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High Yield Production of ^{6}He and ^{8}Li RIB for Astrophysics and Neutrino Physics

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A production scheme by fast secondary neutrons from a 40 MeV deuteron beam impinging on a converter target provides efficient production in exceptionally high yields of light radioisotopes such as ^{6}He and ^{8}Li. Recent optimization simulations indicate the ability to produce orders of magnitude more intense ^{6}He and ^{8}Li beams than presently available. Such high current Radioactive Ion Beams (RIB) open up possibilities for new experiments and measurements in Astrophysics, Nuclear Structure and Neutrino Physics. A test production experiment exhibits the $^{27}Al(n,\alpha)^{24}Na$ reaction and the ensuing measurement of ^{24}Na activity. The experimental results are in good agreement with simulations, paving the way for further experimental efforts of finding the optimal production and extraction capabilities for these light RIB's. The results of this study are of major importance to current facilities such as SPIRAL-II (GANIL, France) and SARAF (Soreq, Israel) and to future neutrino schemes such as the β-beam option.

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1. Simulations

Efficient production and manipulation of radioactive ion beams (RIB) constitute key ingredients for all RIB facilities. In this article we present an efficient production scheme for light radioisotopes, mainly ^6He and ^8Li, using secondary neutrons from a low-energy deuteron accelerator. This scheme enables production and extraction of light RIB with orders of magnitude higher yields than before, and thus opens an opportunity for research in astrophysics and nuclear structure using these high yield beams. Moreover, high yield production of light radioisotope beta emitters is an important part in the design of the future *Beta-Beam* facility and may also allow other research of neutrino physics at lower energies.

The present method of production has been presented earlier [1]; here we provide a more detailed picture of the proposed setup together with results from recent optimization simulations. We emphasize results from a recent test experiment for the production of the γ emitting, light radioisotope ^{24}Na with $T_{\frac{1}{2}} = 15\ h$, using fast neutrons. This test experiment paves the way for further tests of the shorter lived, β emitting ^6He and ^8Li nuclei.

The setup is composed of two targets, with the deuterons impinging the primary one ("converter"), while the secondary serves as a target for the emitted neutrons and the source of the produced radioactive nuclei. The two major difficulties in designing a RIB production target, namely the heat removal and ion extraction are thus dealt with in two separate targets (Figure 1).

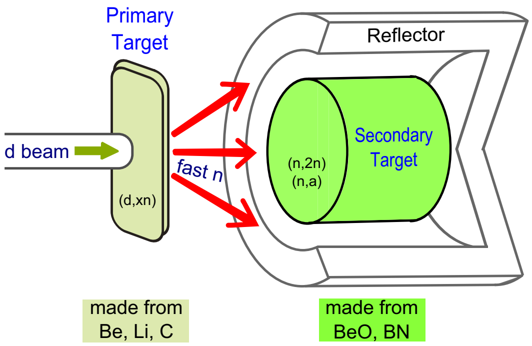

Figure 1: The two-target setup.

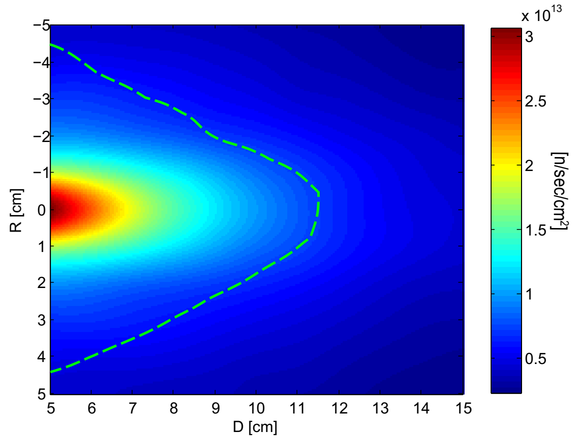

Figure 2: The mean neutron flux inside a thin slice within a cylindrical target of ^9Be. The dashed line presents the boundary of significant ^6He production.

The first target serves as a neutron converter for 40 MeV deuterons and can be made from different light isotopic materials, requiring a high cross section for (d,xn) reactions together with fast and relatively direct neutron emittance. lithium, beryllium, carbon and heavy water are typical candidate materials. Because of the high beam currents (few mA), the heat removal from the target must be considered; for this reason liquid lithium targets and rotating carbon targets are being developed. [2, 3].

The secondary target is placed just within the forward fast neutron flux, and is made from porous

Beryllium-Oxide or Boron-Nitride materials for the production of ^{6}He and ^{8}Li radioisotopes via the $^{9}Be\,(n,\alpha)^{6}He$ and the $^{11}B\,(n,\alpha)^{8}Li$ reactions, respectively. In the simulations one must take into account the cross sections of the $(n,2n)$ reactions that rise up to 500 mb in the corresponding neutron energy range, thus effectively doubling the number of useful neutrons; the cross section of $^{9}Be\,(n,\alpha)^{6}He$ rises to ~ 100 mb at 3 MeV and that of $^{11}B\,(n,\alpha)^{8}Li$ exhibits a maximum value of ~ 30 mb at 12 MeV. We note that other radioisotopes can be produced via fast neutron reactions by varying the material of the secondary target.

