy applications. The nucleosynthesis of the elements beyond iron is mainly produced by the so called *s*- and *r*-processes, which consist of successive neutron-capture reactions and subsequent beta decays (Rolfs & Rodney 1998). Isotopes, which exhibit similar probabilities for neutron-capture and beta decay, are called branching points in the respective reaction paths. The knowledge of the neutron capture cross sections of branching points and of numerous other isotopes are the fundamental ingredients for the calculation of stellar reaction rates used in astrophysical network calculations for obtaining the abundance distribution of the isotopes and elements in the Universe (Smith 2004).

At the stellar sites, where *s*-process nucleosynthesis takes place, neutrons are quickly thermalized and exhibit a Maxwell–Boltzmann spectrum corresponding to the temperature or thermal energy kT typical of the mass and evolutionary stage of the star. For the *s* process the most important stellar thermal energies are 8, 23 and 90 keV.

The astrophysical reaction rates can be calculated from the Maxwellian averaged cross section (MACS), which are defined as

$$\frac{\langle\sigma v\rangle}{v_T} = \frac{2}{\sqrt{\pi}} \frac{\int_0^\infty \sigma(E_n) E_n e^{-E_n/kT} dE_n}{\int_0^\infty E_n e^{-E_n/kT} dE_n}, \quad (1)$$

where T is the temperature and $\sigma(E_n)$ the energy dependent neutron capture cross section. The MACS can be calculated analytically at every stellar temperature. Beer, Voss & Winters (1992) provided that the cross section as a

function of neutron energy is known. This information is obtained in time of flight (TOF) measurements at facilities providing a continuous pulsed neutron spectrum. Because of the necessary neutron flight path in such measurements, the flux at the sample position is several orders of magnitude lower than at the source. This implies a severe limitation for the required sample mass. If samples of a few micrograms or less have to be used, the only alternative are activation measurements, which can be performed in the highest neutron flux directly at the source. However, to measure MACSs by activation, the neutron spectrum must correspond to the thermal distribution of the stellar environment.

The high sensitivity of activation measurements is of particular advantage in case of the radioactive branch point isotopes, where the radiation hazard has to be kept as small as possible and where larger samples are often not available. Moreover, the production of isotopically pure radioactive samples, which will become feasible in the near future at new intense radioactive ion beam (RIB) facilities with 10^9 – 10^{11} nuclei, i.e. SPES at LNL, GSI, or SPIRAL-2, will be limited to samples of 10^{12} to 10^{15} cm^{-2} .

A well characterized neutron spectrum could also be used for validation of evaluated neutron data compiled by international agencies, e.g. by NEA¹ and IAEA²

¹ NEA Nuclear Data High Priority Request List (<http://www.nea.fr/html/dbdata/hpr1/>).

² IAEA, Reference Neutron Activation Library (<http://www.nds.iaea.org/ndspub/rnal/>).

(Sublet & Capote Noy 2004), for energy and other applications (Al-Abyad et al. 2006).

In this work a novel method for generating well characterized stellar neutron spectra is proposed. It is based on Ratynski & Käppeler (1988), which is one of the most important works on the generation of stellar neutron spectra. The activation measurements reported by this group are considered as standard in nuclear astrophysics (Bao et al. 2000). Ratynski & Käppeler (1988) show that a quasi stellar neutron spectrum at $kT = 25$ keV can be obtained by using the ${}^7\text{Li}(p, n)$ reaction with a mono-energetic proton beam of 1.912 MeV, close the threshold of the reaction at 1.881 MeV. In Ratynski & Käppeler (1988) it was also shown that activation measurements at $kT = 25$ keV can be extrapolated to determine the MACS at $kT = 30$ keV by a correction of the direct measurement.

The proposed method for producing a stellar neutron spectrum at a low-energy accelerator relies on the shaping of the proton beam. As a first application we have studied the possibility to obtain a well characterized Maxwellian neutron spectrum at $kT = 30$ keV by shaping the monochromatic proton beam from the superconducting RFQ ($E_p = 5$ MeV, $I_p = 50$ mA in CW mode), which is presently under construction and test in the framework of the SPES project at Laboratori Nazionali di Legnaro (LNL, Prete & Covello 2008). The goal of the SPES project is to deliver RIBs of high intensities. Depending on the intensity, this facility could be used to implant RIBs into a substrate and to activate these samples in the stellar neutron spectrum in order to measure the MACSs of unstable isotopes for nucleosynthesis studies.

