Energy-broadened proton beam for production of quasi-stellar neutrons from the $^7\text{Li}(p,n)^7\text{Be}$ reaction

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Abstract. Production of quasi-stellar neutrons by the $^7\text{Li}(p,n)^7\text{Be}$ reaction has been used for measuring s-process cross sections and efforts to upgrade the proton beam intensity with RF linear accelerators are presently ongoing. We investigated the effect of an energy-broadened proton beam, as is expected for a RF linear accelerator, on the produced 25-keV quasi-Maxwellian neutron spectrum and compared it to that of a Van de Graaff accelerator with well-defined proton energy. Neutron spectrum measurements from 0° to 80° were carried out with a pulsed proton beam at the IRMM Van de Graaff accelerator using time-of-flight techniques, both with a narrow energy spread ($\sigma \approx 1.5$ keV) proton beam and with an energy-broadened beam ($\sigma \approx 20$ keV) obtained by straggling through a Au-foil degrader. In the latter case, the neutron spectrum is closer to the Maxwellian flux distribution in the high neutron energy region.

1. Introduction

The kinematics of the $^7\text{Li}(p,n)$ reaction for 1912 keV protons, ~30 keV above threshold, in a thick lithium target is known to generate forward-collimated neutrons having an energy spectrum which closely simulates the energy dependence of the neutron flux in a stellar medium at a temperature of $\sim 3 \times 10^8$ K (kT$\approx$25 keV) [1]. The neutrons produced by the near-threshold $^7\text{Li}(p,n)$ reaction have been widely used to activate stable (and more recently unstable) nuclides involved in the s-process, providing a direct measurement of the Maxwellian-averaged cross section (MACS) for neutron capture at kT$=25$ keV [2]. There exists currently a strong interest in expanding such activation measurements to unstable nuclides at branching points of the s-process and off the valley of stability or to cases experimentally difficult to measure. Higher proton beam intensities (in the milliampere range) are then required, which are incompatible both with traditional Van de Graaff accelerators and with the poor thermal properties of conventional solid lithium targets. We are presently pursuing the construction of a setup based on the high-intensity proton beam of the superconducting RF linear accelerator at the Soreq Applied Research Accelerator Facility (SARAF) [3] and a high-power Liquid-Lithium Target (LiLiT) [4] to be used in such experiments. However the properties of a high-intensity ion beam from a RF linear accelerator are different from those of Van de Graaff accelerators in two main aspects: a significantly larger energy spread of the beam and a somewhat larger transverse
distribution, limited by space-charge effects. These will in turn affect the shape of the neutron energy and angular distribution and the yield of neutrons emitted in the $^7\text{Li}(p,n)$ reaction and will require to establish a new standard for neutron monitoring. Using the IRMM Van de Graaff accelerator and a solid LiF target, we investigate experimentally for the first time the effects of a broadened-energy proton beam on the neutron energy distribution and yield. The broadened energy was obtained by straggling of the incident protons with a thin gold foil placed in front of the LiF target. Neutrons were detected by $^6\text{Li}$-glass detectors and their energy was measured by time-of-flight (TOF), using a 625-kHz pulsed proton beam. Angular distributions of the neutrons were measured and summed to obtain the integral energy distribution. The neutron energy distribution in the broad-energy case is modified by a cutoff at higher energies and is closer in this region to the $E \cdot \exp(-E/kT)$ dependence of the Maxwellian stellar flux.

2. Experimental procedure

The experiment was performed in the low-scatter target hall of the Van de Graaff laboratory at the IRMM in Geel. Neutron spectra were measured by TOF techniques using $^6\text{Li}$-glass detectors for both a narrow-energy spread proton beam and for a broad-energy spread proton beam. All measurements were performed while minimizing the materials that may cause neutron scatter. In front of the target was a collimator that limited the beam diameter to 6 mm and an electron suppressor enabling charge integration of the proton beam at the target. Typical diameter of the beam on target is estimated as 2-3 mm. The targets were made of LiF evaporated on a 1 mm thick Cu disk. The LiF layer thickness was determined to be thick enough to reduce the proton energy significantly below the reaction threshold.

To enable TOF measurements, the accelerator was operated in pulsed mode using a frequency of 625 kHz. The chopped and bunched proton beam had a pulse width of 1.5-2 ns FWHM. Cooling of the target during irradiation with chopped beams with average current of 100 nA was done by air flow on the target copper backing.

In order to mimic the energy spread expected for a proton beam from a RF linear accelerator, we placed a gold foil degrader directly upstream of the target. SRIM [5] calculations showed that 2096 keV protons traversing through a 2.06 µm gold foil will emerge with energy of 1912 keV and an energy-spread standard deviation of ~20 keV, similar to the energy spread expected for the SARAF high intensity beam at target position. The degrader was glued onto a ring holder which positioned it 1 mm upstream of the LiF layer to minimize beam growth in transversal dimensions caused by the scattering in the gold foil.

