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# On-Line Isotope Separation of Projectile Fragments Produced in Relativistic Heavy-Ion Reactions

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**Abstract**

A new on-line separator was constructed and used successfully for the study on short-lived isotopes at the Bevalac at Lawrence Berkeley Laboratory. The isotopes were produced through projectile fragmentation processes of high energy heavy-ion reactions. Various isotopes were rigidity-separated by use of a beam line and, finally, the desired single isotope was range-analyzed to stop in a catcher. A large number of $\beta$-emitting $^{21}$F nuclei were successfully collected and the nuclear lifetime was determined by detecting $\beta$ rays.

## 1. Introduction

Radioactive isotopes have played an important role in research, not only in nuclear structure but also in fundamental interactions, where the radioactive nucleus serves as a microlaboratory. In addition, they have been indispensable probes in investigating new solid state and electronic structures of rare impurities in metallic and non-metallic materials. Typically, $\beta$-radioactive nuclei have been used to investigate nuclear structure through nuclear moments,[1] nuclear reaction mechanisms,[2] hyperfine interactions,[3] and $\beta$ decays.[3,4]

In preparing $\beta$-radioactive nuclei for these investigations, on-line isotope separators connected directly with the primary beam line enable us to separate an isotope quickly. In the field of high energy heavy-ion nuclear physics it has been found that: 1) a wide variety of radioactive isotopes, including those far from the stability line, can be produced in large numbers through projectile fragmentation processes; 2) the nuclei of an isotope produced in these processes have surprisingly small momentum and angular spread after coming out of production targets. Those facts indicate that radioactive isotope beams (secondary beams) can be handled about as easily as primary beams used for conventional experiments.

At the Bevalac, the secondary beams of projectile fragments are produced through nuclear reactions between primary beams and targets at the exit of the Bevalac accelerator and are transferred through the existing beam lines originally prepared for primary beams. The secondary beams are analyzed by use of a series of dipole magnets and slit-jaws placed in certain positions in the beam lines. A single beam of radioactive isotopes desired for a particular experiment can be obtained at the end of the beam line, where the experiments are carried out.

In one successful experiment done with secondary beams, Tanihata et al. measured interaction cross sections of radioactive nuclei far from the stability line.[5,6] In this experiment, light nuclei in the s and p shells, He isotopes,[5] Li isotopes,[6] and Be isotopes[6] were produced in projectile fragmentation processes between a Be target and a $^{11}$B or $^{20}$Ne beam with energy of $\sim$800 MeV/nucleon. After analysis and purification, these secondary beams were used to bombard three different targets, Be, C, and Al, each between appproximately 5 and 20 $g/cm^2$ thick. In order to deduce interaction cross sections between the secondary beams and the targets, transmission rates of the secondary beams through these targets were observed.

In another application of secondary beams to nuclear physics, it has been planned to determine magnetic moments of mirror pairs in f-shell nuclei[7] by employing an NMR technique applicable to $\beta$-radioactive nuclei.[1,3] In this technique, ions in the analyzed secondary beams are polarized with the tilted foil technique,[8] and are stopped in a catcher material suitable for preserving their nuclear polarization for at least the duration of the nuclear lifetimes. At rest, well defined electromagnetic crystalline fields are available for the hyperfine interaction studies. For such heavy-ion implantations with the tilted foil technique, the kinetic energy of the ion has to be higher than 500 keV/nucleon, which is no problem for the secondary beam technique but poses considerable difficulty for the typical on-line isotope separator (ISOL) unless a post accelerator is employed.

## 2. Experimental

In the present experiment, $\beta$-decay rates of short-lived $\beta$-emitting $^{21}$F ($I^{\pi} = 5/2^{+}$) were observed using a beam line (Beam 44) at the Bevalac, which is shown in Fig. 1. To produce $^{21}$F through the projectile fragmentation process a $^{22}$Ne beam of $\sim$200 MeV/nucleon was used to bombard a Be target 25.4 mm thick, which was set at the first focus (F1) of the extracted beam from the Bevalac. The expected production efficiency for radioactive isotopes is 0.1% of the incident beam. The net momentum spread for the isotope was calculated to be $|\Delta p/p| < 0.5\%$.