For generating a neutron stellar spectrum by means of the ${}^7\text{Li}(p, n){}^7\text{Be}$ reaction (Ratynski & Käppeler 1988), the primary proton energy of has to be reduced from 5 MeV close to the threshold of that reaction. This is achieved by what we call the energy shaper, which transforms the initial beam energy into an energy distribution suited for generating a thermal neutron spectrum for $kT = 30$ keV.

2 The ${}^7\text{Li}(p, n){}^7\text{Be}$ Reaction

The ${}^7\text{Li}(p, n){}^7\text{Be}$ reaction has been widely used as an accelerator-based neutron source because it provides a comparably large flux in the energy range between a few keV up to several hundred keV. 50 keV above the reaction threshold the cross section reaches a value of 270 mb and a broad resonance at 2.25 MeV increases the cross section up to 580 mb (Macklin & Gibbons 1958). From the reaction threshold to 1.92 MeV proton energy the reaction is double-valued, yielding two neutron energies per emission angle. If a monochromatic proton beam impinges on a thick lithium target, the protons are slowed down from the initial energy to below the threshold, producing a continuous neutron spectrum.

For thick lithium targets the angular distributions, energy spectra and neutron yields near the reaction threshold can be calculated by the methods reported in Lee & Zhou (1999). We have written a computer code based on

Lee & Zhou (1999) for proton energies up to 2.37 MeV, corresponding to a maximum neutron energy of 650 keV at 0° . At an energy of 2.37 MeV the threshold of the first excited state of ${}^7\text{Be}$ is reached. Up to this energy the neutrons are preferentially emitted in forward direction, a significant gain for the neutron flux. The code calculates also the small background due to backscattered neutrons.

3 Energy Shaper

According to Ratynski & Käppeler (1988) a stellar neutron spectrum for $kT = 25$ keV can be produced via the ${}^7\text{Li}(p, n){}^7\text{Li}$ reaction with a proton energy of 1.912 MeV (close the threshold). With the high current of the RFQ at SPES the neutron flux could be significantly improved, but the high proton energy of 5 MeV is much higher than the threshold region around 1.9 MeV. Consequently, the proton energy has to be reduced. In this step we benefit from the fact that the proton energy distribution can be shaped to yield the required neutron spectrum without moderating materials, thus reducing neutron losses, backgrounds and radiation hazards.

We propose to shape the proton energy distribution by means of an in-beam energy degrader. The idea is to use a rotating foil, which consists of layers with different thickness and different effective area. This choice allows one to control two degrees freedom, the mean value and the shape of the proton energy distribution. A single layer would yield a rather symmetric, Gaussian-like distribution, where the mean and width are determined by the thickness of the layer. Using a foil with several sectors offers the possibility to tailor the proton energy spectrum corresponding to the weighted convolution of the respective Gaussian-like components.

In order to produce a stellar neutron spectrum via the ${}^7\text{Li}(p, n){}^7\text{Be}$ reaction with the RFQ of the SPES project, the proton energy of 5 MeV has to be reduced to about 1.9 MeV. In this step, most of the 160 kW provided by the 50 mA proton current has to be absorbed and removed. Because direct forced convection on the surface of the foil is impossible, the heat has to be removed by a combination of radiation and lateral forced convection. Accordingly, a material with a high melting point and high emissivity has to be chosen for the degrader. In addition, the material must have a high tensile strength, since the degrader has to be self-supporting, and should not produce disturbing backgrounds under bombardment with 5 MeV protons. These requirements made carbon the material of choice for the energy shaper.

