Presented at 1998 Symposium on Radiation Measurements and Applications, May 11-14, 1998, Ann Arbor, MI. Nuclear Instruments and Methods in Physics Research A 422 (1999) 505-509.

Production of Exotic (or Polarized) Low-Energy Radioactive Beams via Two Successive Nuclear Reactions: Tertiary Beams*

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Abstract

We propose a method to produce usable amounts (1 to 100/s) of low-energy, very neutron-, proton-rich or highly-polarized radioactive nuclear beams (RNBs) via a two-stage production method which utilizes a high-intensity secondary RNB with a second production target. As an example: $^7Li+^9Be \rightarrow {}^8Li \rightarrow {}^8Li+^9Be \rightarrow {}^9Li$. The latter ($^9Li$) is very difficult to produce at low energies (a few MeV/u) as it is several nucleons away from the line of stability and no efficient one-step mechanism exists. In contrast, high-cross-section transfer reactions such as $^9Be(^7Li,^8Li)$ combined with a high-efficiency ion-optical collection devices can produce ^8Li and other near-stability RNBs (^8B, ^7Be, ^6He, ...) at very good intensities, *viz.* 10^4 to $10^8/s$. Thus, it appears feasible to use a second, high cross-section reaction - perhaps now with a radioactive or polarized second production target, to produce an exotic, low-energy tertiary RNBs, including polarized RNBs. These and other aspects are described together with some initial tests using the new UM-UND TwinSol RNB apparatus (see M. Lee, this conference).

PACS:

* Supported in part by NSF Grants PHY9512104, PHY9512199, PHY9804869, PHY9402761, the Fundacao de Amparo a Pesquisa do Estado de São Paulo Brasil and grants from the University of Michigan and the University of Notre Dame.

1 Introduction

While it is relatively straightforward to produce high-energy *very* neutron- or proton-rich unstable, hence radioactive nuclear beams (RNBs) via fragmentation reactions [1-4] of high-energy stable beams (^{18}O, ^{22}Ne, ^{44}Ar, ...) these techniques do not work effectively at lower energies. An example is shown in Fig. 1 where we show the particle identification spectrum (in a $\Delta E - E - XY$ detector telescope) taken near $\theta = 0^o$ of an attempt to produce low-energy neutron-rich RNBs via low-energy fragmentation of 63 MeV ^{18}O on a ^9Be target. Instead, mostly stable species are made with the efficiency of producing exotic RNBs *viz.* ^8He, ^9Li, ... , of $< 10^{-12}$ or so. This test was done as part of the in-beam commissioning of the new UM-UND TwinSol facility [5] now in operation at UND.

Traditionally, low-energy RNBs have been made via selective, high-cross section nuclear transfer reactions or via the use of an on-line isotope-separator ion source and post accelerator (ISOL method) [4]. The former method has been in use for ca. 12 years at UND as part of the UM-UND RNB project there [6,7]. However the transfer and the ISOL methods are limited to beams relatively near β stability–such as ^6He, ^8Li, ^7Be, ^8B, ^{18}F, ... While this can be advantageous with respect to producing high-quality, high-intensity beams one would also like to produce low-energy RNBs which are more proton- and neutron-rich than those in present use. Polarized RNBs are also of interest. Among other features, these more "exotic" RNBs are expected to show anomalous behavior near the Coulomb barrier, for example in fusion reactions, nucleon transfer reactions, elastic and inelastic scattering, etc. [6-10]. In many cases relatively low intensities may be acceptable viz. 1 to 100/sec as one is looking for a large enhancement of cross sections or can use techniques [9-11] which do not require a high beam flux or, even, quality. It is to this end that we have studied, and in some cases tested in-beam, special methods of producing exotic RNBs via *tertiary* processes, that is two-step processes where an intense, near-stability RNB serves as the intermediate ion. A number of these methods seem practical and are under further study with the new UM-UND TwinSol apparatus.

2 Tertiary Beams

We have considered the following two-step methods for producing low-energy "exotic" RNBs: (1) Thick-target or compound-target methods where the two production reactions e.g. for $^7Li \rightarrow {^8Li} \rightarrow {^9Li}$ take place in a thick target at the entrance to the first separation magnetic (Fig. 2), and (2) the second production target is placed after the first RNB separator, between two RNB separators (Fig. 2).

