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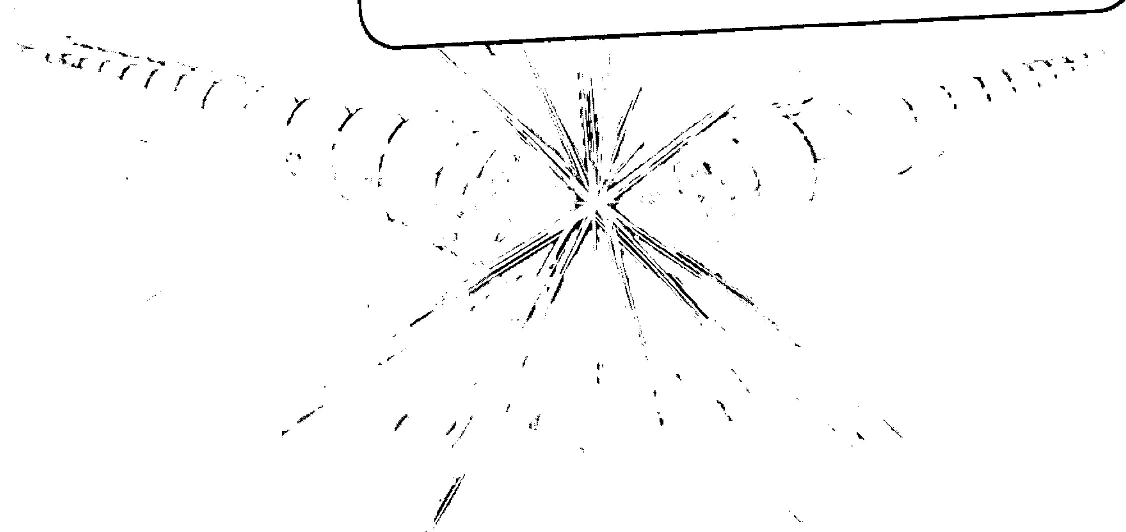

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The Production and Use of Radioactive Nuclear Beams at the Bevalac

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ABSTRACT: Using the fragmentation process, radioactive nuclear beams (RNB) are routinely produced at the Lawrence Berkeley Laboratory's Bevalac. Three beam lines are operational for production and transport of RNB: (1) a line for use in the radiotherapy treatment program (A ≅ 20 amu), (2) a line for low mass (A ≅ 20 amu) nuclear science studies and (3) a line for medium mass (A ≅ 50 amu) nuclear science studies. A fourth beam line is under construction that will allow higher mass RNB (A ≅ 100 amu) to be transmitted to the Bevalac's Heavy Ion Superconducting Spectrometer. Characteristics of RNB production and transport efficiency are described along with the RNB experimental program at the Bevalac.

1. INTRODUCTION

The Lawrence Berkeley Laboratory's Bevalac accelerator, injected by the SuperHILAC, is capable of accelerating all ions from hydrogen to uranium. The ions can be accelerated from a maximum of 2100 MeV/amu for the lighter ions to about 1000 MeV/amu for the heavier ions. An inventory of recently accelerated ions, their accelerating charge states, energies and intensities are given in Table 1. Since the early 1970's, experiments concerning the production, purification and use of radioactive nuclear beams (RNB) have been carried out at the Bevalac accelerator (Heckman 1972). A landmark experiment was carried out in 1979 where over 64 isotopes formed from the fragmentation of ^{48}Ca were transmitted along a beam line, detected and analyzed (Westfall 1979). Presently, three beam lines are in operation at the Bevalac for the production, purification and transmission of radioactive beams. A fourth beam line has been partially constructed and will be completed by mid-1992. The beam lines are shown in Figure 1.

2. PRODUCTION METHOD

Radioactive beams are produced at the first external focal point of the Bevalac by the fragmentation process. This process, and its advantages over