The next step is to find the optimal parameters for a multi-layer carbon foil for producing a Maxwellian neutron spectrum at $kT = 30$ keV. With the code SRIM 2008 (Ziegler et al. 1996) we performed a set of calculations for 5-MeV protons impinging on carbon foils of different thickness and a density of 2.253 g cm $^{-3}$. The neutron spectra produced by the interaction of the resulting proton distribution with ${}^7\text{Li}$ were calculated for emission angles up to 90° (the sample will be practically touching

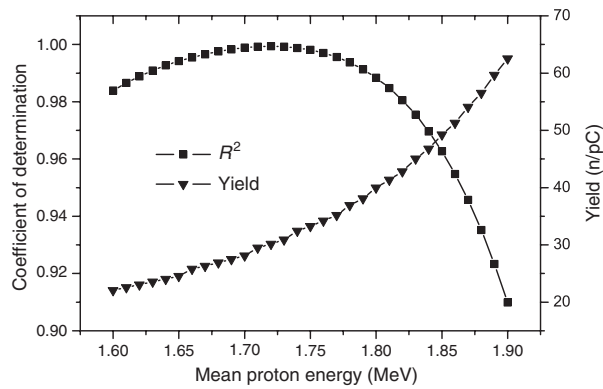


Figure 1 Coefficient of determination, R^2 , between the neutron spectrum and a Maxwell–Boltzmann distribution for $kT = 30$ keV and the neutron yield per pC as a function of the mean value of the Gaussian-like proton distribution after the energy shaper.

the lithium target). For each neutron spectrum we calculated R^2 , the coefficient of determination³ with respect to a Maxwell–Boltzmann distribution for $kT = 30$ keV in order to optimize the thickness and surface structure of the rotating carbon foil. A best value ($R^2 = 0.999$) was found for a multi-layer with three sectors: 21% with a thickness of $153.8 \mu\text{m}$, 54% with $151 \mu\text{m}$ and 25% with $149.6 \mu\text{m}$.

Because of the small differences in thickness we calculated the neutron spectrum for a single layer as a function of the thickness. The resulting R^2 values with respect to a Maxwell–Boltzmann distribution for $kT = 30$ keV are plotted in Figure 1 together with the respective neutron yields.

The maximum of R^2 is 0.997, slightly lower than for the multi-layer foil, but higher than that of Ratynski & Käppeler (1988) for $kT = 25$ keV. The mean proton energy is 1.72 MeV, which corresponds to a thickness of $150.6 \mu\text{m}$. We can conclude that a stellar neutron spectrum at $kT = 30$ keV can be produced with a comparably high neutron yield of 29.2 pC^{-1} by using a uniform degrader. A multi-layer foil could be suited to generate stellar spectra for different kT or other spectral types.

It is important to notice from Figure 1 that minor changes in the proton energy do not produce significant changes in the shape of the neutron spectrum because of the flat behavior of R^2 around the maximum. In principle it would be possible to obtain a higher neutron flux at the price of larger deviations from the ideal stellar spectrum. Depending on the sample under investigation this might be of interest, for example for small sample masses or isotopes with very low neutron capture cross sections.

For a proton current of 50 mA about 164 kW of energy would be absorbed in the energy shaper. First design considerations were performed for a rotating off-center energy shaper consisting of two carbon foils 15 cm in radius and 17 mg cm^{-2} in thickness mounted between two 5 mm thick carbon disks 11 cm in radius. We assumed a proton beam of few millimeters in diameter, which is de-focused

to a diameter of 3.5 cm and hits the carbon foil at a radius of 13 cm. The target rotates at a few hundred rpm to distribute the thermal load. The cooling is based on thermal radiation and on forced flow convection at the axis of rotation. We used a carbon emissivity of 0.9 and a convection coefficient of $0.1 \text{ W cm}^{-2} \text{ K}^{-1}$. The temperature distribution in the carbon foil was calculated with the finite element method using the ANSYS code⁴. The results, which are plotted in Figure 2, showed that the carbon temperature remains well below the melting point (3550°C) and also below the sublimation temperature in vacuum (about 2200°C).

The proton distribution behind the energy shaper for the case of maximum R^2 is given in Figure 3. Protons with energies below the threshold of the ${}^7\text{Li}(p, n){}^7\text{Be}$ reaction will be deflected using common techniques of accelerator physics and the rest will be focused to hit the lithium target on a spot 1.4 cm in diameter for neutron production.

4 Lithium Target

A high neutron flux at the sample position is important for measuring the MACS of radioactive isotopes and/or isotopes with a very small neutron capture cross sections. For unstable isotopes very small samples have to be used to minimize the background from the radioactive decay. Therefore, the dimensions of the beam spot have to be kept as small as possible and the irradiation position of the sample must be as close as possible to the target. After passing the energy shaper and after deflecting the protons with energies below the threshold of the ${}^7\text{Li}(p, n){}^7\text{Be}$ reaction, the proton beam will still deposit about 4.2 kW onto the lithium target. In view of the significantly lower neutron yield of lithium compounds, we have studied a metallic lithium target that can sustain the high power density without exceeding the low melting point of lithium metal of 180.5°C .

