Nuclear Instruments and Methods in Physics Research B56/57 (1991) 554–558
North-Holland

Production and use of ^{6}He, ^{7}Be, ^{8}Li, ^{12}B and metastable nuclear beams *

F.D. Becchetti, J.A. Brown, K. Ashktorab, J.W. Jänecke, W.Z. Liu [1] and D.A. Roberts
Physics Department, University of Michigan, Ann Arbor, MI 48109-1090, USA

R.J. Smith, J.J. Kolata, K. Lamkin and A. Morsad [2]
Physics Department, University of Notre Dame, Notre Dame, IN 46556, USA

R.E. Warner
Physics Department, Oberlin College, Oberlin, OH 44074, USA

A low energy (few MeV/nucleon), modest flux (10^4–10^7/s) radioactive nuclear beam (RNB) facility has been in operation for approximately three years at the University of Notre Dame Van de Graaff accelerator. This facility utilizes a compact superconducting solenoid lens, designed at the University of Michigan, with adjustable apertures to produce momentum-analyzed secondary beams via the direct transfer and other methods. Useable beams of ^{6}He, ^{7}Be, ^{8}Li, ^{12}B, ^{18}F and to our knowledge the first isomeric beam, ^{18m}F, have been produced and a first generation of RNB experiments has been successfully completed.

1. Recent RNB development

The RNB beamline at the University of Notre Dame is shown schematically in fig. 1. The radioactive nuclei formed in the primary target are collected over a large angular acceptance (typically 5–11°) by a compact superconducting solenoid. The solenoid acts as a thick lens [1,2] focusing ions of a given magnetic rigidity to a circle of least confusion, which is typically 5 mm in diameter, at the secondary target ~ 2 m downstream of the primary target. An adjustable aperture in the mid-chamber can be used to block unwanted ion species of lower magnetic rigidity. The cylindrical symmetry and large acceptance solid angle make this a simple and efficient device for RNB production [3–5], avoiding some of the background problems encountered when using dipoles or quadrupoles for this purpose [6–8]. The short flight path and isochronism of the device is also advantageous for time-of-flight measurements and detection of short-lived, isomeric nuclei ($T^{1/2} \geqslant 100$ ns). The use of a simple air core magnet allows one to easily adjust the position of the production target and hence optimize the object and image positions of the beam foci for specific experiments. Thus by moving the production target forward we can increase the secondary RNB energies, although with a reduction ($\times \frac{1}{3}$) in RNB intensity.

The Notre Dame FN tandem Van de Graaff accelerator, with the recent addition of an intense negative ion Cs sputter source (SNICS ion source), is capable of delivering 10 eμA of beam (e.g. 17 MeV ^{7}Li) to our primary production target. We have therefore installed a rotating primary target assembly, thus reducing local target heating by 20 times or more. In addition, to efficiently filter out unwanted scattered particles at lower rigidities than the desired secondary beam, a z-axis (solenoid axis) moveable beam stop has been installed in the mid-plane chamber (fig. 1). This has proved essential to remove $^{8}Li^{*}$ ($E_x = 0.98$ MeV) contaminants from the focused ^{8}Li secondary beam from the $^{9}Be(^{7}Li, ^{8}Li^{*})$ primary reaction.

During the past three years we have investigated several production reactions leading to secondary beams. As an example, the production-reaction spectrum to preferentially form ^{18m}F in its $J^{\pi} = 5^{+}$ metastable level is shown in fig. 2. Table 1 summarizes the yields and characteristics of secondary RNB beams achieved to date [3–5,9–13]. The RNB energy resolution is typically 300–500 keV FWHM at $E \doteq 14$ MeV (i.e. 0.3%). This is usually sufficient to separate low-lying nuclear levels, at least in light nuclei. The RNB energy resolution is an important aspect since a detailed analysis of any phe-

* Supported in part by the US National Science Foundation.
[1] Present address: Texas A & M University, Cyclotron Institute, College Station, TX 77843-3366, USA.
[2] Present address: Centre de Recherches Nucleaires, B.P. 20 CR, 67037 Strasbourg Cedex, France.