Ion	Atomic Weight	Atomic Number	Charge	Energy MeV/n	Intensity Ions/pulse
Hydrogen	1	1	1	4900	1.6×10^{10}
	2	1	1	2100	1×10^{10}
Deuterons	2	1	1	2100	1×10^{10}
Helium	3	2	2	3000	4×10^{9}
	4	2	2	2100	6×10^{10}
Boron	11	5	5	1840	1×10^{9}
Carbon	12	6	6	2100	1×10^{10}
Nitrogen	14	7	7	2100	3×10^{8}
Oxygen	16	8	8	2100	6×10^{9}
	18	8	8	1790	6×10^{9}
Fluorine	19	9	9	1950	1×10^{8}
Neon	20	10	10	2100	1×10^{10}
	22	10	10	1840	9×10^{9}
Magnesium	24	12	12	2100	1×10^{7} *
Aluminum	27	13	13	2000	5×10^{8}
Silicon	28	14	14	2100	1×10^{10}
Sulfur	32	16	16	2100	1×10^{6} *
Argon	40	18	18	1815	2×10^{9}
Calcium	40	20	20	2100	5×10^{9}
Titanium	46	22	22	1976	7×10^{8}
			14	1050	1×10^{8}
Manganese	55	25	25	1840	1×10^{8}
Iron	56	26	24	1700	1×10^{9}
			16	1050	5×10^{7}
Nickel	58	28	26	1810	1×10^{6}
Krypton	84	36	33	1510	1×10^{7} *
Niobium	93	41	35	1420	2×10^{8}
			23	770	8×10^{7}
Silver	109	47	43	1520	1×10^{6}
Xenon	132	54	45	1240	1×10^{6}
	136	54	45	1180	3×10^{6}
			35	817	3×10^{7}
Lanthanum	139	57	52	1410	1×10^{8}
			48	1260	4×10^{7}
			32	690	8×10^{7}
Holmium	165	67	54	1170	1×10^{6}
Gold	197	79	61	1080	1×10^{6}
			37	490	1×10^{7}
Uranium	238	92	68	960	3×10^{7}
			40	410	3×10^{7}

* no attempt was made to maximize intensity

Table 1 Particle Inventory September 1990 other methods, has been described previously (Alonso 1989, Tanihata, 1989) Briefly, however, heavy ions are brought to focus on a light metal target such as beryllium. A variety of radioactive nuclei are produced throughout the target with velocities similar to the incident projectile. Downstream of the production target, at a dispersive focal point, nuclei of similar A/Z ratio are separated by collimators from the remainder of the beam. These nuclei can then be passed through a thin foil and further downstream, at another dispersive focal point, nuclei may be separated according to values of Z. Momentum spread can be reduced using wedges, and time of flight is also often employed to further distinguish between radioactive nuclei.