The main features for the investigated lithium target are small dimensions (1 cm^2) for obtaining a maximum neutron flux, a high heat transfer efficiency based on a heat exchanger with micro-channels for an effective heat removal and liquid metal as cooling fluid for forced convection. We have designed the target in form of stacked tubes, which are at least ten times longer than their diameter, cooled by flowing mercury at temperatures below 0°C . The temperature of the lithium layer was calculated by considering the heat transfer to the liquid mercury. The film convection coefficient,

$$h = \frac{kNu_b}{d}, \quad (2)$$

represents the power supported by area and Kelvin, where d is the pipe diameter, Nu_b the Nusselt number and k the thermal conductivity of the fluid. The Nusselt number can be computed via the Sleicher & Rouse equation for low Prandtl numbers (Sleicher & Rouse 1975),

$$Nu_b = 6.3 + 0.0167 Re_f^{0.85} Pr_s^{0.93}, \quad (3)$$

³For a definition see http://en.wikipedia.org/wiki/Coefficient_of_determination.

⁴Copyright ANSYS Inc., see <https://www.ansys.com>.

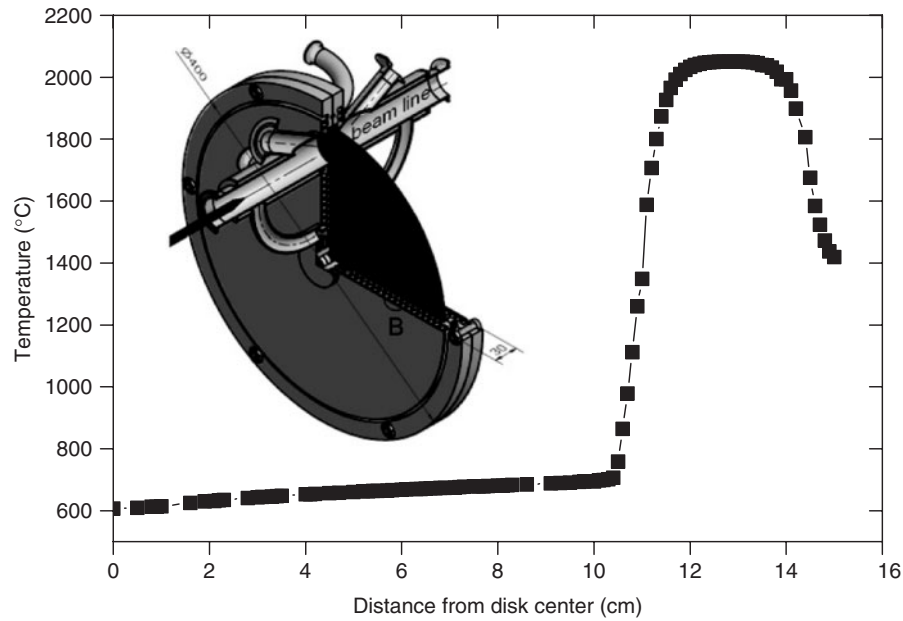


Figure 2 Temperature distribution of a carbon layer 75.3 μm in thickness heated by a 5-MeV, 50-mA proton beam 3.5 cm in diameter. The inset shows a sketch of the system forming the energy shaper.

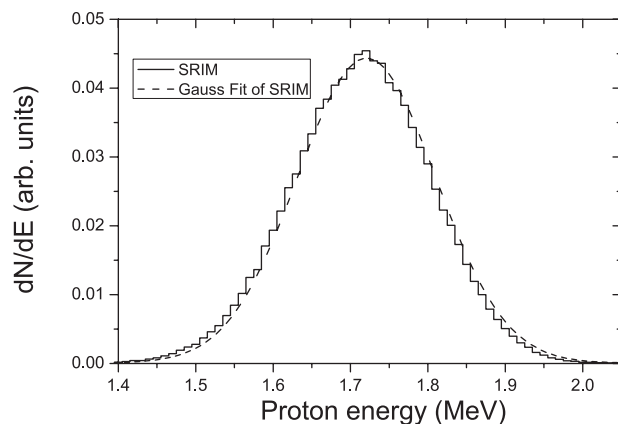


Figure 3 Proton energy spectrum behind the energy shaper calculated with SRIM for a 5-MeV proton beam and a carbon thickness of 150.6 μm .

