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RAPID COMMUNICATIONS

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Production of an isomeric, excited radioactive nuclear beam

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A momentum-analyzed, isomeric, radioactive $^{18}F^m$ beam ($E_x = 1.12$ MeV, $T_{1/2} = 163$ ns) has been produced with the reaction $^{12}C(^{17}O, ^{18}F^m)^{11}B$ at $E(^{17}O) = 70$ MeV. The $^{18}F^m$ ions were focused onto a secondary target using a compact superconducting solenoid lens and scattering of $^{18}F^m$ from Au and carbon targets was observed. A conversion efficiency of $> 10^3$ $^{18}F^m$/s per 100 particle nanoamps of ^{17}O was obtained using a 1.1 mg/cm^2 natural carbon production target.

One of the goals of the many projects underway[1-3] to produce usable radioactive nuclear beams (RNB) is the production of isomeric excited beams. Such beams would permit measurements of elastic and inelastic scattering of a nucleus in an excited state. One could study new phenomena such as "superelastic" scattering, viz., inelastic scattering with positive Q value, such as Coulomb deexcitation, with an acceleration of the projectile.[3] Since isomeric nuclei also can have high spins ($J > 4$) as well as internal excitation, one can study nuclear reactions under new conditions of angular momentum and energy transfers. As an example, the effect of a strongly-coupled positive Q-value channel on near-barrier and subbarrier fusion should be very large. However, few practical methods for producing high-intensity ($> 10^3$/s) isomeric RNB have been demonstrated to date. In this Rapid Communication we report the production of a high-spin isomeric RNB with the direct-transfer method, utilizing a heavy-ion reaction which preferentially forms such radioactive nuclei.

Isomeric states of nuclei are often members of a multiplet of levels of the form $(j_1 \otimes j_2)_J$, where j_1 and j_2 are single-nucleon orbits. The lowest energy levels are usually those with the most coplanar orbits, e.g., with minimum ($\equiv J^{\min}$) or maximum ($\equiv J^{\max}$) angular momentum. Often the $J^{\max}$ level lies just above or below the $J^{\min}$ level which leads to nuclear isomerism. When $J^{\max}$ is the isomeric state and $J^{\min}$ is the ground state one can *preferentially* form the $J^{\max}$ level while suppressing the population of $J^{\min}$ and other low-spin levels by selecting suitable heavy-ion direct-transfer reactions. Thus,[4] the isomer $^{18}F^m(J^\pi = 5^+$, $E_x = 1.1$ MeV, $T_{1/2} = 163$ ns) has the "stretched" configuration $(d^p_{5/2} \otimes d^n_{5/2})_{5^+}$ and can be preferentially formed[5,6] using the reactions $^{16}O(\alpha,d)$, $^{16}O(^{12}C,^{10}B)$ or $^{16}O(^{11}B,^9Be)$. However, these are two-nucleon transfer reactions with modest cross sections of about ~ 1 mb/sr at forward angles. In addition, ^{10}B has low-lying states at 0.72 and 1.74 MeV that can overlap with the ^{18}F ejectile spectrum (Fig. 1). Single-nucleon transfer reactions such as $^{17}O(\alpha,t)$ and $^{17}O(^{12}C,^{11}B)$ or the inverse, $^{12}C(^{17}O,^{18}F)^{11}B$ generally have higher cross sections. The former requires a ^{4}He production target and hence is limited to high incident energies where gas cells can be employed. The latter reaction, in contrast, allows the use of a high-intensity beam and a robust target and is particularly well suited as a production reaction,

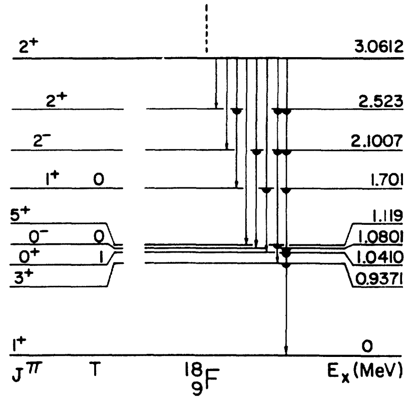

FIG. 1. Low-lying energy levels of ^{18}F (Ref. 4).

even at beam energies below 100 MeV, since the $^{18}F^m$ $J^\pi=5^+$ level is known to be preferentially populated with cross sections ≥ 10 mb/sr at forward angles.[6] Also, the reverse kinematics leads to large solid-angle factors and hence copious production of $^{18}F^m$ at $\theta_{lab}<20°$. We thus employed the $^{12}C(^{17}O,^{18}F^m)^{11}B$ reaction as the primary production reaction.