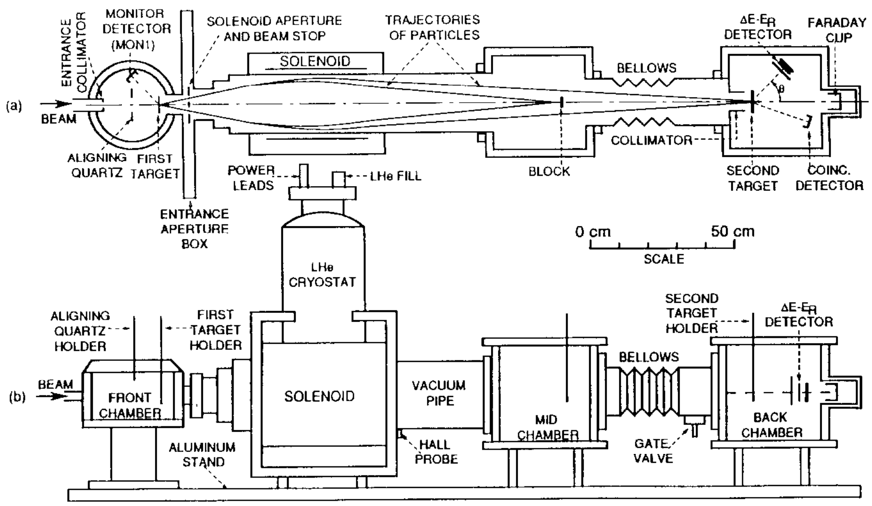

Fig. 1. Schematic diagram of the RNB beamline at the University of Notre Dame.

Table 1
Secondary RNB beams

RNB	Production reaction	Primary target (mg cm^{-2})	E(RNB) [MeV]	FWHM [MeV]	Yield (100 enA^{-1})	Conversion efficiency	Beams achieved [s^{-1}]	Achievable [s^{-1}]
^{8}Li	^{9}Be(^{7}Li, ^{8}Li) at 17 MeV	^{9}Be (2.29)	14.9	0.55	48580 s^{-1}	2.2×10^{-7}	$>1.2\times10^7$	$\geq 5 \times10^7$
^{6}He	^{9}Be(^{7}Li, ^{6}He) at 17 MeV	^{9}Be (2.29)	9.0	0.7	580 s^{-1}	2.6×10^{-9}	1.5×10^4	$\geq 6 \times10^4$
^{6}He	^{9}Be(^{7}Li, ^{6}He) at 14.63 MeV	^{9}Be (2.29)	8.5	0.8	1900 s^{-1}	8.6×10^{-9}	4.8×10^4	$\geq 2 \times10^5$
^{7}Be	^{1}H(^{10}B, ^{7}Be) at 23.5 MeV	^{1}H (0.04)	20.8	1.26	6320 s^{-1}	4.6×10^{-8}	1.6×10^4	$\geq 1.6\times10^4$
^{7}Be	^{12}C(^{3}He, ^{7}Be) at 22.5 MeV	^{12}C (0.5)	15.1	0.88	500 s^{-1}	1.6×10^{-9}	5.0×10^3	$\geq 6 \times10^4$
^{7}Be	^{10}B(^{6}Li, ^{7}Be) at 23 MeV	^{10}B (0.205)	23.0	0.6	940 s^{-1}	4.3×10^{-9}	3.3×10^3	$\geq 1.5\times10^5$
^{12}B	^{9}Be(^{7}Li, α)^{12}B at 17 MeV	^{9}Be (2.29)	22	1.1	~ 5000 s^{-1}	$\sim 2 \times10^{-8}$	$\sim 10^4$	$\sim 10^5$
^{18m}F	^{12}C(^{17}O, ^{18m}F) at 70 MeV	^{12}C (1.1)	52.0	2.1	290 s^{-1}	3.4×10^{-9}	1.5×10^3	$\geq 3 \times10^4$

nomenon requires information about the specific nuclear levels involved. Fortunately many RNB-induced reactions of interest have very positive Q-values, so at least reaction particle groups are often well-separated and unambiguous [11]. Many of the important experiments of astrophysics interest, such as ^{1,2}H(^{8}Li, ^{7}Li) and ^{1,2}H(^{8}Li, ^{9}Be) also are highly exothermic. Recent experiments [3,9–13] at the RNB facility have successfully determined cross sections for these reactions, including an ^{2}H(^{8}Li, ^{9}Be) excitation function [13] down to $E_{cm} < 1$ MeV utilizing energy-loss absorbers with the 14 MeV ^{8}Li beam.