Subsequent to the production, the radioisotopes must be extracted and ionized in a short time compared to their half life (~ 0.8 *sec* for the present cases). The extraction process involves heating the target to temperatures close to the melting point of the host material and the diffusion of the radioisotopes out of the target into the ion source. This process, besides from temperature effects, is also highly effected from The porosity of the host material and its melting point, these are therefore two very important design parameters for an eventual target assembly. For these reasons, the compound materials of *BeO* and *BN* have been chosen. Both materials have relatively high melting temperature, *BeO* can be obtained in fiber form [4], while *BN* could be used in fine powder form.

For the present *Monte Carlo* simulations, we have used the neutron transport code MCNP4b [5]. In this approach we treat the first target as a fast neutron source with known dimensions, spectra and angular distribution, and thus the only particles that need to be simulated are neutrons. We used an experimental double differential spectra of neutrons that was accurately measured for thick targets of various materials, and especially for the case of 40 MeV deuterons on Li [6]. This data presents a total yield of $\sim 4\cdot 10^{14}$ $n/sec/mA$ for a 40 MeV beam of deuterons on a thick lithium target and a significant fast neutrons peak at ~ 15 MeV.

As an example of the optimization simulation results, we have cut a thin slice through a cylindrical beryllium secondary target in order to probe the inner neutron flux distribution inside the target, and thereby conclude what are the areas of high and low production of ^{6}He. The results are summarized in Figure 2, in which the mean neutron flux across the inner slice is presented. In this figure the neutrons enter with the appropriate angular distribution from a point like source placed 5 cm to the left of the figure, where R and D stands for the radial and horizontal depth axes of the cylinder target, respectively. The fluxes were calculated for the case of 2 mA and 40 MeV deuterons beam such as intend at SARAF, and a thick lithium target as the primary target. According to these results the high neutron flux is concentrated just in front of the neutron source, and gradually decreases with the distance from the neutron source. The production areas of ^{6}He, however, cannot be deduced in a trivial way from this result, because of the dependence of the production on the neutron's spectrum that changes as it penetrates the target, and also because of different reaction channels that may take place in the production process. Taking these two points above into account, we have calculated the areas of higher and lower ^{6}He production, as indicated in Figure 2 by a dashed line which represent a boundary between areas in which the production is higher (lower) than $1\cdot 10^{10}$ $\left[{}^{6}He/sec/cm^{3}\right]$.

One immediate conclusion is that in order to keep the volume of the secondary target as small as possible for reasons of easier extraction, the optimal shape should resemble an overturned cone. However, as were indicated from simulations, a cone-like target increases the production of ^{6}He by only *7%* compared to a cylindrical shaped target with the same volume. Regarding the technical difficulties that may arise in manufacturing and handling a conic target, this small increase may not

be sufficiently significant.
In a similar way we have conducted numerous other simulations in order to find the optimized set of parameters for the design of this production scheme. The production numbers for an optimized geometry for BeO and BN with their natural densities are $1 \cdot 10^{13}$ $^{6}He/sec$ and $2 \cdot 10^{12}$ $^{8}Li/sec$, respectively, for a current of 2 mA of 40 MeV deuterons. We must note that for the purpose of neutrino production only (with no need to consider issues of diffusion and extraction), these yields can increase by one order of magnitude when using pure Be or B and a larger secondary target.