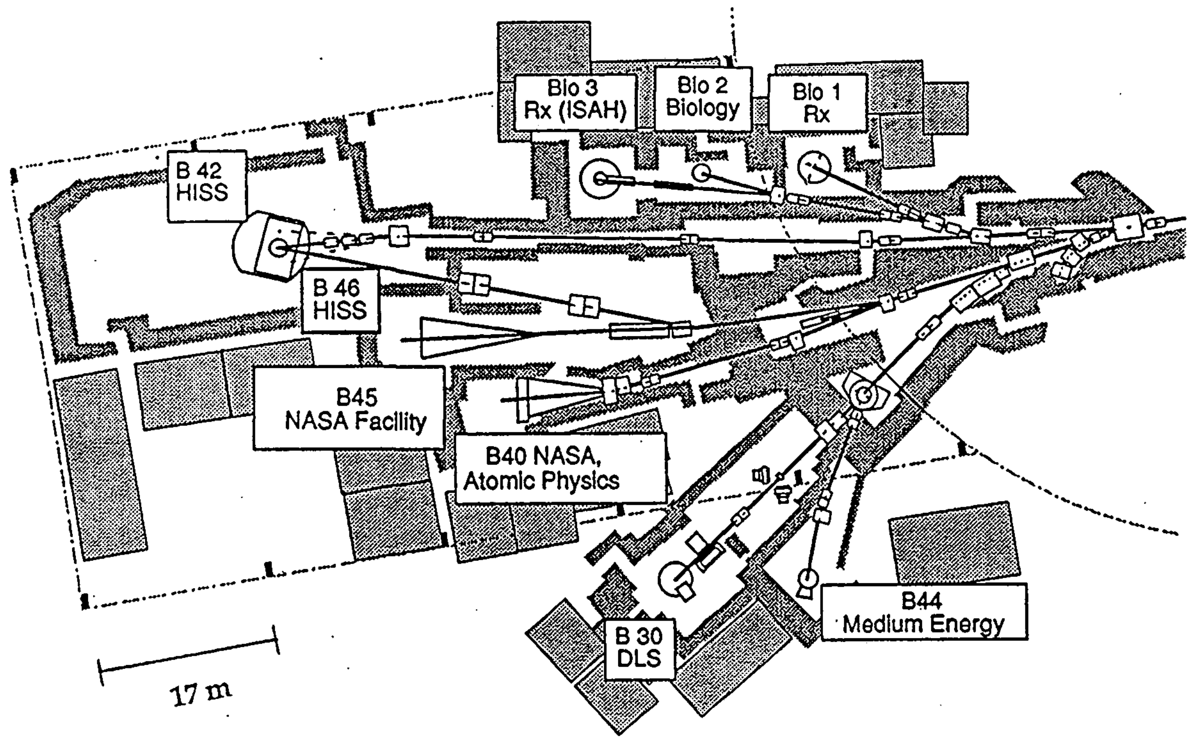

Figure 1 Bevalac Experimental Area

XBL 917-1651

3. BEVALAC PROGRAMS

The Bevalac carries out a biomedical program where various localized tumors are treated with ion beams (Chatterjee 1981, 1982, Alonso 1979). Due to the considerable density variation in tumor tissue, the program has utilized ^{19}Ne as a tracer beam prior to treatment. The β emission from ^{19}Ne stopped in the tumor is detected giving the beam position accurate to better than 1 mm. To produce the ^{19}Ne beam, a 600 MeV/amu ^{20}Ne beam is brought to a focus on a 1 in. beryllium target. The yield of ^{19}Ne is about 0.5% that of the original beam at an energy of 550 MeV/amu. The beam is then transmitted to the treatment

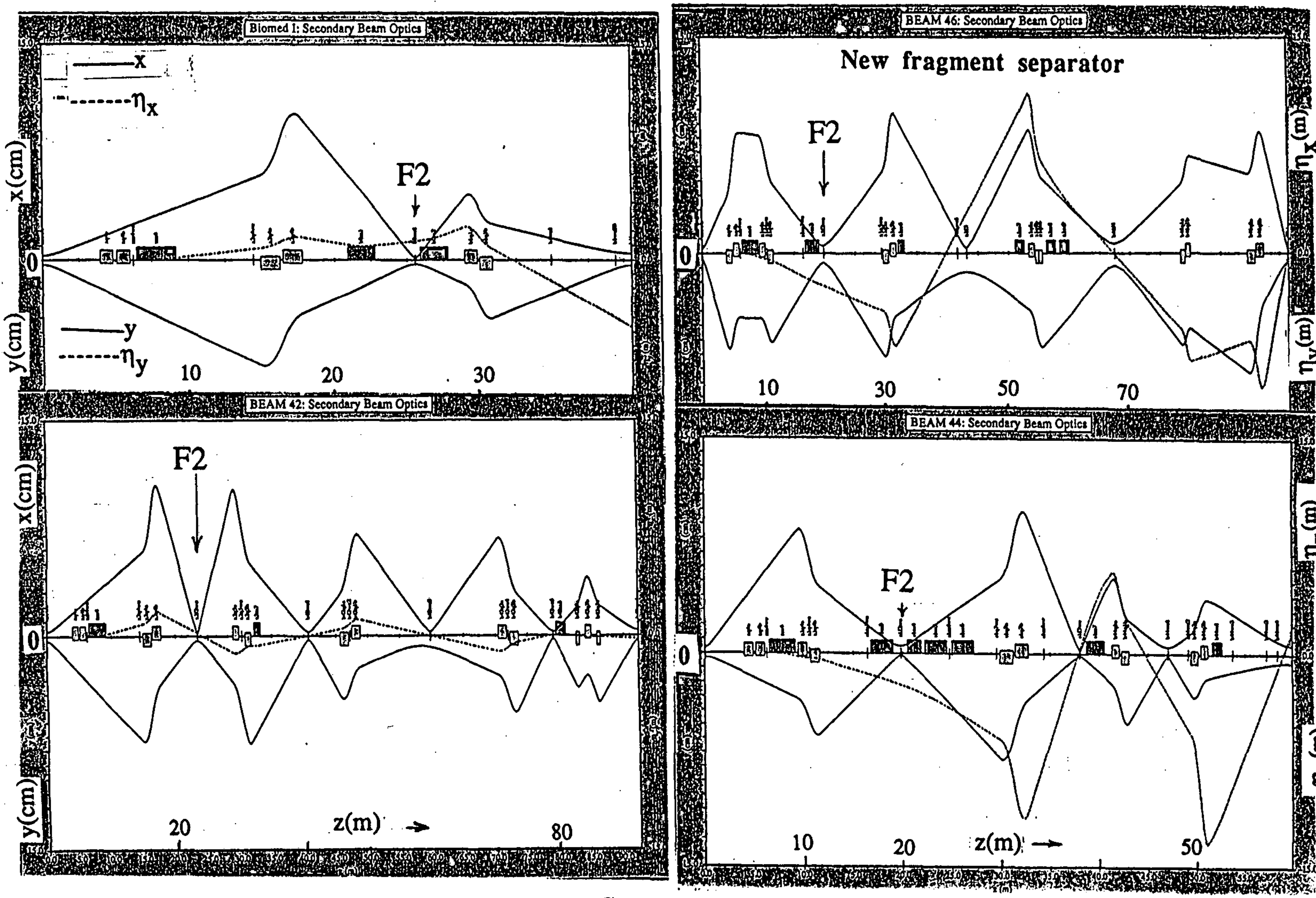

Figure 2 Horizontal and Vertical Beam half widths (XBL917-1650)

area with about 30% efficiency. Further details of the fragmentation process for this program are given in Table 2. The transport optics are shown in Figure 2.