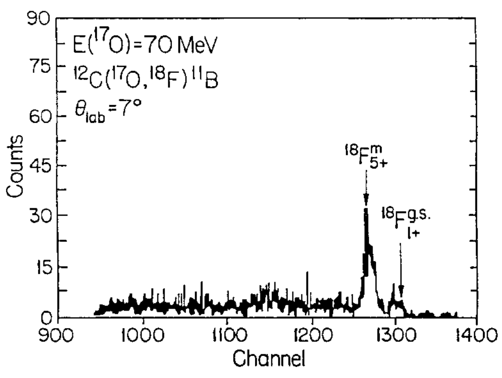

Fig. 2. Production reaction used to preferentially produce [12] the metastable RNB ^{18m}F.

2. Recent experimental results

2.1. ^{8}Li beams

2.1.1. Elastic and inelastic scattering of ^{8}Li

Beams of 13.8–14.9 MeV ^{8}Li^{3+} ions having an energy resolution of 0.4–0.6 MeV have been scattered from ^{197}Au, ^{nat}Ni, ^{nat}C and other targets [9–11]. Angular distributions for elastic scattering of ^{8}Li from ^{12}C are fit well using optical-model parameters derived from ^{7}Li parameters. Inelastic transitions to ^{8}Li* ($J^\pi = 1^+$;

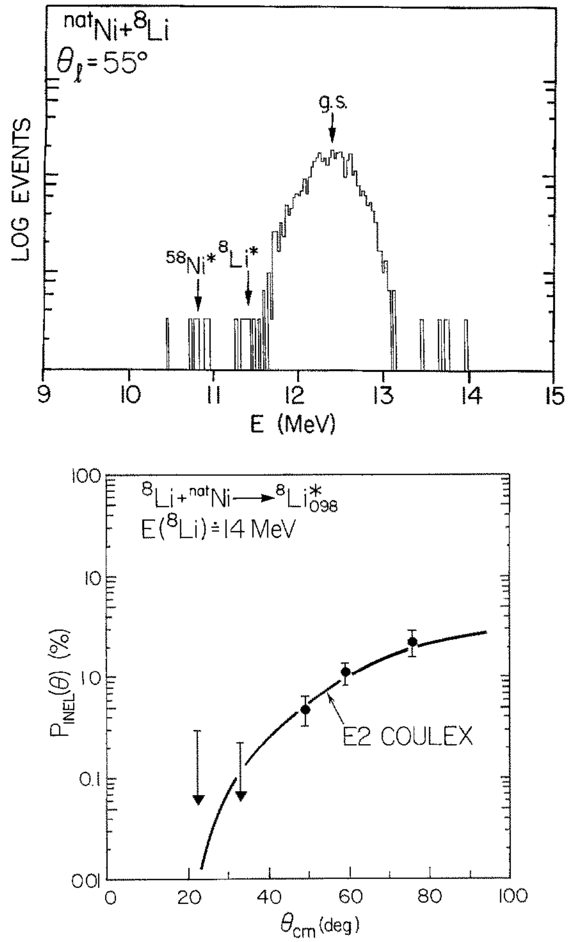

Fig. 3. Spectrum (top) and cross section (bottom) for ^{8}Li* + Ni. The curve is a classical Coulomb excitation calculation assuming an E2 transition with BE2↑ adjusted to fit the data.

$E_x = 0.98$ MeV) are also observed. The results suggest a BE2↑ value for ^{8}Li* which is subtantially greater than that observed for ^{7}Li* excitation.

