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PRODUCTION AND USE OF RADIOACTIVE ^{7}Be BEAMS

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A beam of $^7Be^{4+}$ ions having $E = 20.7$ MeV and intensity 1.5×10^4 s^{-1} has been produced via the ^{1}H (^{10}B,^{7}Be)^{4}He reaction. The beam had an energy resolution of 1.0 MeV FWHM, 1 cm spot size, and 3° angular divergence. The effect of a z-moveable secondary stop on beam purity was investigated. A $^7Be^{4+}$ ion beam of $E = 15.2$ MeV, intensity 5×10^3 s^{-1}, and similar energy resolution and emittance characteristics was produced via ^{12}C(^{3}He,^{7}Be)^{8}Be reaction. The maximum feasible ^{7}Be secondary beams from these two reactions are extrapolated to be 5×10^4 and 1×10^5 s^{-1}, respectively. Elastic scattering data for ^{7}Be from Au and C targets are presented as an example of the use of this radioactive beam in secondary scattering experiments.

1. Introduction

As part of our program to produce beams of radioactive ions and utilize them to study nuclear reactions [1,2], we have begun a series of experiments aimed at achieving an intense ^{7}Be beam. The elastic scattering of ^{7}Be on ^{12}C has recently been measured [3] at a beam energy of 140 MeV. However, many of the most interesting studies with this projectile involve the determination of reaction rates at low energy for astrophysical purposes. We report here on our first attempts to produce a ^{7}Be beam at energies $E \leq 25$ MeV. The reactions utilised were ^{1}H(^{10}B,^{7}Be) using 1 mg cm^{-2} TiH_2 targets at an incident energy of 23.5 MeV, and ^{12}C(^{3}He,^{7}Be), using a 0.5 mg cm^{-2} ^{12}C target and incident beam energy of 22.5 MeV. Early $^{10}B + TiH_2$ data from this project have been reported previously [4].

2. Experiments

The experimental apparatus used to collect and focus radioactive beams has been described in detail elsewhere [1]. Recent additions to this apparatus are a z (beam axis) moveable beam stop in the mid-plane chamber, and a rotating primary target assembly. The z-moveable stop consists of a 3 cm diameter disc which can be positioned under vacuum at distances between 156 and 190 cm from the primary target. This may be used to filter out lower rigidity ions including primary beam scattered particles. Although increasing the magnetic field of the solenoid may achieve the same ends, the improved beam purity comes at the expense of the secondary beam focus. The yield, purity, and energy resolution of the secondary ^{7}Be beam was investigated as a function of secondary stop position and solenoid current for two different production reactions.

2.1. $^1H(^{10}B,^7Be)$

A 23.5 MeV ^{10}B beam was used to bombard a 1 mg cm^{-2} TiH_2 target. The solenoid acceptance was limited to 4–8° (47 msr) because of the rather large kinematic broadening associated with this inverse reaction. A solenoid current of 97 A gave the secondary target focus for the 20.65 MeV ^{7}Be ions shown in fig. 1. At this current the inelastically scattered ^{10}B ions have already passed through their focal plane (circle of least confusion) and display a ring image on the position sensitive detector. Also shown is the ^{7}Be beam energy profile.

The 1 mg cm^{-2} TiH_2 targets (1 cm diameter) were made at Daresbury National Laboratory and Birmingham University, UK. Because of embrittlement induced by hydrogen loading of the titanium metal, these foils are extremely fragile and also contain pinholes which degrade the secondary beam energy resolution. Primary ^{10}B beams in excess of 200 electrical nA (enA) caused H_2 evolution from the TiH_2 target due to local heating. While use of a rotating primary target assembly would increase beam tolerance, it is difficult to manufacture foils of large enough diameter to make this feasible.