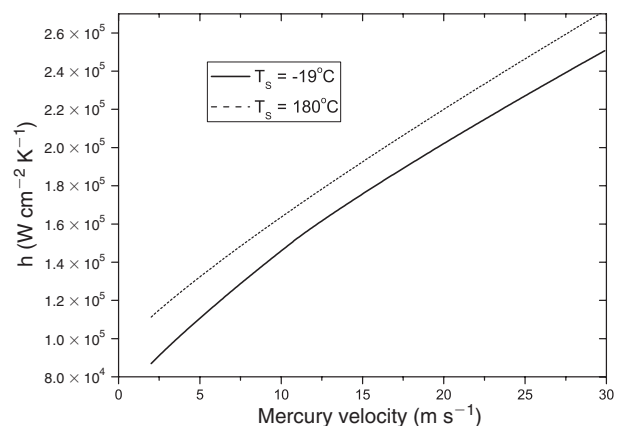


Figure 4 Film convection coefficient as a function of the fluid velocity for tubes 0.5 mm in diameter and different surface temperatures.

where $Re_f = \rho v d / \mu$ and $Pr_s = c_p \mu / k$, ρ are the fluid density, v the fluid velocity and c_p the heat capacity of the fluid. The subscripts, b, s and f indicate that the variables are evaluated for the bulk, surface and film temperature (arithmetic mean of the bulk and surface temperatures), respectively.

The ratio between the heat transmitted to a moving fluid by convection and the heat transfer rate determines the fluid temperature at the outlet as a function of the inlet temperature and the surface temperature of the tube. For a tube containing a constant density fluid one has (Kreith et al. 1999)

$$\ln \frac{T_s - T_i}{T_s - T_o} = - \frac{h}{\rho v c_p}, \quad (4)$$

where T_s , T_i and T_o are the surface, bulk inlet and outlet temperatures, respectively. We have calculated the film

convection coefficient as a function of the mercury velocity (Lienhard 2008), assuming a tube 0.5 mm in diameter and $T_i = -20^\circ\text{C}$. The results are plotted in Figure 4 for $T_s = -19^\circ\text{C}$ and 180°C , corresponding to the minimum and maximum values of h .

We would like to mention that the conductivity could be doubled by using liquid alloys such as Ga–In–Sn, but because not all properties of this material were available to us, this option was not included in this work.

The structure of the investigated target is shown in Figure 5. The part of the proton beam above threshold (Figure 3) hits the target with the lithium layer, which is plotted in the inset. The thickness of the lithium was assumed to be 30 μm , sufficient that all protons are slowed down below the ${}^7\text{Li}(p, n){}^7\text{Be}$ threshold. In this way, one prevents unnecessary energy deposition in the lithium layer while maintaining the maximum neutron yield. We have

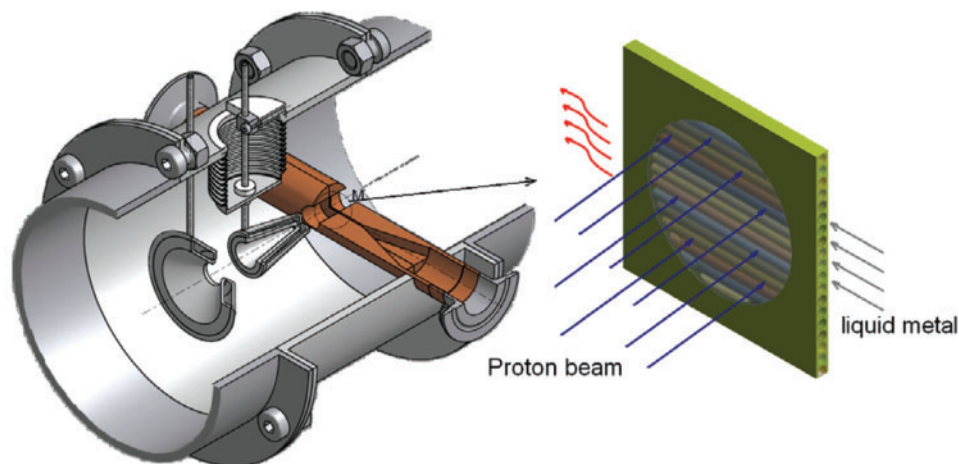


Figure 5 Sketch of the beam pipe and target structure.

calculated that 13% of the proton beam power is absorbed in the lithium. The remaining power is deposited in the backing structure.