In method (1), a thick target e.g. ^9Be ($\times$ 10 usual thickness) could be used with the latter portion of the target designed to produce the tertiary reaction. Time-of-flight techniques can possibly then be used to determine the tertiary beam energy ion-by-ion to compensate for the thick target. Unfortunately this method requires a very robust target due to the high intensity primary beam needed (1 to 10 μA) and would produce a beam with high impurity e.g. intense $^{7,8}Li$ mixed with ^9Li. This would require additional magnetic or electric separation. Another major limitation to this method is the unfavorable Q values for most robust targets, such as ^9Be (Table 1). As an example $^8Li \rightarrow {}^9Li$ has an optimum Q-value close to zero. If $Q << 0$, this results is a poorly mismatched single-neutron transfer mechanism which greatly suppresses the cross section [1-4]. Some in-beam tests at UND using thick production targets have confirmed the problems noted for method (1). A better-matched Q-value may require the use of an enriched, non-robust or, even, a *radioactive* target such as ^{14}C or ^3H (Table 1).

If a second magnet can be used, then an alternate scheme is method (2) where a second production target is placed between the two magnets (Fig. 2). In this mode, the high-intensity primary beam (e.g. ^7Li) is eliminated and the second target need not be very robust and, indeed, could be a radioactive target, non-robust gas cell, or cryogenic target (see below). Specifically, deuterated or even tritiated targets could be used to produce ^9Li, ^8He, and other very neutron rich species (Table 1). The reaction $^8Li(d,\ p)^9Li$ has a Q-value of +1.83 MeV which is well Q-matched and can be expected to have a conversion efficiency of about 10^{-5} or better i.e. $10^2/s$ ^9Li for a ^8Li beam of $10^7/s$ [8]. This production efficiency ($\geq 10^{-10}$) would be higher than observed for other mechanisms for ^9Li (above).

The situation for proton-rich RNBs can also be favorable in that a ^3He gas cell can be utilized either as a compound target [method (1)] or as the second production target in method (2) [Table 1].

3 In-Beam Tests

As of this writing, a number of in-beam tests are taking place to determine which of the above methods (if any) can be used to produce high-quality, useable amounts (1 to 100/s) of ^9Li, ^8He and other exotic RNBs at energies of a few MeV/nucleon. Many of the critical components of the new TwinSol RNB apparatus needed to produce useful tertiary beams have been successfully tested in-beam [5] and further tests are in progress. In addition, an extensive experimental program utilizing RNBs already developed as part of this project (^{8}Li, ^{6}He, ^{8}B, ^{7}Be, ...) has been underway for some time and will continue in parallel [6,7,10,11]. We have also previously verified [12] that one can effectively use an active-aperture (e.g. PPAC) at the entrance to a solenoid RNB separator to obtain accurate angle and TOF information. This would permit the use of a very thick tertiary RNB production target (Fig. 2) since one can determine the RNB energy on an ion-by-ion basis for these low intensity beams and hence compensate for the large energy spread in the thick production target [12].

4 Cryogenic Targets

As noted above, the second production target which is at the cross over point (Fig. 2) need not be robust since there is essentially no beam heating at that target. This opens the possibility of using thin-film frozen-gas cryogenic targets [13]. These targets consist of a thin metal foil cooled to cryogenic temperatures and then coated, usually on one side, with a thin film of frozen gas. Thus thin planar targets of $^{1,2,3}H$, $^{16,17,18}O$, $^{20,22}Ne$, ^{18}O, SF_6, can be made. Many of these could prove suitable as the second RNB production target for a tertiary beam or, of course, as a "normal" RNB reaction target. In any case, the low beam heating and hence low cooling needs greatly facilitate the use of these types of targets, e.g. mechanical refrigerators can be utilized for cooling.

5 Polarized Tertiary RNBs

An important application of cryogenic targets is the production of polarized targets such as $^{1,2}\vec{H}$ [14-16]. This brings up the obvious possibility of utilizing a polarized cryogenic target to produce a polarized, tertiary RNB via spin-transfer scattering e.g. $^{8}Li(\vec{p},\ \vec{p})^{7}\vec{Li}$. Since these reactions are done in reverse kinematics, even a modest RNB angular acceptance in the magnetic separators (Fig. 2) can correspond to rather larger c.m. scattering. At these angles the spin transfer to the RNB can be quite large ($\rightarrow$ 100%).