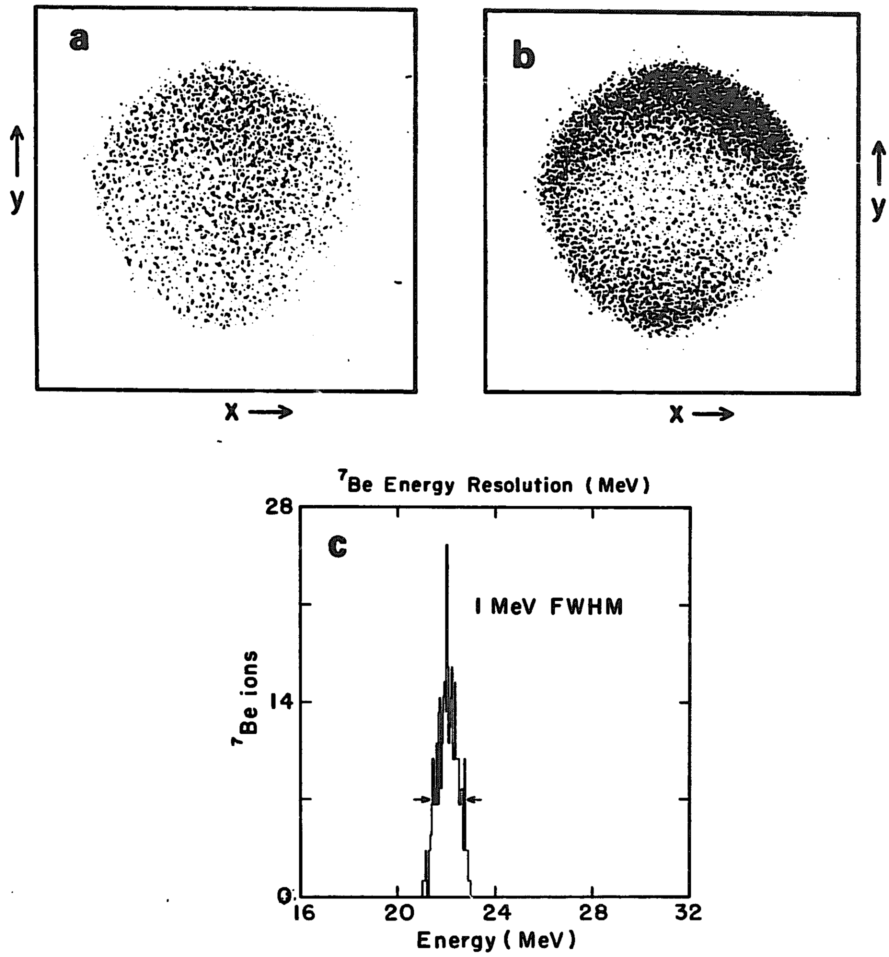

Fig. 1. (a) Focal plane image of a focussed ^{7}Be beam. (b) Ring image of an unfocussed ^{10}B beam at the same magnet current. (c) Energy profile of ^{7}Be beam. The missing segment of the ring in the ^{10}B image is due to the secondary beam block support structure which has been reduced in size in the present design.

Another significant problem in this system is the substantial yield of $^{10}B^{5+}$ inelastically scattered ions reaching the secondary target (fig. 2). The ΔE–E_R figures presented here were obtained with a 300-mm^2 23-μm ΔE and 300-μm E detector at 12.2 cm from the secondary target, and are for secondary beam scattering from Au at 30°.

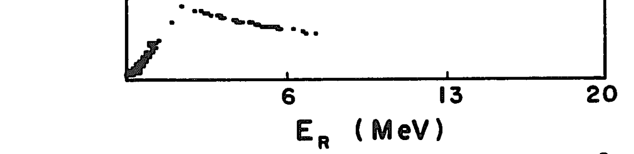

Fig. 2. ΔE vs E_R for the scattering of a 20.7 MeV ^{7}Be secondary beam on ^{197}Au at 30°. The ^{7}Be beam was produced from the ^{1}H(^{10}B,^{7}Be) reaction.