The ^{17}O beam was produced at the FN tandem facility at the University of Notre Dame using a negative Cs ion sputter source with an enriched $Ti^{17}O_2$ cathode. This produced ≥ 2 particle μA of $^{17}O^-$ ions, which were then accelerated to $E(^{17}O)=50$–80 MeV. The resulting ^{17}O beam intensity was limited to 100 particle nA by the charge-state distributions and transmission through the accelerator at the terminal voltage of 8.7 MV. The $^{12}C(^{17}O,^{18}F^m)$ cross section was measured as a function of $E(^{17}O)$ at several forward angles using two ΔE-E Si counter telescopes. Figure 2 shows an ^{18}F spectrum at $E(^{17}O)=70$ MeV, where the most intense group is identified to be primarily $^{18}F^m$. The well-known Q-window effect in heavy-ion reactions[7] causes the cross section for $^{18}F^m$ to rise rapidly with increasing incident ^{17}O energy, while the ground state (g.s.) and other low-spin levels of ^{18}F are still suppressed due to their negative Q values. At 70 MeV and $\theta_{lab}=7°$, we measured a laboratory cross section of 14 ± 2 mb/sr for $^{18}F^m$ production.

The $^{18}F^m$ ions are momentum analyzed and focused onto a secondary target using a compact superconducting solenoid[8–11] having a short flight path of 2.1 m during which time approximately 40% of the $^{18}F^m$ nuclei decay. The decayed $^{18}F^m$ then form a beam contamination of $^{18}F_{g.s.}$. The yield and focusing of the $^{18}F^m$ RNB was verified by observing, with a Ge detector, the γ rays ($E_\gamma=182$ and 937 keV) which accompany the isomeric decay of $^{18}F^m$ when stopped in a thin Ta foil placed behind the secondary target position. A small collimator (2 cm diam) placed well ahead of the secondary target ensures that only focused ^{18}F ions strike the secondary target. The Ge detector was shielded from the collimator (and production target) by Pb bricks. In addition, scattering from thin Au (0.86 mg/cm^2) and ^{nat}C(0.59 mg/cm^2) secondary targets was observed at $\theta=20°$–$40°$ using an xy position-sensitive ΔE-E Si detector telescope.[8]

The production of focused $^{18}F^m$ ions as a function of various solenoid magnet focusing currents is displayed in Fig. 3. The background γ lines, which arise primarily from (n,γ) reactions from fast neutrons produced at the production target and beam stop, exhibit no systematic change with focusing current, whereas the two γ lines from $^{18}F^m$ exhibit a maximum near the magnet current expected for focusing $^{18}F^m(q=8^+)$ at the secondary target. Also, unlike the background γ lines, the $^{18}F^m$ isomeric-decay γ lines are absent when the production target is removed. Using the measured Ge γ detector efficiency and the known geometry, we deduce a production rate of 1000 ± 200 $^{18}F^m$/s for a primary $^{17}O^{7+}$ beam of 350 na (50 particle nA) and a 1.1 mg/cm^2 ^{nat}C production target.

The spectrum of $^{18}F^m$ scattered from Au at $\theta_{lab}=20°$, near the optimal current for focusing $^{18}F^m$ at the secon-

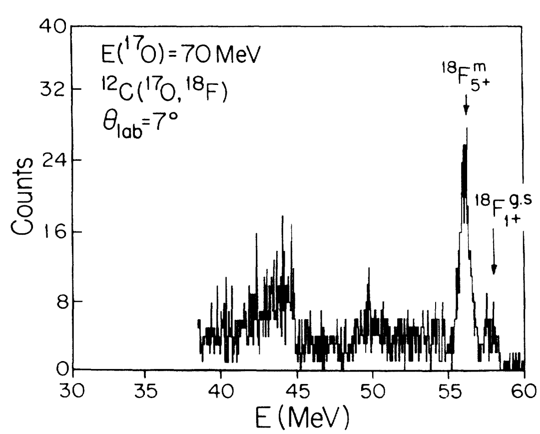

FIG. 2. The ^{18}F production spectrum observed for the $^{12}C(^{17}O,^{18}F)^{11}B$ reaction at $E(^{17}O)=70$ MeV using a 0.1 mg/cm^2 carbon target.

