

Neutron Energy Spectra and Yields from the ${}^7\text{Li}(p, n)$ Reaction for Nuclear Astrophysics

M Tessler¹, M Friedman¹, S Schmidt², A Shor³, D Berkovits³, D Cohen¹, G Feinberg^{1,3}, S Fiebiger², A Krása⁴, M Paul^{1*}, R Plag², A Plompen⁴ and R Reifarth²

¹ Racah Institute of Physics, Hebrew University, Jerusalem 91904, Israel

² Goethe University, Max-von-Laue-Straße 1, 60438 Frankfurt, Germany

³ Nuclear Physics and Engineering Division, Soreq Nuclear Research Center, Yavne 81800, Israel

⁴ European Commission, Joint Research Centre, Institute for Reference Materials and Measurements, Retieseweg 111, 2440 Geel, Belgium

E-mail: *paul@vms.huji.ac.il

Abstract. Neutrons produced by the ${}^7\text{Li}(p, n){}^7\text{Be}$ reaction close to threshold are widely used to measure the cross section of s -process nucleosynthesis reactions. While experiments have been performed so far with Van de Graaff accelerators, the use of RF accelerators with higher intensities is planned to enable investigations on radioactive isotopes. In parallel, high-power Li targets for the production of high-intensity neutrons at stellar energies are developed at Goethe University (Frankfurt, Germany) and SARAF (Soreq NRC, Israel). However, such setups pose severe challenges for the measurement of the proton beam intensity or the neutron fluence. In order to develop appropriate methods, we studied in detail the neutron energy distribution and intensity produced by the thick-target ${}^7\text{Li}(p, n){}^7\text{Be}$ reaction and compared them to state-of-the-art simulation codes. Measurements were performed with the bunched and chopped proton beam at the Van de Graaff facility of the Institute for Reference Materials and Measurements (IRMM) using the time-of-flight (TOF) technique with thin ($1/8''$) and thick ($1''$) detectors. The importance of detailed simulations of the detector structure and geometry for the conversion of TOF to a neutron energy is stressed. The measured neutron spectra are consistent with those previously reported and agree well with Monte Carlo simulations that include experimentally determined ${}^7\text{Li}(p, n)$ cross sections, two-body kinematics and proton energy loss in the Li-target.

1. Introduction

Nucleosynthesis of heavy elements ($A > 60$) in stars involves neutron-capture processes [1, 2]. Abundances of these elements are determined by the stellar rates of the slow (s -) process and rapid (r -) process and the half-life of relevant nuclides. Hence neutron capture cross sections on stable and unstable nuclides in the stellar regimes of energy are essential quantities in nuclear astrophysics. Due to the need for an appropriate intense neutron source, these values have not been measured yet for a large number of nuclides at or near important branching points of the s -process. The neutrons produced by the ${}^7\text{Li}(p, n){}^7\text{Be}$ reaction for an incident proton energy around 30 keV above the reaction threshold (1880.4 keV) on a thick Li target (thick enough that the proton energy is reduced to below the threshold energy while still in the Li) are emitted in a cone of $\sim 120^\circ$ angular opening with an energy distribution close to that of a Maxwellian flux



with $kT \approx 25$ keV which is close to the temperature of some of the s -process sites [3]. Intense ${}^7\text{Li}(p, n){}^7\text{Be}$ neutron sources are being developed for the measurements of such cross-sections at the Soreq Applied Research Accelerator Facility (SARAF) and Goethe University Frankfurt, based on high-intensity RF accelerators.

2. SARAF

The Soreq Applied Research Accelerator Facility (SARAF) [4] is based on a continuous wave (CW), proton/deuteron RF superconducting linear accelerator capable of delivering currents up to 2 mA. Phase I of SARAF (see figure 1) will produce proton and deuteron beams with energies up to ~ 4 and 5 MeV respectively.

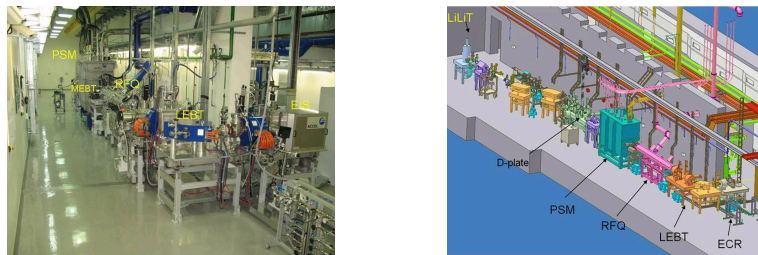


Figure 1. SARAF Phase I: Photograph (left) and sketch (right) showing ion source (ECR), low energy beam transport (LEBT), radio-frequency quadrupole (RFQ), and prototype superconducting module (PSM) consisting of six half-wave resonator accelerating cavities.

