# NEW HIGH-DISPERSION BEAMLINES AT THE BEVALAC FOR THE PRODUCTION, PURIFICATION AND TRANSPORT OF RADIOACTIVE BEAMS*

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## Introduction

The external particle beam transport area of the Lawrence Berkeley Laboratories Bevalac was redesigned so that radioactive beams may be more efficiently analyzed and transported. Using a variety of relativistic heavy ions available at the Bevalac, radioactive beams can be formed at the first external focal point of the accelerator by the well known process of nuclear fragmentation[1]. The large cross-section and small deflection of the projectile fragments leads to high production and delivery efficiency for these beams. Previously, at the Bevalac light radioactive ions of He, Li, Be, B, C[2] have been delivered to an experimental area. Routinely $^{19}Ne$ is delivered to the biomedical treatment site[3]. This paper reports on the production, purification and delivery of radioactive beams of $^{20,21}F$ and $^{39}Ca$.

## Radioactive Beam Production

The intensity and purity of radioactive beams produced from the fragmentation process are dependent to a large degree on the choice of target material and thickness. Increasing target thickness and mass arbitrarily in an effort to increase isotope production results in a large increase in the isotope's momentum and emittance spread due to energy loss from ionization and multiple scattering. A maximum useful production can be obtained using a low Z target material and choosing a target thickness which results in a momentum spread in the radioactive beam particles due to dE/dx that is similar to the momentum spread due to the production reactions. In one experiment at the Bevalac a 2.5 cm thick beryllium production target and a 215 MeV/amu $^{22}Ne$ beam were used to produce radioactive beams of $^{20}F$ and $^{21}F$[5]. In another Bevalac experiment a 1.27 cm thick beryllium production target and a 220 MeV/amu $^{40}Ca$ beam were used to produce a radioactive beam of $^{39}Ca$[6]. Production yields are on the order of 0.1 to 1% of the primary beam intensity[4]. In both experiments the isotopes were initially identified by means of a ΔE-E detector and finally identified by stopping them in foils and measuring their half-lives by beta-ray emission.

## Beam Transport

Shown in Fig. 1 is the transport system of dipole and quadrupole magnets for radioactive beams. The system consists of a production target at F1 (the first external focal point of the Bevalac), five quadrupole doublets, eight dipoles, three sets of horizontal and vertical collimators along with various monitoring wire chambers and vertical correction magnets. Focal points at F2, F3 and F4 are used to separate out and reduce the energy spread of the desired radioactive beam. Analysis of the radioactive beam is carried out at F5. The total length of the transport system is 55 m with a maximum rigidity of 6.5 T-m. The principle change between the present system shown in Fig. 1 and the previous transport system is the introduction of quadrupoles XQ4A, XQ4B just downstream of the production target and the widening of the vertical aperture at its most restricted location, the XM4, XM5 dipole magnets.

Shown in Figs. 2A, 2B are the new transport optics both with (Optics A) and without (Optics B) the new quadrupoles. The horizontal and vertical beam envelope half-widths are shown above and below the center axis of each figure, respectively. Using the new quadrupoles increases the vertical aperture by a factor of 4. The dispersion is given as a dashed line for a beam momentum spread of 1%. Shown on each figure at the top are the magnets used in the beamline. In the following table a comparison of the parameters of the Old Optics with Optics A and Optics B is given, where x', y' are the horizontal and vertical divergences, respectively. In addition, M is the magnification, Δp/p is the momentum acceptance (defined by aperture restriction between F2 and F3), and $D_x$ is the dispersion parameter all at F2. The most dramatic change with the new optics is the three-fold increase in the dispersion parameter $D_x$. In the past the peak of the $^{39}Ca$ distribution would have been separated from $^{40}Ca$ at F2 by about 20.4 mm. With the increased dispersion at F2 we now find $^{39}Ca$ and $^{40}Ca$ separated by 60 mm. Thus the new arrangement allows for easier collimation over a wider mass range.

| | X' | Y' | M | Δp/p | $D_x$ (at F2) |
|---|---|---|---|---|---|
| Old Optics | 8.3 mr | 3.3mr | 1.8 | 1.1% | 8.4 mm/% |
| Optics A | 7.5 mr | 20.0 mr | 1.6 | 0.68% | 24.5 mm/% |
| Optics B | 7.5 mr | 5.0 mr | 1.7 | 0.73% | 21.4 mm/% |