Hence, given typical cross sections an ^{8}Li beam of $^{8}10/s$ one could in principle obtain a highly polarized secondary beam of intensity $\sim 10^2/s$ – $10^3/s$ from elastic scattering and similarly 1–100/sec from transfer reactions such as $(\vec{d},\ \vec{p})$.

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6 Figure Captions

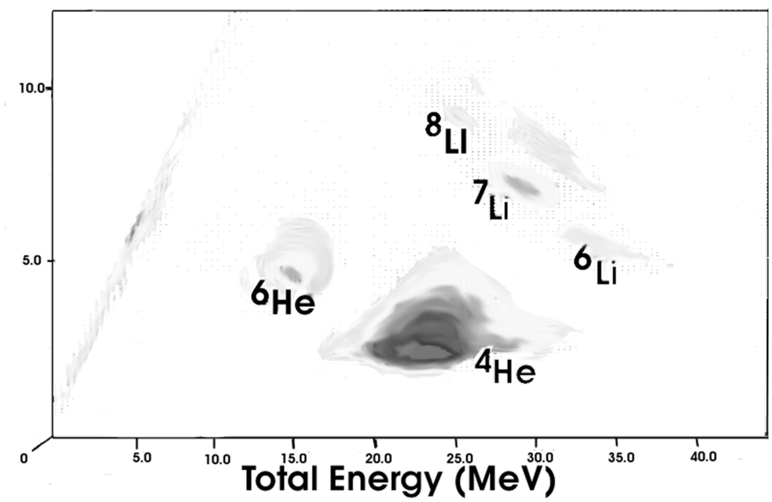
Figure 1: An RNB identification spectrum (ΔE vs. E_{total}) taken with a $(\Delta E - t) - (X - Y - E)$ silicon counter telescope located at the secondary RNB focus (Fig. 2) for the reaction of an ^{18}O beam (E = 63 MeV) on a 12.7μm Be production target. The running time was ca. 2000s with a beam of about 5 particle nA. Based on this and the events observed the conversion efficiency (RNB/primary beam) for production of ^{8}He, ^{9}Li etc. is estimated to be $< 10^{-13}$.

Figure 2: The TwinSol magnets configured for the insertion of a second RNB production target (at cross over), active-aperture and tertiary RNB separation and focussing using the second magnet.

Table I
Typical Reactions to Produce Tertiary Beams$^{a)}$

Final RNB	Intermediate Reaction	Q-Value (MeV)	Estimated Conversion Efficiency	Comments
^8He	$^6He(t,p)^8He$	-6.35	10^{-7}	Tritium target; not well Q-matched
	$^8Li(t,\ ^3He)^8He$	-10.6	10^{-6}	Tritium target; not well Q-matched
^9Li	$^8Li(d,\ p)^9Li$	$+1.83$	10^{-4}	Can use thick, active CD_2 target (TOF); Q-matched
	$^8Li(t,\ d)^9Li$	-2.19	10^{-6}	Tritium target; not well Q-matched
	$^8Li(^9Be,\ ^8Be)^9Li$	$+2.40$	10^{-5}	^9Be target; Q-matched
	$^8Li(^{13}C,\ ^{12}C)^9Li$	-0.88	10^{-5}	^{13}C target; Q-matched; poor kinematic focusing
	$^8Li(^{17}O,\ ^{16}O)^9Li$	-0.08	10^{-5}	^{17}O target; Q-matched, poor kinematic focusing
	$^9Be(t,\ ^3He)^9Li$	-13.6	10^{-7}	Stable beam; use ring focus; poor Q-match
^9C	$^8B(^3He,\ d)^9C$	-4.19	10^{-5}	^3He gas cell; Q-matched
	$^7Be(^3He,\ n)^9C$	-6.28	10^{-7}	^3He gas cell; poor Q-match
	$^{10}C(^3He,\ \alpha)^9C$	-0.70	10^{-5}	Needs ^{10}C beam; good Q-match
^{10}C	$^8B(^3He,\ p)^{10}C$	$+14.9$	10^{-5}	^3He gas cell; highly exothermic; good Q-match
	$^8B(^6Li,\ \alpha)^{10}C$	$+18.8$		highly exothermic; good Q-match
	$^{11}C(^3He,\ \alpha)^{10}C$	$+7.45$	10^{-5}	^3He gas cell; exothermic; good Q-match (near $Q-0$)
	$^{10}B(^3He,\ t)^{10}C$	-3.67	10^{-7}	stable beam; ^3He gas cell
^{12}N	$^{11}C(^3He,\ d)^{12}N$	-4.89	10^{-7}	^3He gas cell; Q-matched
	$^{11}C(^7Li,\ ^6He)^{12}N$	-9.4		poor Q match
	$^{11}C(^6Li,^5He)^{12}N$	-3.99	10^{-5}	Q-matched
	$^{13}N(^3He,\ \alpha)^{12}N$	$+0.51$	10^{-5}	^3He gas cell; good Q-match