We have also done experiments to observe the Coulomb excitation (COULEX) of ^{8}Li*. The original experiments [11] using ^{8}Li scattered from Au were contaminated by ^{8}Li* from the production reaction. As noted, recent improvements allow us to eliminate most of this contamination hence permitting measurements of such reactions (fig. 3). Again the results indicate a BE2↑ for ^{8}Li which is substantially higher than that observed for ^{7}Li*, but this will need to be confirmed by future experiments. Good RNB energy resolution and energy profile are obviously critical for these types of measurements. This type of measurement can also be used in the search for unusual excitation modes of RNB projectiles (E1 GDR) which have been predicted [14].

The elastic scattering of 13.4–14.5 MeV ^{8}Li from ^{9}Be, $^{13}CH_2$ Melamine, Al and $^{nat}TiD_2$ has also been measured as a function of angle out to a lab angle of 55° and show deviations from Rutherford scattering, as expected from optical model calculations based on ^{7}Li or ^{6}Li OM parameters [11].

2.1.2. (^{8}Li, ^{7}Li) transfer reactions

Single nucleon transfers of the type X(^{8}Li, ^{7}Li) have been studied for X = ^{12}C, ^{13}C, ^{14}N, ^{9}Be and ^{2}H for ^{8}Li energies of 13.4–14.4 MeV over an angular range to 45° in the laboratory [3–5]. These transfer reactions have positive Q-values of +2.9 to +6 MeV which leads to unambiguous identification of the transfer product, in its ground state, at energies higher than the secondary beam. Also, the Q-values are often near to optimum Q-values. Typical angular distributions for this transfer process are shown in refs. [3,11]. The large cross sections observed for the (^{8}Li, ^{7}Li) reaction on light nuclei suggest [3–5] that this is one of the dominant ^{8}Li reaction channels and must be considered in any nucleosynthesis calculations. Surprisingly, this reaction channel is often not included in such calculations.

2.2. Elastic scattering of ^{6}He

Beams of ^{6}He ions of 8.8–9.3 MeV and intensity up to 5×10^{4} s^{-1} have been used to study elastic scattering of ^{6}He from ^{197}Au, $^{nat}TiD_2$, ^{27}Al, ^{nat}C and ^{9}Be targets [9]. This elastic scattering data is, to our knowledge, the first systematic experimental study of ^{6}He scattering albeit at low energy.

Some of the ^{6}He elastic scattering data [9] are presented in fig. 4. Scattering from Au, Ti and Al follows the Rutherford formula but the angular distributions for elastic scattering from C and Be show deviations that can be reproduced with optical model (OM) potentials based on ^{7}Li rather than ^{4}He suggesting the data is

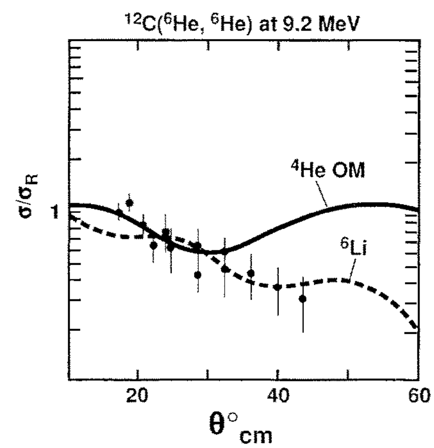

Fig. 4. Elastic scattering of ^{6}He compared with optical model calculations based on ^{4}He and ^{6}Li parameters [9].

best reproduced with an imaginary potential corresponding to strong absorption of ^{6}He.

2.3. Elastic scattering of ^{7}Be

Beams of ^{7}Be ions ($q = 3+$ and $4+$) of 22.4, 20.7, 15.2 and 8.5 MeV (table 1) have been used to scatter from ^{197}Au and ^{nat}C targets [10]. The ^{7}Be ions at 22.4 MeV from ^{nat}C show distinct deviations from Rutherford scattering which can be represented by a simple OM calculation with parameters similar to those used for ^{10}B scattering.