3. FRANZ

The Frankfurt neutron source at the Stern-Gerlach-Zentrum (FRANZ) [5] is currently under construction at the Institute for Applied Physics at the Goethe University in Frankfurt (see figure 2). It will be capable of delivering a proton beam with a current up to 20 mA in CW mode, resulting in beam powers of ~ 40 kW, with energies up to 2 MeV. There will be several target stations, for activation and time-of-flight measurements.

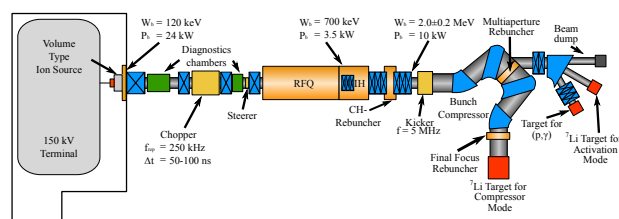


Figure 2. FRANZ: Frankfurt neutron source at the Stern-Gerlach-Zentrum.

4. Li targets

4.1. LiLiT target at SARAF

The SARAF high intensity beam requires a Li target that can withstand its beam power, incompatible with solid Li or Li-compounds. The Liquid-Lithium Target (LiLiT) [7] is a windowless forced-flow closed loop of liquid Li, producing a jet with a velocity of 3-7 m/s, acting as the target (figure 3 (left)). The target was successfully tested with an electron beam (1.6 kW) showing dissipation of ~ 2 MW/cm³, equivalent to a proton beam of ~ 3 mA. The

combination of SARAF and LiLiT will produce an intense quasi-stellar neutron source peaked at $E_n \approx 25\text{-}30$ keV with a neutron flux of about $10^{10}\text{-}10^{11}$ neutrons per second (a factor 10-100 larger than presently available).

4.2. The FRANZ target

The current design of the FRANZ setup is based on a solid Li target (with a Cu or Ag backing) cooled by water flowing in two water channels (figure 3 (right)). A large diameter cooling channel is expected to take a major part of the heat from the copper target assembly. A small second channel, which cools the target backing directly, is an attempt to move as close to the heat source as possible while trying to keep neutron distribution aberrations minimal.

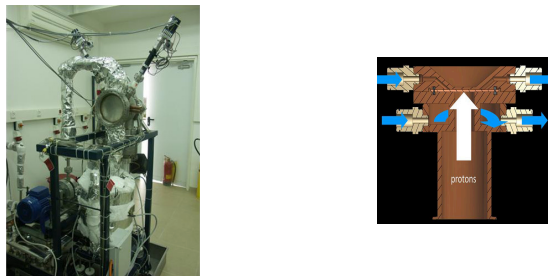


Figure 3. (left) Photograph of the Liquid Lithium Target - LiLiT; (right) FRANZ Li Target design. Blue arrows indicate water flow.

5. ${}^7\text{Li}(p,n)$ Simulated Neutron Spectra

A simulation code, SimLiT [6], that uses experimentally determined ${}^7\text{Li}(p,n)$ cross sections, two-body kinematics and proton energy loss in the Li-target, was developed to calculate neutron spectra, intensities and angular distribution. In the LiLiT setup there is a significant amount of material surrounding the target, which may affect the neutron energy spectrum and intensity. We therefore need to simulate this environment for actual experiments. Detailed simulations using the codes SimLiT as the neutron source and GEANT4 for neutron transport, with a particular emphasis on the detector response, were carried out (see figures 4 and 5).

6. ${}^7\text{Li}(p,n)$ Experimental Neutron Spectra

A series of experiments were conducted at the IRMM Van de Graaff accelerator. The 1912 keV proton beam, with energy spread of ~ 1.5 or 15 keV, irradiated a LiF target. We used ${}^6\text{Li}$ glass detectors (1/8" and 1" thick) to measure the neutron time-of-flight (TOF) in the relevant angular range. If we denote the neutron flightpath by L , and the neutron TOF by t , the nominal neutron energy is given by: $E_n = \frac{1}{2}m_n(\frac{L}{t})^2$. However, the effect of the neutron detector thickness is important for a reliable extraction of the neutron energy spectrum. We present below experimental spectra (figure 4) obtained with each detector compared with the detailed simulations done with the SimLiT and GEANT codes. The simulations reproduce correctly the TOF spectra. In figure 5, we show that a simple approach taking the mean geometrical distance between target and detector results in consistent extracted energy spectra for the two detector thicknesses, in reasonable agreement also with the neutron spectrum emitted by the lithium target as calculated by the code SimLiT. Figure 6 shows the experimental spectrum integrated over all angles compared with the simulation, as reported in [8].