Beam line 42, which incorporates a heavy ion superconducting spectrometer (HISS) in the experimental area, has an ongoing RNB program studying the properties of s-d shell nuclei (Tanihata 1988) A paper to be given at this conference by I. Tanihata will describe in more detail the physics carried out in the program. ^{11}Li nuclei are produced from fragmenting 870 MeV/amu ^{18}O nuclei. Typically, 10^{10} oxygen nuclei per Bevalac pulse are focused on a beryllium target. With a production cross section of about 1μb and a beam transport efficiency of 7%, a few hundred ^{11}Li nuclei per pulse are transported to the HISS facility for further analysis via interactions with a secondary target. The optics for this beam line are given in Figure 2 with various production parameters shown in Table 2.

	Biomed B1	HISS B42	B44	B46
Acceptance (x',y')	(±3.9,±5.0mr)	(±3.9,±5.0mr)	(±9.2,±3.4mr)	(±9.4, ±16mr)
Momentum (Δp/p)	±4.2%	±6.0%	±0.75%	±0.9%
Fragment Separation: Focal Point F2(F3) — Horizontal magnification m_x	0.30	0.22	1.64	1.63 (1.13)
Fragment Separation: Focal Point F2(F3) — Horizontal dispersion η_x	1.29 m	0.20 m	2.23 m	2.29 m (2.73 m)
Fragment Separation: Focal Point F2(F3) — Resolution η_x/m_x	4.3 m	0.91 m	1.36 m	1.40 m (2.42 m)
Reaction	$^{20}Ne \rightarrow ^{19}Ne$	$^{18}O \rightarrow ^{11}Li$	$^{46}Ti \rightarrow ^{43}Ti$	
Incident energy	600 MeV/A	870 MeV/A	250 MeV/A	
Cross section	≈100 mb	≈1μb	=5mb	
Yield from tgt	0.5%	5×10^{-7}	2×10^{-4}	
2ndary bm energy	550 MeV/A	800 MeV/A	90-60 (1.5±1)	
Xport efficiency	30%	7%	10% (strong momentum selection)	
Net yield (2nd/1st)	1/600	3×10^{-8}	2×10^{-5}	
Primary ions	10^{10} ipp	10^{10}	10^{9}	
2nd ions available	≈10^{7} ipp	≈10^{2}	≈10^{4} ipp	

Table 2. Characteristics of Bevalac radioactive nuclear beams

A third program at the Bevalac utilizing RNB is carried out at beam line 44. Beam line 44 was constructed in 1985 specifically for the separation of RNB (Krebs 1987). In this program a study is being carried out of mirror nuclei in the $f_{7/2}$ shell region; magnetic moments and lifetimes are measured (Nojiri 1987, 1990 Matsuta 1990). Recently, the collaboration has extended their studies to include the polarization of RNB. A paper to be given at this conference by K. Matsuta will describe in detail the physics studied in this program. In one of the studies a 250 MeV/A beam of ^{46}Ti of intensity 10^{10} ions per pulse was used to produce ^{43}Ti nuclei. The ^{43}Ti nuclei were magnetically separated according to A/Z and then finally Z. Time of flight information was also utilized in the experiment to identify the ^{43}Ti nuclei from other reaction products. In this difficult experiment the ^{43}Ti nuclei were finally stopped in a crystal and the lifetime and magnetic moment measured. The optics of the beam line are shown in Figure 2, with production parameters given in Table 2.

Finally, the Bevalac expects to make available a new RNB line fragment separator for far heavier radioactive nuclei. This beam line (B46), shown in Figure 1, bends into the HISS facility. It is expected, in the near future, that the beam line will be utilized by the collaboration studying neutron rich nuclei. The optics for the beam line are shown in Figure 2 with further information in Table 2. It is expected that fragments in the A≤100 region may be separated by increasing the dispersion and increasing the beam size for more effective collimation. As well, the angular acceptance has been increased considerably from previous beam lines. A preliminary design for this beam line was presented previously (Feinberg 1991). With the addition of another quadrupole doublet, the optics and design parameters shown in Figure 2 and Table 2 reflect further improvements to the fragment separation capability of the line.

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