Four dipole magnets and quadrupole doublets were used to analyze and transfer the produced isotopes down to the experimental area (F5). At two momentum dispersive focus points of the beams (F2 and F4), a desired isotope of a certain rigidity was separated by a pair of horizontal slit-jaws from other isotopes with different rigidities. The maximum rigidity was 65 kG·m, and the momentum acceptance was $\pm 0.65\%$. Momentum dispersion of the beams at F2 is designed to be $\Delta x/(\Delta p/p) = 25$ mm/%. In between F2 and F4, the beams have achromatic focus at F3, where two pairs of slit-jaws were prepared as cleaning slits to reject scattered particles with different trajectories from the main beams. The total length from the target to the catcher was 55 m.

In order to stop a desired isotope in the thin catcher, a plastic plate 2 mm thick, a set of variable energy wedge absorbers made of thick plastic was employed in the beam course to control the energy of the isotope before it was caught. To determine the half life of $^{21}$F nuclei, time spectra of $\beta$ rays from those nuclei stopped in the catcher were measured. For those measurements two sets of plastic scintillator counter telescopes were placed above and below the stopper. Two thin $\Delta$E-counters (1 mm thick each) and one thick E-counter (30 mm thick) were used in each telescope in order to reduce detection of background radiations. The E-counter was thick enough to stop the $\beta$ rays from $^{21}$F decay (maximum $\beta$-ray energy is 5.7 MeV). The beam pulse gating method was used to separate counting periods of $\beta$ rays from production periods of the nuclei. For the case of $^{21}$F, 3 ordinary beam spills (4 sec apart) of the Bevalac were used for production, followed by a 45-sec period of counting $\beta$ rays. Beam pulse gating was controlled through gating the rf oscillator of the Bevatron. The half life of $^{21}$F was measured by multi-scaling the pulses for the $\beta$ detectors. The initial counting rate of the $\beta$ particles was as many as 2000 c/sec.

## 3. Results and Discussions

The present result of $^{21}$F $\beta$ decay is shown in Fig. 2. The time spectrum was fitted to a decay function consisting of two exponential decays and a constant background. The minority group among the decaying components was identified as $^{20}$F, which was produced through nuclear reactions between the separated isotope beams and the energy absorber placed in front of the stopper. The decay constant for $^{20}$F in the spectrum was chosen in the analyses to be $T_{1/2} = (11.03 \pm 0.06)$ sec, also shown in Fig. 2, which was measured in the next lifetime measurement on $^{20}$F and was consistent with known data.

The deduced half life of $^{21}$F was $(4.21 \pm 0.03)$ sec. The previous values reported for $^{21}$F half life were $(4.21 \pm 0.05)$ sec,[9] $(4.34 \pm 0.04)$ sec,[10] and $(4.158 \pm 0.020)$ sec.[11] These values are consistent within the errors, except for the one in Ref. 10 in which the uncertainties for the results were considered to be underestimated as discussed in Ref. 11.

In summary the present on-line separator has been successfully used for determination of lifetime of a $\beta$-radioactive nucleus. In the near future, the apparatus will be used for magnetic moment measurements of $\beta$-radioactive nuclei in the f-shell.[7] For these experiments, an NMR technique applicable to $\beta$-radioactive nuclei will be combined with the separator. This will surely open up new applications of the technique to much wider varieties of studies using $\beta$-radioactive nuclei produced through relativistic heavy-ion reactions.