2.4. ^{12}B beams

Usable beams (10^3–10^4/s) of ^{12}B ($J^\pi = 1^+$, $T_{1/2} =$ 20 ms) have been made at $E = 15$–25 MeV using the fusion-evaporation reaction $^7\mathrm{Li} + {}^9\mathrm{Be} \rightarrow {}^{16}\mathrm{N}^* \rightarrow \alpha + {}^{12}\mathrm{B}$. This compound nuclear reaction has a moderately large (~ 1 mb/sr) cross sections for emission of an α particle at large θ_{cm} and hence forward emission of a fast ^{12}B in the lab. Initial measurements of projectile excitation of ^{12}B are in progress.

2.5. ^{18m}F isomeric beam: elastic scattering ^{18m}F + ^{197}Au, ^{nat}C

Production [12] of the isomeric beam ^{18m}F ($J^\pi = 5^+$, $E_x = 1.1$ MeV, $T_{1/2} = 160$ ns) was achieved via the reaction ^{12}C(^{17}O, ^{18m}F) at 70 MeV. As can be seen from the energy spectrum at 7° in fig. 2, the 5^+ isomeric state of ^{18}F is strongly populated in this reaction with a differential cross section of about 14 mb sr^{-1}. The first observations of scattering of ^{18m}F from ^{197}Au and ^{nat}C did not exhibit]12] a "superelastic" scattering peak (acceleration of the scattered ion). However, more intense beams and ^{18m}F coincidence γ-detection will be needed for a more thorough search for such phenomena. Other isomeric RNB candidates, all feasible using the direct-transfer method of production in conjunction with a solenoid lens, are listed in table 2. Attempts will be made to produce some of these nuclei in the near future.

Table 2
Suitable RNB metastable nuclei

Nucleus	J^π_{GS}	J^π_M a)	E_x [MeV]	τ b)	Typical production reaction
^{18}F	1^+	5^+	1.12	0.15 μs	^{12}C(^{17}O, ^{18}F)
^{19}F	$1/2^+$	$5/2^+$	0.19	89 ns	(^{18}O, ^{19}F)
^{22}Na	3^+	1^+	0.58	0.24 μs	(^{23}Na, ^{22}Na)
^{24}Na	4^+	1^+	0.47	20 ms	(^{23}Na, ^{24}Na)
^{26}Al	5^+	0^+	0.228	6.36 s	(^{27}Al, ^{26}Al)
^{34}Cl	0^+	3^+	0.146	32 m	(^{35}Cl, ^{34}Cl)
^{38}Cl	2^-	5^-	0.671	0.71 s	(^{37}Cl, ^{38}Cl)
^{38}K	3^+	0^+	0.13	0.93 s	(^{37}Cl, ^{38}K)
^{40}K	4^-	0^+	1.64	0.33 μs	(^{41}K, ^{40}K)

a) Spin and parity of metastable level.
b) Lifetime of metastable level (must be > flight path through RNB solenoid).

3. Future plans

In addition to some of the improvements mentioned above, we have plans for future enhancement of the quality and/or intensity of the RNB available. This includes addition of a fast beam-pulsing system to permit TOF measurements and upgrade of the UND accelerator to achieve higher accelerating voltages and hence heavier RNB. Also a 7 T solenoid lens is under construction [11] which can be used at the UND facility and elsewhere to permit RNB production up to significantly higher energies, e.g. 10–50 MeV/u. This magnet, as well as the present magnet, is designed to include radial electrostatic elements or other devices [15] to achieve the high-purity RNB needed for experiments such as fusion and fission. We have recently done tests using a mid-plane energy-loss absorber to provide higher-purity RNB but this did not prove successful due to the inherent energy straggle in the absorbers. Other means must therefore be developed to achieve this goal.

Acknowledgements

We thank Ed Berners, the other staff, and the students at the University of Notre Dame nuclear structure laboratory for their assistance. This work was supported by the US National Science Foundation grants PHY-8605907, PHY-8911831, PHY-8803035 and PHY-8900070 as well as grants from the University of Notre Dame and the University of Michigan.

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