$^{a)}$Reactions with highly unfavorable Q-values or low primary RNB intensity are not shown; a few stable-beam reactions are also included for reference.
$^{b)}$Based on typical conversion efficiencies for producing RNBs via one- and two-nucleon transfer and other reactions e.g. $^7Li(^9Be,\ ^8Be)^8Li$, $\epsilon \doteq 10^{-5}$ using the UM-UND TwinSol apparatus with stable beams. (Refs. [5-7,11]).



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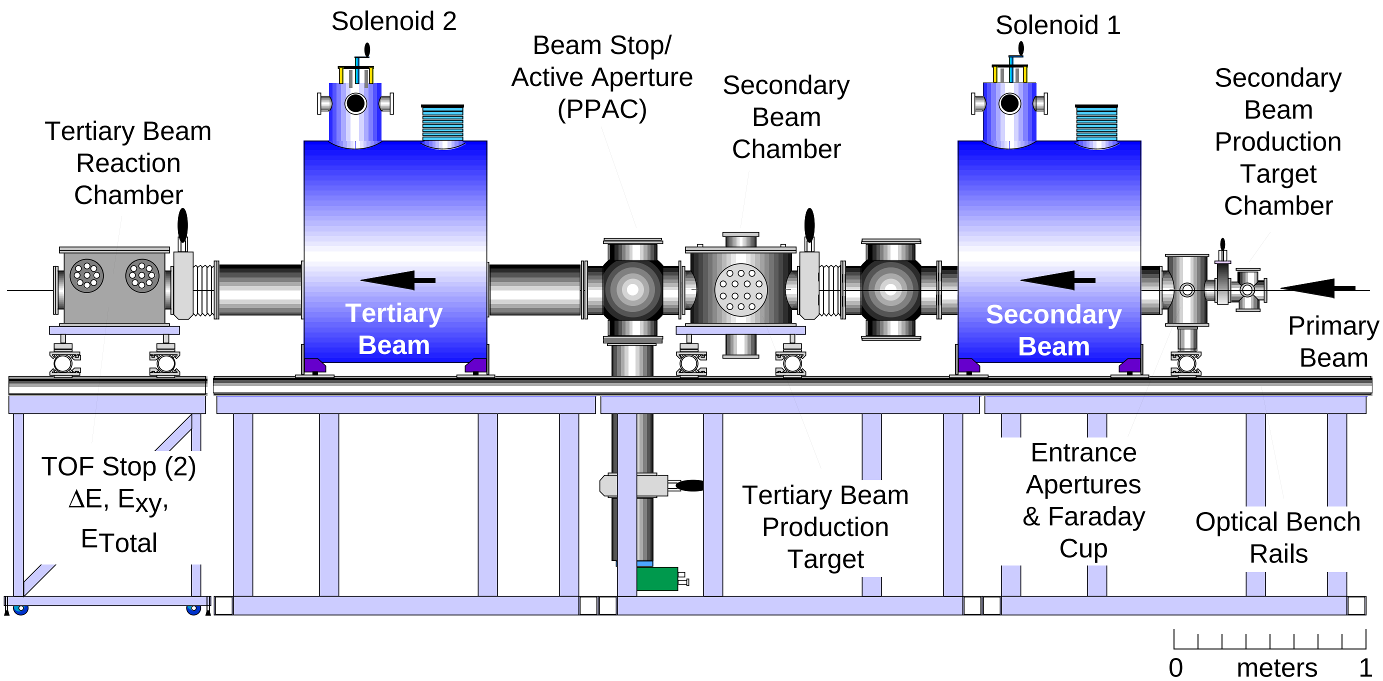

Fig. 2. The TwinSol magnets configured for the insertion of a second RNB production target (at cross over), active-aperture and tertiary beam RNB separation and focussing using the second magnet.