Towards an intense radioactive $^8$Li beam at SARAF Phase I

T Y Hirsh$^{1,2}$, D Berkovits$^2$, M Hass$^1$, P Jardin$^3$, A Pichard$^3$, M L Rappaport$^1$, Y Shachar$^1$ and I Silverman$^2$

$^1$Weizmann Institute of Science, Rehovot, Israel
$^2$Soreq NRC, Yavne 81800, Israel
$^3$GANIL, Caen, France

Abstract. The $^8$Li($\alpha$,n)$^{11}$B reaction plays an important role in the r-process nucleosynthesis occurring in type II supernovae and in binary neutron stars. At high rates, this reaction can lead, despite the short $^8$Li half-life, to production of seed nuclei through a chain of reactions, which can then cause the formation of heavier nuclei via ($n,\gamma$) reactions. Several measurements of this reaction were carried out in the last few years using fast $^8$Li beams that are available at several RIB facilities at limited currents. A new production method for light Radioactive Ion Beams (RIB) via fast neutron reactions is conceptually able to provide orders of magnitude higher RIB currents, up to $10^{12}$ pps. The high efficiency of the two-target production method has been experimentally proven for $^6$He production, in a similar manner to the $^8$Li production. We present a unique apparatus for $^8$Li production and extraction at the Soreq Applied Research Accelerator Facility - SARAF. In 2011, it is expected that SARAF Phase-I will produce high intensity, 5 MeV deuteron beams for limited experiments. By using a LiF neutron converter, neutrons with energies of up to 20 MeV and a total yield of $10^{12}$ fast n/sec will be available per 1 mA of deuterons. As a secondary production target we are using discs of 65% porous B$_4$C, mounted inside a high temperature furnace. $^8$Li, produced via the $^{11}$B(n,$\alpha$)$^8$Li reaction channel, diffuses out of the B$_4$C target and is ionized in a thin rhenium surface ionizer. The total efficiency of $^8$Li RIB creation will be measured by means of alpha and beta measurements. Following the experiment at SARAF Phase I, better production and extraction schemes of light RIB, of great interest in various nuclear and astrophysics-related measurements, may become possible.

1. Introduction
In the last few years we have embarked on a program to develop light Radioactive Ion Beams (RIB), to be used in nuclear astrophysics and neutrino physics. In particular, we propose a scheme of order-of-magnitude increase in intensities of short-live isotopes such as $^6$He and $^8$Li. This program is motivated by the newly-constructed SARAF accelerator at Soreq, but is also of major importance to leading European facilities such as SPIRAL2 at GANIL as well as ISOLDE and the future $\beta$-beam neutrino facility at CERN. One of the main directions is the production of RIB’s by secondary neutrons from intense deuteron beams that will be available at SARAF.

Continuing this line of research, we are proceeding now to perform a first optimized production and extraction experiment for $^8$Li RIB at SARAF. Our approach for light RIB production consists of a two targets system [1]. This method was found to produce $^8$Li and $^6$He beams with orders of magnitude more yield than available today. Detailed Monte Carlo simulations indicate that production yields of the order of $10^{12}$ for $^8$Li and $10^{13}$ for $^6$He are possible with the future SARAF-II 40 MeV 2...
mA deuteron beam [1]. However, the RIB release and manipulation efficiencies of this system are not yet fully known [2].

High intensity \(^{6}\)Li beams may used, e.g., to re-measure the \(^{6}\)Li(\(\alpha\),n)\(^{11}\)B cross section, which is believed to have a dominant part in some schemes of the r-process following a type II SN explosion [3]. This reaction was previously measured in several experiments, although a large discrepancy has emerged between the respective results. Recently, this discrepancy has been suggested to be due to technical limitations of the detection system in some of the measurements [4]. A new set of measurements, using more intense beams that may achieve better precision, mostly at the lower energy range where the cross section is lower and thus higher statistics is required, may shed a clearer light on the diversity of cross section measurements.

In this paper we present the first experiment that is planned to take place during SARAF phase I experimental period.

2. Two stage irradiation setup
The present scheme consists of a sequential irradiation of two targets. A primary target for deuterons, which is practically a fast neutron converter, and a secondary target that serves as a production target, positioned in the proximity of the primary target to maximize the neutron flux. The effectiveness of this setup stems from the separation of the two most major problems in RIB production, namely, heat removal of the beam power and extraction of the radioisotopes, which are now handled in two separate targets. It is a similar scheme to the one used recently at ISOLDE for the production of \(^{6}\)He [5].

Inside the secondary target, production of \(^{6}\)He, for example, is obtained through a two-reaction channel, \(^{6}\)Be(n,2n)\(^{8}\)Be and the actual production reaction of \(^{6}\)Be(n,\(\alpha\))\(^{8}\)He. The first reaction effectively doubles the number of neutrons and in addition lowers the neutron energy, resulting in a better fit between the neutron energy and the (n,\(\alpha\)) reaction cross section and thus also contributes to an increase in the \(^{8}\)He production.