The yield, ^{7}Be/^{10}B ratio, ^{7}Be energy and FWHM were evaluated as a function of the secondary beam stop position and are presented in table 1 and figs. 3 and 4. A maximum yield of 10^4 ^{7}Be ions per second per 100 enA of primary beam was observed. While the

Table 1
Yield, ^{7}Be/^{10}B ratio, ^{7}Be energy and energy resolution (FWHM) as a function of z STOP position: 20.65 MeV ^{7}Be ions, 97 A solenoid current and 4–8° acceptance.

STOP [cm]	Yield [^{7}Be s^{-1} per 100 enA]	$10^3\times{}^7$Be/^{10}B ratio	E [MeV]	FWHM [MeV]
156	10000	5.5	20.78	1.26
166	4000	9.7	20.51	0.77
171	2200	17.1	20.49	0.83
176	890	30.7	20.68	0.66

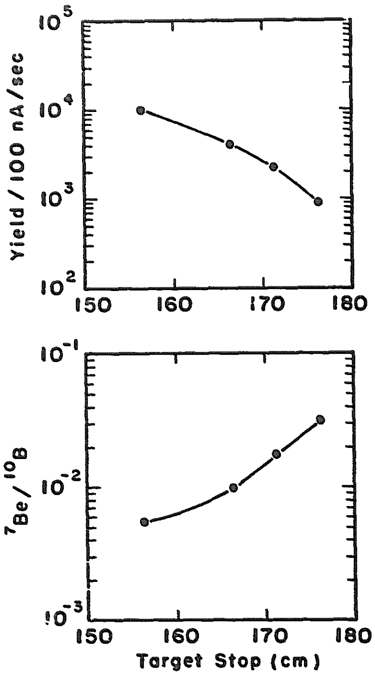

Fig. 3. Yield and $^7Be/^{10}B$ ratio versus STOP position for 20.7 MeV ^7Be.

z-moveable stop may be used to greatly reduce the ^{10}B at the secondary target, it does this at the expense of ^7Be yield. Absorbing foils can also be used to filter out the ^{10}B.

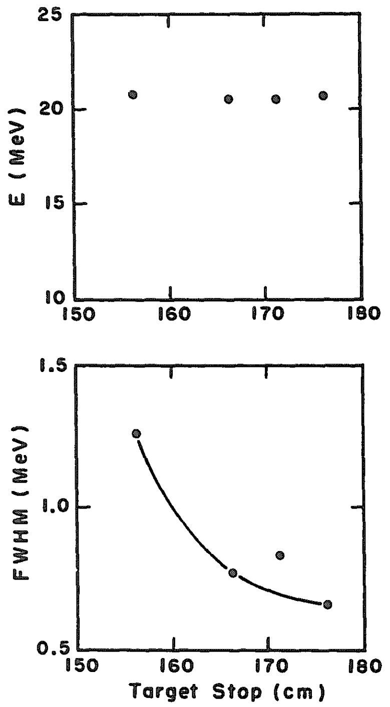

Fig. 4. Energy and energy resolution (MeV) for 20.7 MeV ^7Be.

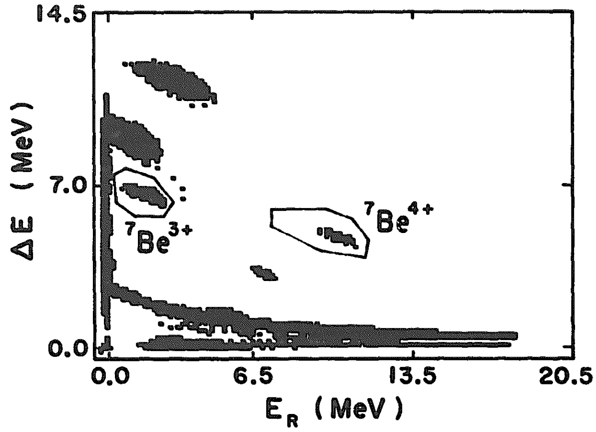

Fig. 5. ΔE vs E_R for the scattering of a 15.2 MeV ^7Be secondary beam on ^{197}Au at 12°. The ^7Be beam was produced from the $^{12}C(^3He,^7Be)$ reaction.