## Isotopic Distributions

The ability to extract a particular radioactive isotope from the multitude of fragments produced at F1 depends on the intensity, separation and width of the isotopic distribution at focal points F2 and F4. Shown in Fig. 3 are some calculated isotopic distribu-

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tions produced from the fragmentation of a 215 MeV/amu $^{22}Ne$ beam by a 4.5 gm/cm$^2$ beryllium target. The intensity of a particular isotope was calculated from measured and interpolated cross sections[1] while the width comes from Fermi momentum distribution. The horizontal separation, $d_x$, of the isotope peaks was calculated by the difference in rigidity of the isotopes where $d_x = D_x (\Delta R/R)$ and R is the rigidity and $D_x$ is given in the previous table. Isotopes below 8 x $10^{-3}$% production, such as $^{14,16}N$, $^{12,14}C$ and $^{11}B$, are not included in Fig. 3 for clarity. The distributions shown in Fig. 3 do not include various important effects which serve to broaden the distributions making isotope separation more difficult. The horizontal beam size $X_0$ is broadened since the monoenergetic radioactive beam size, given by the optics, has a magnification at F2. $X_0 = MX_1$, where $X_1$ is the beam size at the exit of the beryllium target. $X_0 \simeq 1.6$ cm diameter. Shown in Fig. 4 is one isotope distribution ($^{21}F$) whose rigidity spread has been broadened from the following effects:

(i) The primary beam's energy spread.
(ii) Energy straggling in the production target.
(iii) Fermi momentum kick from the production reaction. Here the effect of the Fermi momentum at the entrance to the target (right side of Fig. 4) is different than at the target exit (left side of Fig. 4) since they suffer different amounts of dE/dx.
(iv) A production 'target effect' which produces a flat-top broadening of the energy distribution of the isotopes. This is caused because a particular ion may interact at any depth in the target. The primary and secondary ions then suffer different energy losses depending where in the target the fragmentation occurs.

## Experimental Procedures and Results

Isotopes produced by fragmentation of heavy ions extend over a wide range of rigidity. The basic procedure in separating out a single isotope from the many isotopes produced was to utilize the dispersive qualities of the beamline. The first step in the process was the tuning of the beamline with the primary beam at the same rigidity as the desired isotope to be studied. After tuning was completed only the energy of the primary beam in the accelerator had to be adjusted such that the desired isotope would emerge from the target with the set beamline rigidity (from 186 MeV/amu to 221 MeV/amu in the case of $^{22}Ne$). Initial separation of unwanted isotopes from the beamline occurred at F2 where the dispersion vector is large (See Fig. 2a, b). At F2 the horizontal slit opening was set such that only those isotopes of similar rigidity were transmitted downstream. Since the downstream acceptance of the beamline was $\Delta p/p = 0.73\%$, the horizontal slits were set to transmit the isotope of interest within that rigidity window. The rigidity window used for the separation of $^{21}F$ is shown in Fig. 3. The next step in the separation procedure involved isolating the isotope of interest from the family of nuclei with similar rigidity but different Z. To accomplish this the nuclei were degraded at F3 (to a nominal energy of 50 MeV/amu) so that they slowed down by different amounts according to their Z value. After bending some 23° by the S1M7 magnet the isotopes were separated horizontally by $\Delta x/\Delta p/p = 18$mm/% rigidity at the dispersive focal point F4. Collimation at F4 then accomplished the separation of isotopes with different Z. The degrading procedure at F3 introduced some additional divergence to the beam from multiple scattering, about 8 mr for one experiment, and increased the rigidity spread to ±2%. At F4 a thin Lucite wedge was introduced to compensate for these increases. The wedge degrader had a pitch of 0.17 degrees and was oriented such that higher momentum beam particles passed through the thicker region of the wedge. In addition, the wedge was able to rotate about the horizontal axis allowing the pitch of the wedge as seen by passing particles to be varied. This changing of the pitch made it possible to compensate for the difference in dE/dx of different nuclei. The wedge reduced the rigidity spread in the beam particles to ±0.3%. Finally, detection of the radioactive beam occurred at F5.