3. \(^{6}\)Li RIB production apparatus
At phase I of SARAF we are planning to conduct an optimized full \(^{6}\)Li production and extraction experiment. Measurement of the entire system’s efficiency would later allow performing a scale-up for SARAF phase II or SPIRAL2 light RIB yields. The experiment is composed of several stages, presented below:

3.1. The primary target - LiFTit
The primary target, LiFTit – Lithium Fluoride Thick Target is essentially an accelerator based high power neutron converter. The fast neutrons are a consequence of high positive Q-Value deuteron induced reactions. By using the 5.2 MeV deuteron beam of SARAF Phase-I, fast neutrons of up to 22 MeV are generated, enabling the possibility to produce high intensity \(^{6}\)He and \(^{8}\)Li beams already in Phase-I.

The material chosen to serve as a target is Lithium-Fluoride, in which both compound elements contribute to the total fast neutron yield due to the high Q-values for the (d,n) and (d,2n) channels in both cases. Calculations preformed using the TALYS code [6] have resulted in \(6 \times 10^{11}\) n/sec for neutrons with energies higher than 4 MeV, emitted in a directed cone of \(\Omega<90^\circ\) and for a 2 mA, 5.2 MeV deuteron beam. For instance, a 200 ml BeO target placed in vicinity of this would produce \(~10^9\) \(^{6}\)He/sec.

LiFTit consists of a 350 micrometer-thick LiF crystal welded to a copper back that comprises an inner water cooling loop (fig.1). To guarantee an efficient cooling of the copper back during dissipation of the few kW beam power, water is pressurized through thin micro-channels [7]. The water channels, 300 \(\mu\)m in the short dimension, were drilled using spark and wire EDM processes and significantly reduce the chance of a breakdown due to water bubbling.
3.2. The secondary B4C target

The $^8$Li isotopes are produced inside a secondary porous target of Boron-Carbide via the $^{11}$B(n,α)$^8$Li reaction enabled by energetic neutrons. Fast release rate of the short lived $^8$Li out of the target is one of the main concerns, and since it proceeds through a diffusive-effusive process, the high melting point and porous structure of the secondary B4C target (65% of the nominal density and 1-5 µm grain size) are essential.

The secondary target is 80 mm in diameter and 40 mm in length. The large volume is necessary to provide a large solid angle and is also due to the long mean free path energetic neutrons. The B4C is contained inside a 1500 deg C vacuum furnace, to accelerate the diffusion process. The furnace was designed in a way that only a thin layer of molybdenum heat shield separates the primary and secondary targets to avoid slowing of the neutrons.

The target is capsulated inside an inner smaller Ta cavity which has one small diameter exit. Due to the high temperature, the $^8$Li atoms released from the B4C will pass through the small exit port, and reach the surface ionizer which is connected to that port.

![Figure 1 – LiFTiT target](image1)

![Figure 2 – The irradiation setup at SARAF phase I](image2)

3.3. Surface ionizer

A thin sheet of rhenium wrapped as a small diameter tube is used as a surface ionizer, based on the design of SPIRAL2 surface ionizer [8]. The thin Re setup was found to be efficient for ionization of all alkalis [8].

The ionizer is heated to high temperature by means of Joule heating; this process also has a side effect of a small voltage difference which favors the $^8$Li ions direction towards the extraction electrode. It is assumed that this small applied voltage has much larger effect on the total extraction efficiency than, for example, the ionizer temperature [9].

The entire ionizer and B4C cage are kept biased to several kV so the extracted $^8$Li are immediately accelerated towards the detection station (fig.2).

3.4. $^8$Li decay measurements

Schematically, the detection station is located 1 m from the main targets, leaving enough space to introduce radiation shielding, for reduction of the background levels that might be introduced by the intense neutron source. In between, the RIB is manipulated and shaped to be focused on the detection station. Inside the detection station the $^8$Li ions are being implanted in a thin 5 µm Ni foil in the center of the detection station that is aligned by 45° to the beam. The $^8$Li nuclei decay by a beta and
consequently, two alphas due to the spontaneous decay of the $^8$Be daughter. Two sets of detectors are placed in the vicinity of the foil to measure the resulting alpha and beta radiation, including two silicon detectors and a thick plastic scintillator which are grouped as a dE-E monitor. Even though a high gamma background is expected due to radiation from the neutron source, a major part of it would be discriminated by combining the dE-E telescope and alpha coincidence measurement. For the current setup we expect to obtain sufficient data to allow an efficiency calibration of the entire setup and the various components within.

4. Future Perspectives
Once the efficiency values for the two-stage irradiation setup are measured, the scheme could be easily scaled up to accommodate for the larger-scale experiment with 40 MeV beams. At these energies, the production yields are 3 orders of magnitude higher, intense beams of light RIB, of great interest in various nuclear and astrophysics related measurements, may become feasible. For instance, $^6$Li and $^6$He are considered to be two major candidates for the beta-beam $\beta^-$ emitters, for which these isotopes must be produced at sufficiently high intensity as a pre-requisite to the implementation of this concept. The double-target production method, coupled with high intensity fast neutrons sources based on a deuteron LINAC, may achieve a $^6$He or $^6$Li sources which are intense enough to be facilitate the beta-beam project.

5. Conclusions
During the period of SARAF phase-I we are planning to conduct an optimized production and extraction series of experiments for $^6$Li RIB. These experiments may provide better understanding of the method and consequently maximize the production and extraction mechanisms for light RIB’s. These intense beams may facilitate more precise measurements in astrophysics and various nuclear-physics related measurements.

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Note added in Proof:
The first test run using the LiFTiT production target has taken place after submission of this manuscript; the resulting data is presently being analysed.