The material for the target structure has to meet the required mechanical and thermal properties and must be suited for obtaining the small dimensions. The solution presented here consists of a slab made of 1 mm thick UNS C15720, a commercially available copper–aluminum oxide alloy (Davis 2001). In total 19 cylindrical holes 0.7 mm in diameter and 16 mm long serve as cooling channels. Liquid mercury with a temperature of -20°C is pumped through the target with a velocity of 20 m s^{-1} . Because of the high reactivity of metallic lithium, the deposit is protected against oxidation by $15\text{ }\mu\text{g cm}^{-2}$ of carbon.

Since the proton beam profile of the RFQ-SPES is not yet known, we have studied some possible proton beam profiles in the target calculations. Figure 6 shows the surface temperature for a Gaussian profile of the proton beam plotted along the diameter of the target in the direction of the mercury flow. In the calculations we assumed a beam 1.4 cm in diameter and varied the width stepwise from 0.5σ to 2.5σ , where σ is the standard deviation of the Gaussian. The total power deposited on the target is 4.2 kW. As illustrated in Figure 6 the proton beam spot has to be sufficiently large not to exceed the melting point of lithium.

For a beam profile for 1.5σ and a power density of 3 kW cm^{-2} the calculations yield the surface temperature distributions shown in Figure 7. In this case, the temperature remains sufficiently low so that stable operation can be expected. The parameters of the setup are summarized in Table 1.

The neutron spectrum at the surface of the target presented in (Figure 5) was obtained by a Monte Carlo simulation with MCNPX (Pelowitz 2005). The input files for the complete energy and angular distribution of the ${}^7\text{Li}(p, n){}^7\text{Be}$ reaction were generated from the code that we developed from Lee & Zhou (1999). We also modeled the detailed geometry of the target and of the liquid mercury flow. Figure 8 shows the neutron spectrum seen by

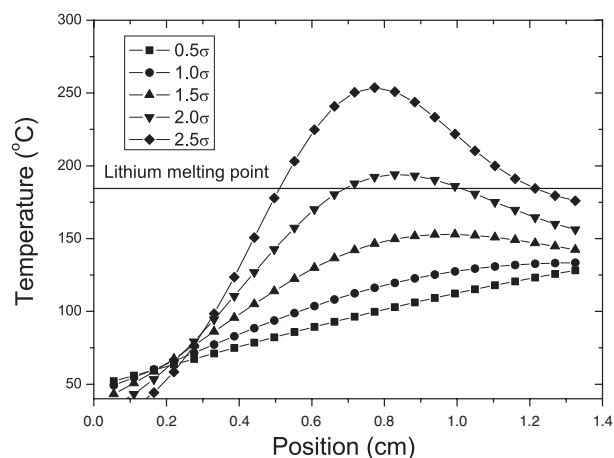


Figure 6 Target surface temperature along the diameter in the direction of the mercury flow. The average beam power density is 3 kW cm^{-2} .

a sample of about 1 cm^2 at 1 mm distance from the target compared to a Maxwell–Boltzmann distribution for $kT = 30$ keV. The fit gives a coefficient of determination of 0.997. With such neutron spectrum it is possible to measure MACSs for $kT = 30$ keV directly without the two corrections required by the method of Ratynski & Käppeler (1988), one related to the missing high-energy tail of the neutron spectrum with respect to a Maxwell–Boltzmann distribution for $kT = 25$ keV, and a second one for the extrapolation to $kT = 30$ keV. The calculated neutron flux at the sample position of the setup presented here is $5 \times 10^{10}\text{ cm}^{-2}\text{ s}^{-1}$.