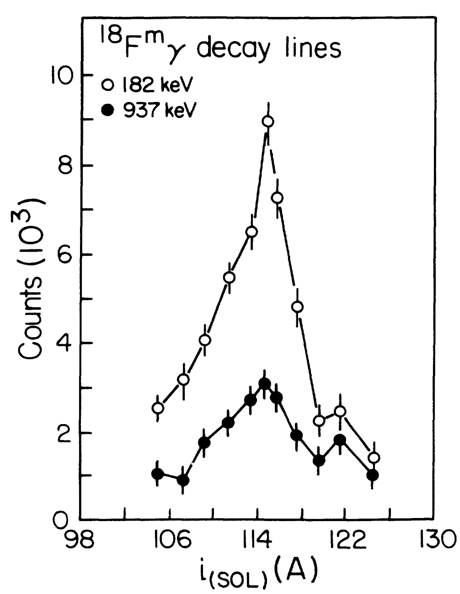

FIG. 3. The $^{18}F^m\gamma$-ray peak intensities at 182 and 937 keV observed in a Ge detector as a function of solenoid magnet focusing current. Data points are connected to guide the eye.

dary target position, is shown in Fig. 4. Although the beam is not entirely $^{18}F^m$ ($\approx 50\%$ due to decay of $^{18}F^m$ in flight and other unresolved nonisomeric ^{18}F states produced) the spectrum demonstrates the feasibility of scattering and reaction studies using isomeric, excited nuclei. The yield of scattered $^{18}F^m$ on Au at $\theta_{lab}=20°$ and 40° is consistent with the $^{18}F^m$ production rate deduced from the γ-ray measurements, assuming Rutherford scattering from the Au target. The existing forward-angle spectra from Au (e.g., Fig. 4) and carbon do not exhibit any anomously large ($>50\%$) positive Q-value superelastic peaks relative to the main $^{18}F^m$ group. However, better energy resolution, obtained, for example, using dispersion-matching energy-loss spectroscopy will be needed to study such phenomenon in detail. Other reactions involving $^{18}F^m$ can be uniquely identified by the extra 1.1 MeV positive Q values or in the case of the elastic scattering and inelastic target excitation, observing the $^{18}F^m$ decay γ rays in fast coincidence (<200 ns) with the $^{18}F^m$ stopped in a Si ΔE-E or other detector.

In the near future, the tandem accelerator will be modified to permit double stripping of the injected ^{17}O beam and improved transmission. This, together with the use of an existing rotating production target mechanism, should result in a primary beam of ≥ 1 particle μA and hence a $^{18}F^m$ RNB of $\geq 10^4$/s.

The method described here should also be applicable to the production of various J^{max}-type isomeric RNB using heavy-ion production reactions, such as $^{18}F^m(5^+)$, $^{19}F^m(\frac{5}{2}^+)$, $^{34}Cl^m(3^+)$, $^{38}Cl^m(5^-)$, $^{42}Sc^m(7^+)$, $^{43}K^m(\frac{7}{2}^-)$ and other, heavier isomeric nuclei including fission shape isomers.

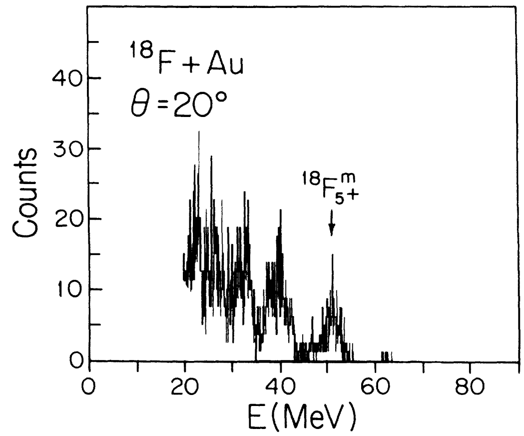

FIG. 4. Spectrum of focused secondary ^{18}F ions scattered from a 0.86 mg/cm^2 Au target. The group identified as primarily $^{18}F^m$ ($J^\pi=5^+$), $q=8^+$ ions is indicated (see text). The other groups below $E=50$ MeV are ^{18}F ions in lower charge states.

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