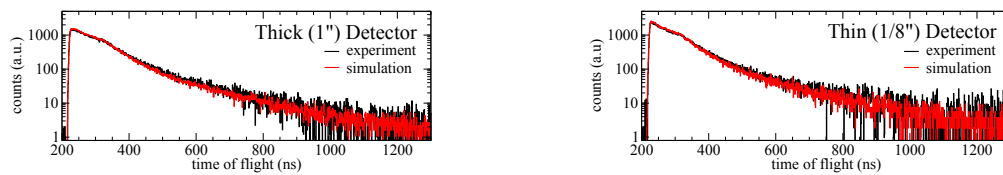


Figure 4. Time-of-flight (TOF) spectrum at 0° detected with (left) thick ($1''$) and (right) thin ($1/8''$) detectors. We can see good agreement between the experimentally measured spectrum (black) and the simulated (SimLiT+GEANT4) spectrum (red).

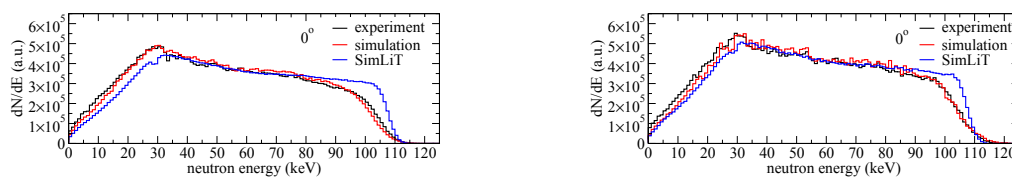


Figure 5. The energy distribution at 0° converted from the detected TOF spectrum with (left) thick ($1''$) and (right) thin ($1/8''$) detectors. The blue spectrum is calculated by SimLiT for neutrons emitted by the Li target.

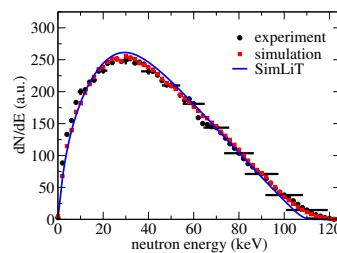


Figure 6. The energy distribution, after integrating over all angles, for the thick ($1''$) detector. We can see good agreement between the experimentally measured spectrum (black), the simulated (SimLiT+GEANT4) spectrum (red) and the spectrum calculated directly by SimLiT (blue). The horizontal bars represent uncertainties in neutron energy determination. Typical statistical counting errors are shown.

Acknowledgments

M.P. and R.R. wish to gratefully acknowledge the support of the German-Israeli Foundation (GIF Research Grant No. G-1051-103.7/2009). M.P. gratefully acknowledges the Pazi Foundation for its support in the design and construction of the LiLiT setup.

References

- [1] Burbidge E M *et al.* 1957 *Rev. Mod. Phys.* **29** 547
- [2] Käppeler F *et al.* 2011 *Rev. Mod. Phys.* **83** 157
- [3] Ratynski W and Käppeler F 1988 *Phys. Rev. C* **37** 595
- [4] Kreisel A *et al.* 2014 Proceedings of Linac 2014, Geneva (Switzerland), WEIOB02 770; and references therein; available online: <http://accelconf.web.cern.ch/AccelConf/LINAC2014/papers/weioB02.pdf>
- [5] Meusel O *et al.* 2012 Proceedings of LINAC 2012, Tel Aviv (Israel), MO3A03 130; available online: <http://accelconf.web.cern.ch/accelconf/LINAC2012/papers/mo3a03.pdf>
- [6] Friedman M *et al.* 2013 *Nucl. Instr. Meth. Phys. Res. A* **698** 117
- [7] Feinberg G *et al.* 2009 *Nucl. Phys. A* **827** 590c
- [8] Feinberg G *et al.* 2012 *Phys. Rev. C* **85** 055810