In one experiment recently carried out on the described beamline it was not necessary to further separate out isotopes at F3[5]. In this experiment where $^{21}F$ was studied, isotopes of $^{20,21}F$, $^{18,19}O$, $^{15,16}N$, $^{13,14}C$ and $^{11}B$ were transmitted to F5. A ΔE-E detector at F5 detected the isotopes as shown in Fig. 5. The content and intensity is consistent with Fig. 3. The $^{21}F$ isotope was studied by stopping it in a plastic catcher at F5 and studying its half-life by beta-ray emission. The other isotopes (with lower Z) passed through the catcher and so were not a contaminant in the experiment. In the experiment producing, purifying and transmitting $^{39}Ca$ the complete procedure with a degrader at F3 and wedge degrader at F4 was carried out[6]. Contamination from other beta emitting isotopes at F5 was estimated to be less than 2 x $10^{-3}$.

## Summary

In summary, the design of the beamline for the production and transporting of radioactive beams at the Bevalac has been successfully tested. Ca and F isotopes were produced, purified and delivered to a detector. In the future we expect to further explore the mass separation and purity limitations of the beamline. As well, in the near future the beamline will be used for magnetic moment measurements of beta radioactive nuclei. We expect in the upcoming months the group of experiments to continue to grow as the unique opportunity to utilize and examine heretofore unavailable nuclei becomes possible.

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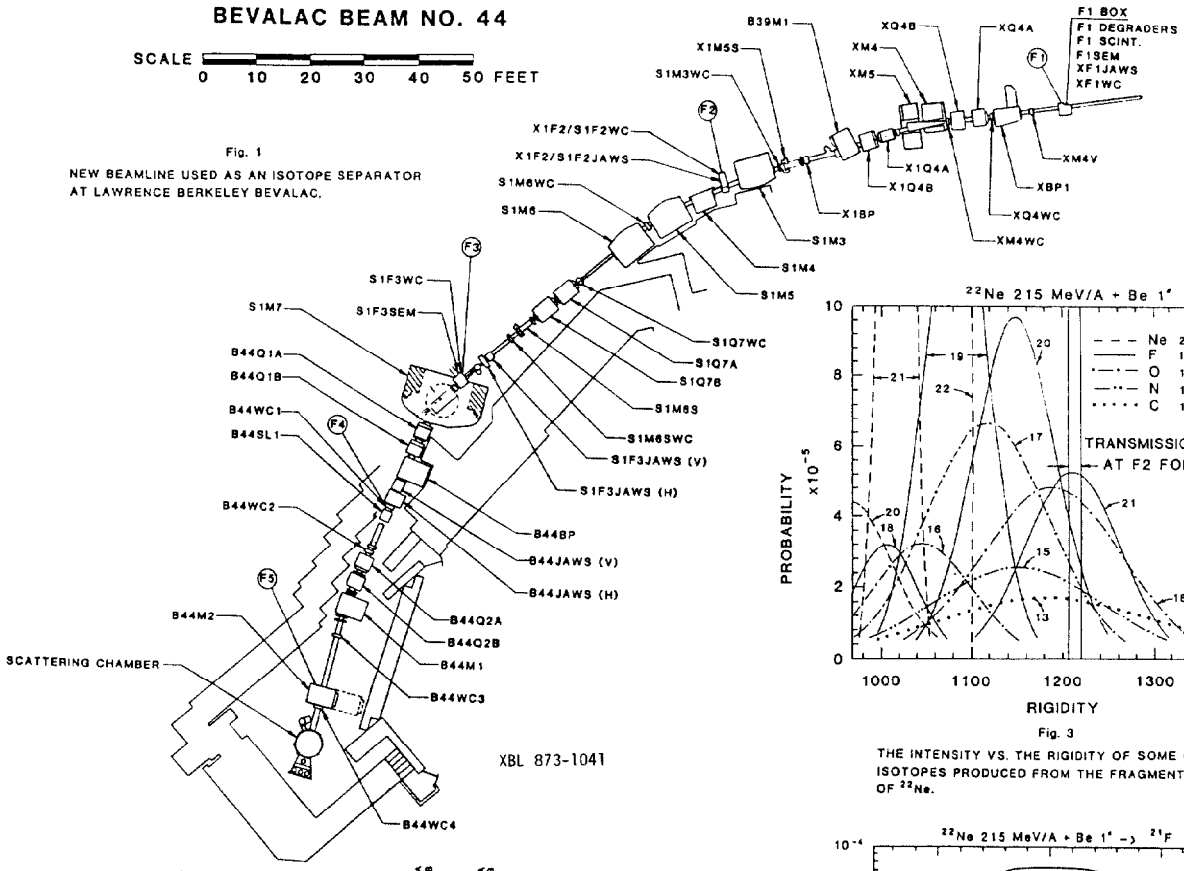


Fig. 1

NEW BEAMLINE USED AS AN ISOTOPE SEPARATOR AT LAWRENCE BERKELEY BEVALAC.