The maximum feasible yield, assuming a 2 mg cm^{-2} TiH_2 production target and 200 enA of ^{10}B is calculated to be 5×10^4 s^{-1}.

2.2. $^{12}C(^3He,^7Be)$

Also investigated was the α pickup reaction $(^3He,^7Be)$ on a 0.5 mg cm^{-2} ^{12}C target at incident ^3He beam energy of 22.5 MeV producing a 15.2 MeV ^7Be beam. The full 5°–11° solenoid acceptance range (95 msr) could be utilised, and the solenoid current to focus the ^7Be beam was 82 A. The ΔE–E_R plot for secondary beam scattering from Au at 12° is presented in fig. 5. The effects of solenoid current and acceptance angles were investigated and are presented in tables 2 and 3 and figs. 6 and 7. Note that this ^7Be beam is quite clean due to the large magnetic rigidity difference between

Table 2
Yield, ^7Be energy and energy resolution as a function of solenoid current, for $^{12}C(^3He,^7Be)$ with 4–8° solenoid acceptance. $^7Be^{4+}$ ions

	Solenoid current [A]	Yield [^7Be s^{-1} per 100 enA]	Energy [MeV]	FWHM [MeV]
$^7Be^{4+}$ ions	83.0	480	15.12	0.66
	82.5	600	15.01	0.88
	82.0	710	14.97	0.94
	81.5	880	14.80	0.78
	81.0	870	14.72	1.17
	80.5	920	14.22	1.70
$^7Be^{3+}$ ions	83.0	280	8.38	0.70
	82.5	450	8.24	0.97
	82.0	300	8.11	0.93
	81.5	340	8.04	0.79
	81.0	300	8.02	0.69
	80.5	350	7.89	0.70

Table 3
Yield, ^{7}Be energy and energy resolution as a function of solenoid current for $^{12}C(^{3}He,^{7}Be)$ with 5°–11° solenoid acceptance.

	Solenoid current [A]	Yield [^{7}Be s^{-1} per 100 enA]	Energy [MeV]	FWHM [MeV]
$^{7}Be^{4+}$ ions	83.0	460	15.23	0.70
	82.0	760	15.14	0.77
	81.0	1320	15.05	0.88
	80.0	1920	14.31	0.93
	79.0	2340	14.44	1.59
$^{7}Be^{3+}$ ions	83.0	460	8.68	0.70
	82.0	580	8.55	0.97
	81.0	540	8.32	0.93
	80.0	760	8.10	0.79
	78.0	720	8.22	0.70

22.5 MeV ^{3}He and 15.2 MeV ^{7}Be ions. $^{7}Be^{3+}$ inelastic events at 8.45 MeV are also accepted by the solenoid bandpass, although the yield is lower. The Q-distribution for 15.2 MeV ^{7}Be is 53%/36% for $^{7}Be^{4+}/^{7}Be^{3+}$ while at 8.5 MeV it is 45%/46%. Substantial yield is lost by this charge fractionation. The optimum useable yield of $^{7}Be^{4+}$ is 8×10^{2} s^{-1} per 100 enA of primary beam. Since ^{12}C targets can support ^{3}He beams in excess of 10

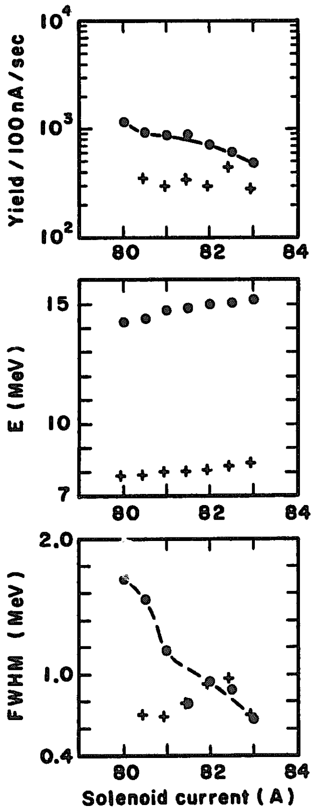

Fig. 6. Yield, energy and energy resolution of ^{7}Be beam versus solenoid current. The ^{7}Be beam was produced from the $^{12}C(^{3}He,^{7}Be)$ reaction and the solenoid acceptance was 4°–8°.