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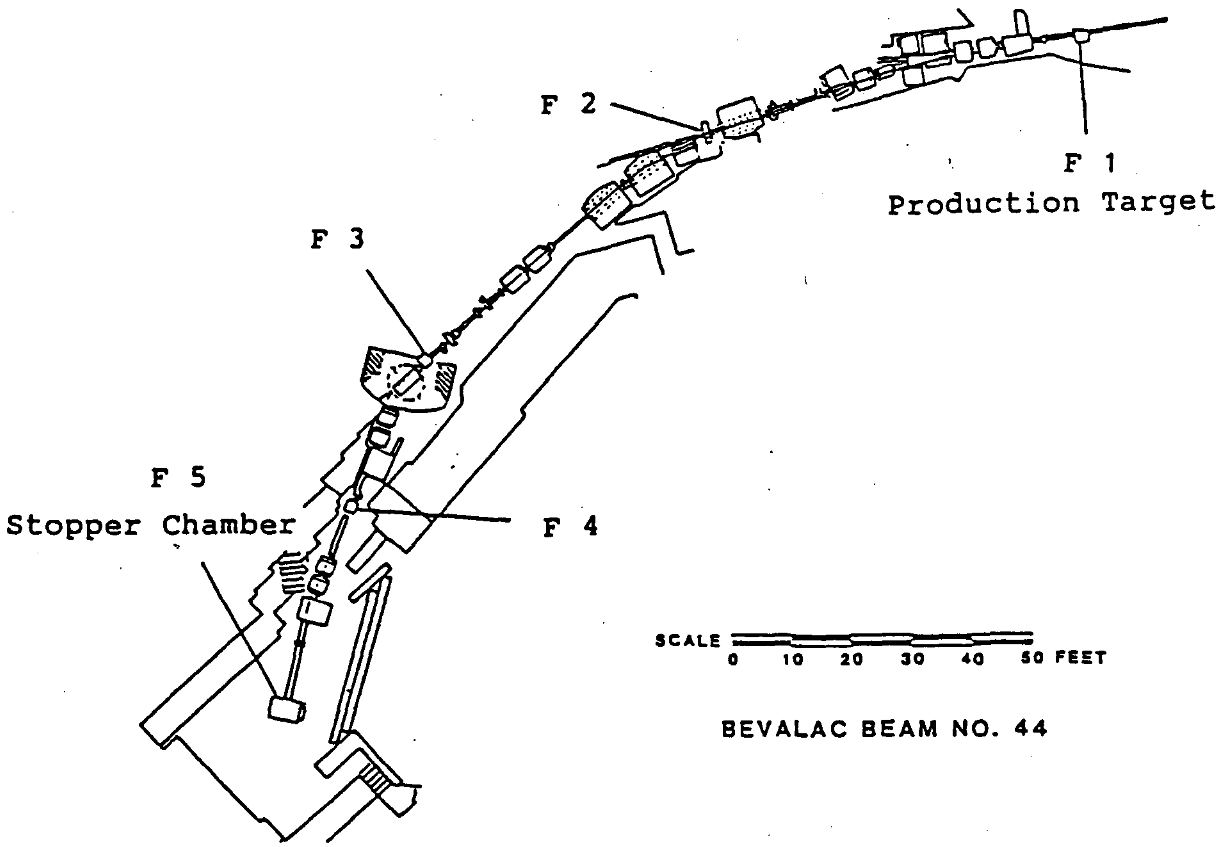


Fig. 1. Beam transport system in Beam 44 at the Bevalac.

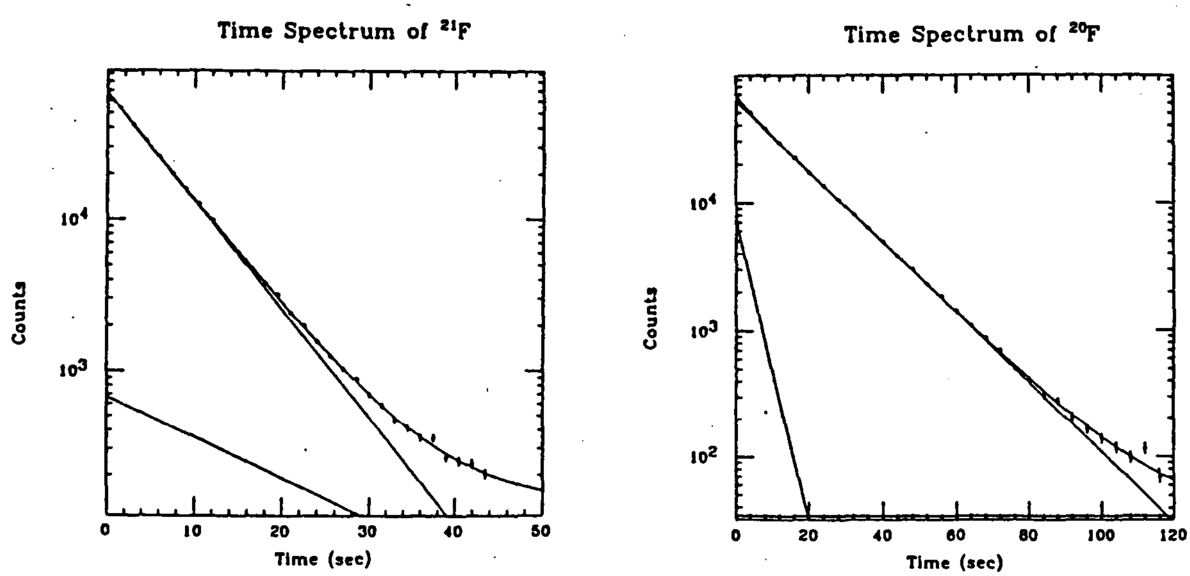


Fig. 2. Typical $\beta$-ray time spectra of $^{21}F$ and $^{20}F$. The theoretical lines best fitted to the data consist of 3 components that are also separately shown, respectively.

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