Fig. 3

THE INTENSITY VS. THE RIGIDITY OF SOME OF THE ISOTOPES PRODUCED FROM THE FRAGMENTATION OF $^{22}$Ne.

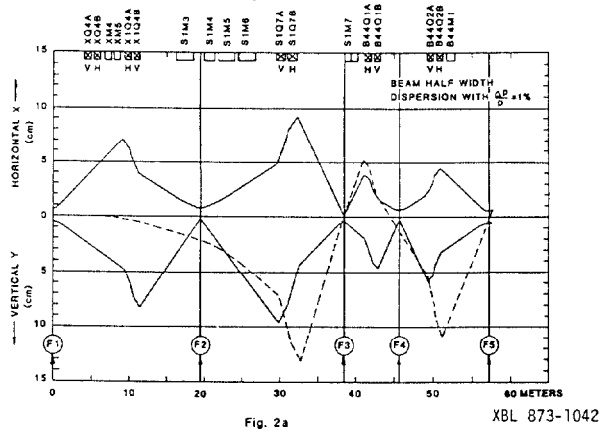


Fig. 2a

OPTICS OF THE ISOTOPE SEPARATOR USED TO PURIFY A $^{38}$Ca BEAM. THE HORIZONTAL AND VERTICAL BEAM ENVELOPE ARE SHOWN ALONG WITH THE DISPERSION.

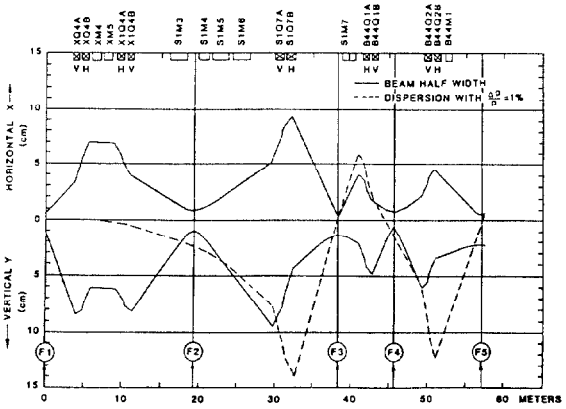


Fig. 2b

THE HORIZONTAL AND VERTICAL BEAM ENVELOPES USED FOR SEPARATING $^{20,21}$F BEAMS AT THE BEVALAC.

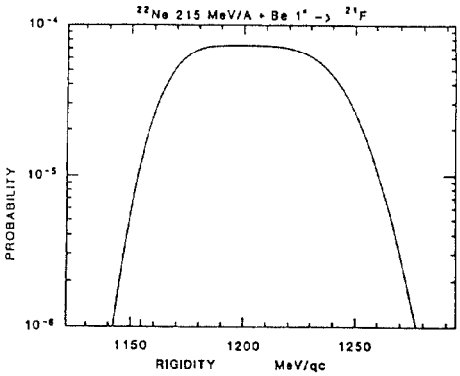


Fig. 4

THE INTENSITY VS. THE RIGIDITY OF $^{21}$F SHOWING THE BROADENING DUE TO FERMI MOMENTUM AND "TARGET dE/dx EFFECTS".

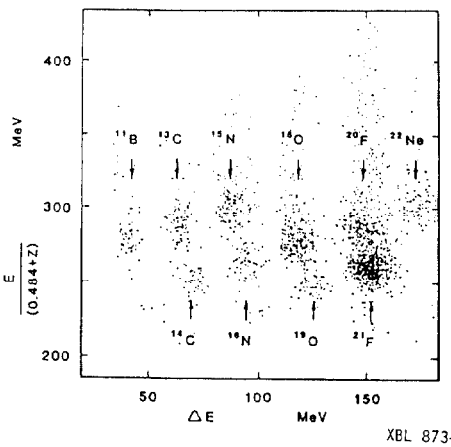


Fig. 5

ISOTOPES PRODUCED FROM THE FRAGMENTATION OF $^{22}$Ne BY BERYLLIUM, DETECTED IN A dE-E DETECTOR LOCATED AT F5.