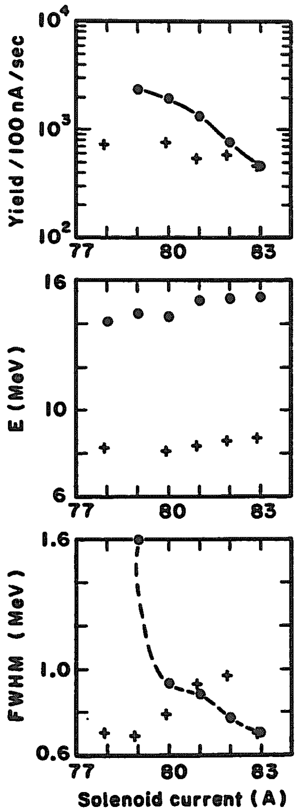

Fig. 7. Yield, energy and energy resolution of ^{7}Be beam versus solenoid current. The ^{7}Be beam was produced from the $^{12}C(^{3}He,^{7}Be)$ reaction and the solenoid acceptance was 5°–11°.

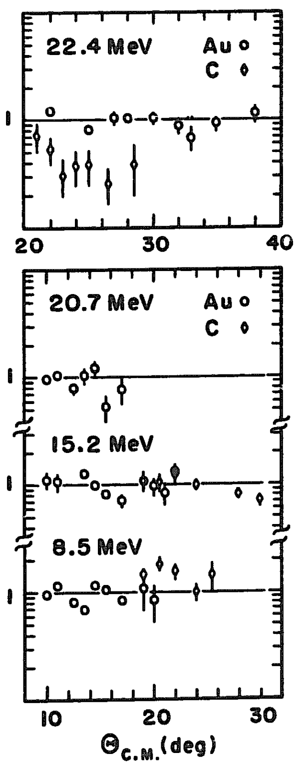

Fig. 8. Rutherford scattering of ^{7}Be: $^{197}Au(^{7}Be,^{7}Be)$ and $^{12}C(^{7}Be,^{7}Be)$ at ^{7}Be energies of 22.4, 20.7, 15.2 and 8.5 MeV.

Table 4
Cross section ratio to Rutherford for ^{7}Be scattering from ^{197}Au and ^{12}C at 22.4, 20.7, 15.2 and 8.5 MeV ^{7}Be energies.

a) ^{197}Au elastic scattering: cross section/Rutherford cross section

θ_{cm} [deg]	22.4 MeV	θ_{cm} [deg]	20.7 MeV
22.0	1.20±0.10	10.0	0.96±0.10
25.0	0.80±0.08	11.0	1.03±0.10
27.0	1.05±0.15	12.5	0.79±0.10
28.0	1.04±0.13	13.5	1.03±0.18
30.0	1.04±0.14	14.5	1.20±0.21
32.0	0.88±0.15	15.5	0.53±0.15
33.0	0.68±0.18	17.0	0.77±0.22
35.0	0.93±0.14		
38.0	1.14±0.22		
10.0	1.10±0.20	10.0	0.95±0.07
11.0	1.06±0.22	11.0	1.14±0.07
13.5	1.26±0.10	12.5	0.80±0.07
14.5	0.98±0.10	13.5	0.68±0.07
15.5	0.82±0.09	14.5	1.15±0.07
17.0	0.71±0.09	15.5	1.05±0.08
19.0	1.09±0.23	17.0	0.83±0.08
20.0	0.96±0.19	19.0	1.08±0.41
21.0	0.83±0.19	20.0	0.84±0.32
22.0	1.28±0.27		