For the TOF measurements, $^6\text{Li}$-glass detectors (Scionix Ltd.) were used. It was deemed necessary to use relatively thick detectors (1” in thickness) to keep beam time within practical limits. The $^6\text{Li}$-glass detector could be placed on a goniometer at various angular positions with 5° spacing and at a fixed distance of 51 cm from the LiF target. Accuracy of better than ±0.3° was obtained after proper alignment of the goniometer on the target hall floor. For all TOF measurements, another $^6\text{Li}$ detector used as monitor was placed at fixed position – at a distance of 85 cm and at angle of 12° from the goniometer symmetry axis and 10° upward out of plane.

The signal from the photomultiplier of each detector was split to a fast timing circuit and to a pulse height circuit. The fast timing circuit was comprised of a timing filter amplifier followed by a constant-fraction discriminator (CFD). The pulse height circuit consisted of a preamplifier and a spectroscopy amplifier. The timing signal from each detector provided the TOF start signal in an allocated time-to-amplitude converter (TAC) channel. A beam pick up monitor placed upstream of the target provided a signal that was processed through a timing filter amplifier and a CFD and provided the common TOF stop. The total TOF resolution for the combined system, as measured for the prompt-gamma peak, was ~4 ns for most of the runs. Data for each detector were acquired independently, where the timing and pulse height information for each detector were acquired in coincidence.
3. TOF spectra

Figure 1 displays a raw TOF spectrum, the prompt gamma peak (off-scale) and neutron spectra at longer flight times (left of the gamma peak) are observed. The insert highlighting the gamma peak exhibits a Gaussian TOF distribution with FWHM ≈ 4 ns. The large amount of prompt gamma rays are primarily from $^7\text{Li}(p,p'\gamma)$, $^7\text{Li}(p,\gamma)$, $^{19}\text{F}(p,\alpha\gamma)$ and $^{19}\text{F}(p,\gamma)$ reactions.

Figure 2 shows a 2D scatter plot of pulse height vs. TOF for the $^6\text{Li}$-glass detector. The pulse height spectrum exhibits a neutron peak with a FWHM of ~15%. Figures 1 and 2 also contain scattered events, due to stray uncorrelated gamma rays and neutrons.

The neutron angular spectra were measured for both the narrow-energy and broad-energy proton beam. Spectra were taken at all angles from 0° to 65° at 5° intervals for the narrow-energy beam, and from 0° to 80° at 5° intervals for the broad-energy beam. The stationary $^6\text{Li}$-glass detector was used to monitor beam stability and for normalization. Conversion of TOF to neutron energy was through an iterative method which takes into consideration the finite thickness of the detector [6]. Figure 3 shows the neutron energy spectra at angles of 0°, 10°, …, 60° for the data taken with the narrow-energy beam.
proton beam and \(0^\circ, 10^\circ, \ldots, 80^\circ\) for the broad-energy proton beam (the double differential spectrum is integrated over 2\(\pi\) radians in azimuth). The individual neutron spectra taken with the broad-energy proton beam exhibit pronounced spectral broadening compared to the spectra taken with the narrow-energy proton beam. It should be noted that the measured neutron energies extend slightly beyond the kinematical endpoint due to detector thickness effects.

Figure 4 shows the combined neutron spectrum for the narrow-energy beam, and also the combined neutron spectrum for the broad-energy beam. These spectra were obtained by summing the spectra from \(0^\circ, 5^\circ, \ldots, 80^\circ\) with appropriate normalization. The horizontal error bars reflect the uncertainty in energy due to the \(^6\text{Li}\)-glass detector thickness. Although the individual spectra at each angle look markedly different for the narrow-energy and the broad-energy proton beams, the combined neutron spectra are remarkably similar, except in the high energy tail above 80 keV. Also shown in figure 4 is a fit to the distribution:

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 f(E) = a \cdot E \times e^{-E/kT}
\]

corresponding to a Maxwellian flux at temperature T. For all the data from 10 to 80 keV, a best fit is obtained with \(kT=28\) keV. The integrated neutron energy spectrum corresponding to the broad-energy proton beam shows considerably better agreement with the Maxwellian flux distribution at the higher neutron energies.

Figure 4. Measured neutron energy spectra for the \(^7\text{Li}(p,n)^7\text{Be}\) reaction. Total angle integrated spectrum obtained for a narrow energy proton beam, \(\sigma\approx1.5\) keV (blue) and for a broad energy proton beam, \(\sigma\approx20\) keV (green). Both neutron spectra include the same normalization coefficient. Fit to a semi-Maxwellian yields \(kT=28\) keV.

In the same experiment, measurements of the average cross section of the \(^{197}\text{Au}(n,\gamma)^{198}\text{Au}\) reaction over the neutron energy distribution for both the narrow- and broad-energy spread beams were performed. The results are presently being analyzed.

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