2. Verification Experiments

In order to verify the simulations we have embarked on a series of productions experiments of light radioisotopes. Since detecting beta emitters with half-life of less then a second is more complicated, we had decided to begin with an analogue production scheme in which the produced radioisotope is a γ emitter with much longer half-life of 15 h, ^{24}Na, via the $^{27}Al\,(n,\alpha)^{24}Na$ reaction channel. The cross section for this reaction exhibits a threshold of 3.25 MeV, suitable for fast neutrons irradiation.
The 15 MeV mean spectrum of fast neutrons from the 40 MeV deuteron beam onto a neutron converter that is planned to be available at SARAF, SPIRAL-II and other future drivers could be approximated by using a d-T neutron generator which emits 14.1 MeV neutrons. Therefore as a first preliminary verification experiment we had measured the production of ^{24}Na via irradiation of fast neutrons by a $\sim 10^{9}$ n/sec neutron generator, placed currently at SARAF for shielding experiments.
A rectangular rod of Aluminum 6061 (97% ^{27}Al) was cut into 27 cubes of $1.9 \times 1.9 \times 1.9\ cm^{3}$, with an average mass of $19.02 \pm 0.02\ g$. The 27 cubes were grouped to form a larger (Rubik like) cube of $3 \times 3 \times 3$ *Cubes*. This geometry was chosen in order to be able to identify the inner distribution of ^{24}Na production yields. Four copper foils, $5.7 \times 5.7 \times 0.025\ cm^{3}$ each, were attached to the front, middle and back sides of the aluminum walls of the large cube, in order to monitor the fast neutron flux using the reaction $^{63}Cu\,(n,2n)^{62}Cu$, with a large negative Q-value of $-10.8\ MeV$. The large aluminum cube was surrounded by a 5 cm thick lead reflector and the entire structure was placed 5 cm in front of the Neutron Generator. The general setup is shown in Figure 3.
The target was irradiated for 20 minutes by the neutron generator and the 27 cubes individual cubes were subsequently taken for a γ-activity determination using a Ge-detector system, extensively used for precision measurements [7] . Figure 3 shows the results of the measurement compared to the simulation results. The mean deviation is 5.5 % which mostly stands for slight misalignments of the experimental setup. The experiment was repeated using the same geometry but without the lead reflector, however both the simulations and experiment results did not show any significant difference in production. This fact his is due to the relatively high threshold of the $^{27}Al\,(n,\alpha)^{24}Na$ reaction, which can be initiated only by fast reflected neutrons, that are hardly available. For the production of ^{6}He and ^{8}Li (see below), we expect the reflector arrangement to be more significant.
In the next experiment of this series it is planned to use a Boron-Nitride target to produce ^{8}Li, exhibiting the short half-life of 0.8 sec and the need to measure the β activity far from the large neutron flux. We have therefore designed a "rabbit-like" device in which the BN target could be quickly transported between the irradiation and detection ports, which are placed in separate

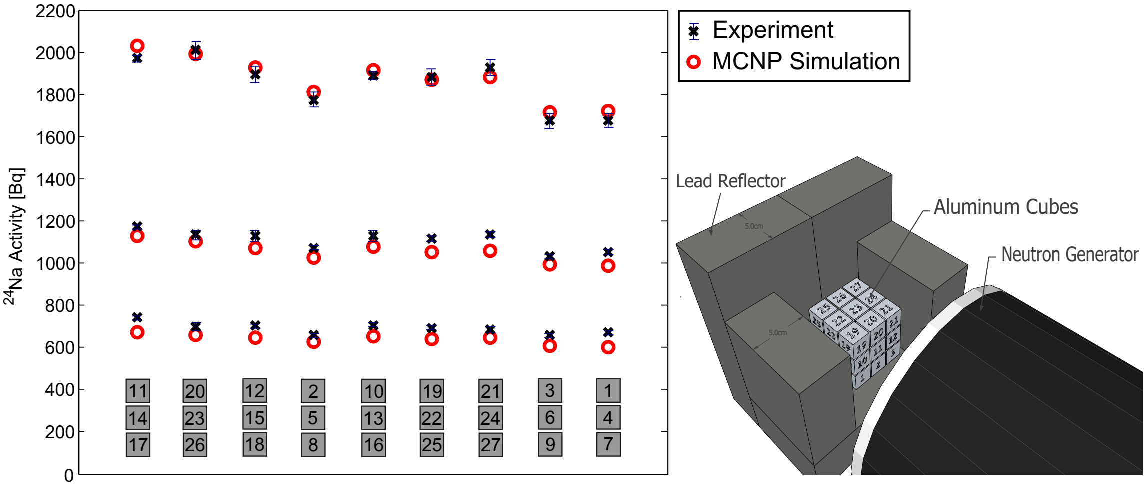

Figure 3: A comparison between the measured and simulation results for each of the cubes in the first Aluminum irradiation experiment. The irradiation setup, together with the correct numbering of the cubes, is also shown.

shielded locations. We intend to measure in this way the production of ^{8}Li, and later that of ^{6}He (using a BeO target) and to verify simulations presented above.

Next we intend to repeat these experiments using fast neutrons from a neutron converter bombarded with the 5.2 MeV deuteron beam of SARAF phase I. We also plan to perform similar experiments for irradiation of BN and BeO with fast neutrons from spallation source in ISOLDE (CERN) and from the $^{12}C+^{12}C$ reactions at SPIRAL-I (GANIL); in these experiments we will intend to examine also extraction issues.

In summary, a production of light radioisotopes, mainly ^{6}He and ^{8}Li, in exceptionally high yields may be possible using this proposed two target scheme. We have preformed a series of simulations in order to optimize the production details using such a setup. In order to have some benchmark to the simulations we have started a series of verification experiments of measuring the production of light radioisotopes using fast neutrons. The first verification experiments of aluminum irradiation demonstrate a good agreement between simulations and experiment. Future test experiments to measure the extraction parameters in several future facilities are currently in progress.

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