b) ^{12}C elastic scattering: cross section/Rutherford cross section

θ_{cm} [deg]	22.4 MeV [deg]	θ_{cm} [deg]	15.2 MeV	θ_{cm}	8.5 MeV
21.0	0.71±0.21	19.0	1.10±0.20	19.0	1.46±0.18
22.0	0.54±0.16	20.5	1.06±0.22	20.5	1.83±0.26
23.0	0.31±0.12	22.0	1.26±0.10	22.0	1.56±0.26
24.0	0.38±0.14	24.0	0.98±0.10	24.0	1.00±0.19
25.0	0.39±0.15	28.0	0.82±0.09	25.0	1.45±0.42
26.5	0.26±0.10	30.0	0.71±0.09		
28.5	0.39±0.20				

Note: The Centre of Mass energies for these ^{7}Be ions on ^{12}C are 14.1, 9.6 and 5.3 MeV, respectively, while the Coulomb barrier energy is 10.1 MeV.

μA without significant degradation, beams approaching 10^5 ^{7}Be s^{-1} are feasible assuming, e.g, 10 μA of ^{3}He beam and a 0.6 mg cm^{-2} ^{12}C target. The ^{12}C primary target thickness is limited by the large energy spread of ^{7}Be ions produced from the front and back of the ^{12}C foil. Lower solenoid currents result in more ^{7}Be ions, but the energy resolution deteriorates significantly (table 2).

Finally, scattering of 22.4, 20.7, 15.2 and 8.5 MeV ^{7}Be beams from ^{197}Au and ^{12}C is reported in table 4 and fig. 8. While the Au scattering is, as expected, entirely Rutherford scattering, that on ^{12}C for higher energy ^{7}Be beams shows distinct deviation from Rutherford as expected by a simple Optical Model calculation [5]. It should be noted that scattering of the first excited state of ^{7}Be (0.43 MeV) is included in these differential cross sections.

3. Conclusions

Beams of ^{7}Be, produced from the $^{1}H(^{10}B,^{7}Be)$ reaction between 4° and 8° outgoing angle, had a rate of 10^4 ions s^{-1} 100 enA^{-1} with an energy resolution of 1.0 MeV. Beams of ^{7}Be from the reaction $^{12}C(^{3}He,^{7}Be)$, between 5° and 11° outgoing angle had a rate of 8×10^2 ions s^{-1} 100 enA^{-1}, and with an energy resolution of 1.2 MeV. This compares favourably with the results reported by Yamagata et al. [3] who produced a beam of 2×10^4 ions s^{-1}, with an energy resolution of 1.6 MeV, by the reaction $^{1}H(^{7}Li,^{7}Be)$ at 0°.

The large cross section for the $^{1}H(^{10}B,^{7}Be)$ reaction, and the increased hydrogen atom concentration in plastics, make a polyethylene or similar hydrocarbon target attractive. However, our own experience suggests that ^{10}B beams in excess of a few enA burn through such targets. Cooling the target by aluminizing the surfaces and rotating the plastic may increase its maximum beam current tolerance.

In summary, while beams of 10^5 ^{7}Be s^{-1} are achievable by the reactions investigated above, beams of 10^6 s^{-1} or more are required for the sequence of nuclear reactions $X(^{7}Be,^{8}Be)$, and the astrophysically important reaction $^{1}H(^{7}Be,^{8}B)$, to be conveniently investigated. To this end we shall shortly investigate the $^{10}B(^{6}Li,^{7}Be)$ reaction as well as $C^{1}H_2(^{10}B,^{7}Be)$ using aluminium-coated rotating targets.

Note added in proof: We have recently measured the cross section and secondary beam yield for ^{7}Be produced via the $^{10}B(^{6}Li,^{7}Be)$ reaction, using a 23 MeV ^{6}Li beam, a 205 μg/cm^2 ^{10}B target, 94.2 A solenoid current, and 5–11° acceptance. The lab differential cross section is 26.2 mb/sr at 8°, and the yield is 940 Be ions per second per 100 enA.

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