5 Summary

We have proposed a general method to shape the neutron energy spectra at low-energy accelerators by modification of the initial proton energy distribution. As a first application we have studied the possibility to generate a Maxwell–Boltzmann neutron spectrum for $kT = 30$ keV by using the 5 MeV, 50 mA proton beam from the RFQ under construction and test in the framework of the SPES

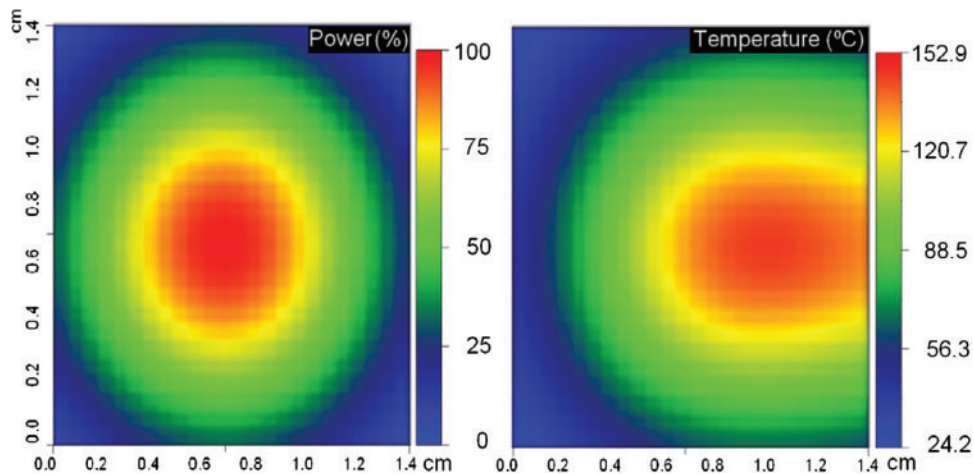


Figure 7 Left: Power profile for an assumed proton beam width of 1.5σ (see text). Right: Target surface temperature distribution with the backing structure and cooling system described in the text.

Table 1. Parameters of the setup for an initial proton beam profile of 1.5σ

Energy shaper (two carbon layers)	
Total thickness	150.6 μm
Power absorbed	164 kW
Radius	15 cm
Proton beam radius	1.75 cm
Maximum temperature	2065°C
Lithium target	
Thickness of Li layer	30 μm
Geometry	16 \times 16 \times 1 mm
Micro-channels	19, diam. 0.7 mm
Backing material	Copper UNS C15720
Copper density	8.81 g cm^{-3}
Thermal conductivity	353 W mK^{-1}
Tensile strength	586 MPa
Coolant	Liquid mercury
Velocity	20 m s^{-1}
Inlet temperature	-20°C
Maximum Li temperature	153°C
Power density	3 kW cm^{-2}

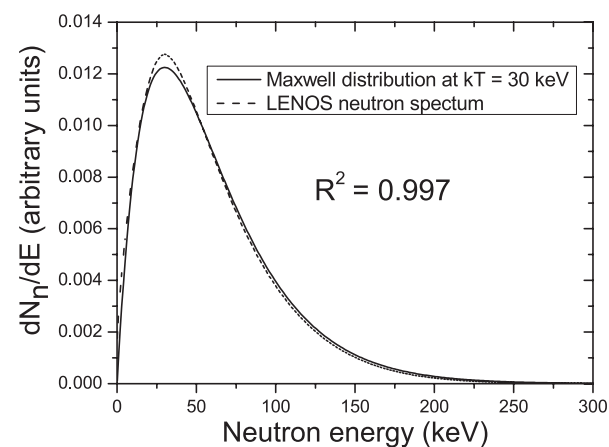


Figure 8 Simulated neutron spectrum obtained with the proposed setup compared with a Maxwell–Boltzmann distribution for $kT = 30$ keV. The coefficient of determination is 0.997.

project at LNL. The solution for a setup based on an energy shaper consisting of a double carbon foil and a metallic lithium target on a mercury cooled copper backing was discussed in some detail. Simulations confirm that a neutron spectrum can be produced with a coefficient of determination of 0.997 with respect to a Maxwell–Boltzmann distribution for $kT = 30$ keV and with an integrated neutron flux of $5 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$ at the sample position. This neutron spectrum can be used for the direct measurement of MACSSs of stable and unstable isotopes of interest in Astrophysics and for the validation of evaluated cross section data. The method could be suited to investigate unstable isotopes by implanting the RIB of SPES on a substrate and by subsequent activation in the well defined neutron field described here. For these reasons we propose the construction of a neutron source based on this method, called LENOS, in the framework of the SPES project at LNL.

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