INTRODUCTION

A cold cloud of rare atoms is desirable in several fields. High-resolution spectroscopy of poorly-known atomic levels and tests of the Standard Model in atomic systems are examples of studies pursued in laboratories around the world [1]. Francium is particularly suitable because it is the heaviest alkali metal and it has several isotopes with relatively long lifetimes. Also, one expects enhanced parity-violating effects and reduced theoretical uncertainties from isotope comparisons. By accumulating atoms in a trap, one partially compensates for their scarcity. Our group and the one at SUNY Stony Brook, who pioneered the field [2], are focusing on the isotopes with mass numbers in the range 208–211. A production target, a beam transport line and a magneto-optical trap (MOT) are operating at INFN’s National Laboratories in Legnaro. An overview of our work is given in Refs. [3, 4]. Here we summarize the performance of the Fr sources.

PRODUCTION METHOD

We produce francium in the mass range 208 ≤ A ≤ 211 via fusion of 18O and 197Au and successive evaporation of neutrons from the compound nucleus: 197Au(18O, kn)215–218Fr. Gold is chosen for several reasons. It is monoisotopic and chemically inert. Its melting point (1337 K) is relatively low, so that diffusion of nuclei produced inside the target can be greatly enhanced by heating it to about 1200 K without damage. Moreover, the work function of gold (5.1 eV) is higher than francium’s first ionization energy (4.07 eV). According to Langmuir’s surface-ionization efficiency, practically all Fr released from the gold surface is in ionic form and can be accelerated and injected into the secondary beam line for transport to the trap cell.

The observed yield $Y$ depends on the fusion-evaporation production rate $P$ and on the combined efficiency $\varepsilon$ of the following processes: diffusion in the target bulk, surface desorption, surface ionization, and transport to a catcher foil where the ions are detected: $Y = \varepsilon P$. Table I gives our calculation of the expected production rates for some francium nuclei as a function of oxygen beam energy $E_0$, for an incident flux $j = 10^{12}$ particles/s, based upon cross sections measured in Ref. [5]. The theoretical uncertainty on these estimates is approximately 20%.

The maximum yield does not necessarily correspond to the maximum production rate. Higher bombarding energies exploit a larger fraction of the excitation curve, but production takes place deeper inside the target bulk. Temperature strongly influences the diffusion process, as well as surface desorption and ionization. Optimal operating conditions are to be found experimentally. Nonetheless, the above estimates provide upper limits on the attainable yields.

MEASUREMENTS OF PRODUCTION YIELD

We have performed experiments with several targets at different energies, fluxes, and temperatures. The target design and the experimental setup are described in detail in Ref. [4].

The production yield is measured by identifying the $\alpha$ decays of francium. A retractable aluminum catcher foil intercepts the ion beam 555 mm downstream of the target. The catcher’s normal forms an angle of 135° with the beam direction. A silicon surface-barrier detector (SSBD) is used to detect $\alpha$ particles from francium nuclei implanted on the catcher’s surface. The $\alpha$ particles from 208Fr and 209Fr have an energy difference of 5 keV and cannot be resolved by our system. The same is true for 210Fr and 211Fr, with an energy difference of 9 keV.

### Table I: Calculated francium production rates, for $j = 10^{12}$ particles/s.

<table>
<thead>
<tr>
<th>Energy $E_0$ (MeV)</th>
<th>Production rate $P$, Hz</th>
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<tbody>
<tr>
<td>86</td>
<td>7.6 × 10$^3$ 3.8 × 10$^5$ 8.9 × 10$^5$</td>
</tr>
<tr>
<td>94</td>
<td>1.8 × 10$^6$ 1.2 × 10$^5$ 2.9 × 10$^5$ 1.2 × 10$^6$</td>
</tr>
<tr>
<td>102</td>
<td>3.1 × 10$^3$ 1.5 × 10$^5$ 4.3 × 10$^5$ 1.2 × 10$^6$</td>
</tr>
<tr>
<td>110</td>
<td>2.3 × 10$^5$ 2.9 × 10$^6$ 4.4 × 10$^6$ 1.2 × 10$^6$</td>
</tr>
<tr>
<td>118</td>
<td>1.8 × 10$^6$ 3.2 × 10$^6$ 4.4 × 10$^6$ 1.2 × 10$^6$</td>
</tr>
</tbody>
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The francium yield $Y$ of each isotope is proportional to the observed steady-state event rate $S$ after correcting for the $\alpha$ decay fraction $f$ and for the geometric acceptance $a$ of the SSBD: $Y = S / (f \cdot a)$. The decay fractions of 208Fr and 209Fr are almost equal. Moreover, the 208Fr production rate is expected to be negligible at low energies. The total yield can therefore be measured directly: $Y_{208} + Y_{209} = (S_{208} + S_{209}) / (f_{209} \cdot a)$. We are also interested in estimating the yield of 210Fr. For this, decay fractions $f_{210} = 0.6$ and $f_{211} = 0.9$ are assumed. We also rely on the relative production rates $P$ calculated above, under the hypothesis that the release efficiencies of 210Fr and 211Fr are the same: $Y_{210} = P_{210} \cdot (S_{208} + S_{209}) / [(f_{210} \cdot P_{210} + f_{211} \cdot P_{211}) \cdot a]$. Due to these assumptions, this measurement has a larger systematic uncertainty.

In Figure 1 the measured normalized yields $(Y_{208} + Y_{209}) / j$ and $Y_{210} / j$ are plotted as a function of primary beam energy and compared with production estimates $(P_{208} + P_{209}) / j$ and $P_{210} / j$. From the 208,209Fr data, one can see that the yields are lower than the expected rates by a factor that does not depend appreciably on beam energy. This is an indication that there is a negligible difference in the diffusion of the four isotopes. In this energy range, the variations in production depth are comparable with the depth differences among isotopes. Therefore, the diffusion process appears to be efficient. We deduce that the average extraction efficiency $\varepsilon \equiv (Y_{208} + Y_{209}) / (P_{208} + P_{209})$ is $(15 \pm 9)\%$ above 1200 K. Similar values are obtained for $Y_{210} / P_{210}$.

More information on the efficiency of the diffusion process comes from the study of the relative intensity of the observed 208,209Fr peak with respect to 210,211Fr. In this isotope ratio, the atomic and ionic features of production (surface desorption and ionization, transport) should cancel out. In fact, we do not observe any dependence of the isotope ratio on target temperature or voltage. We find that the ratio of expected production rates as a function of beam energy reproduces the data, indicating that the diffusion time of the four isotopes is short compared to their lifetime, at least over distances of the order of the difference in production depth.

The oxygen beam energy is deposited locally on the gold surface, on a volume that is approximately 2 mm in diameter and 30 $\mu$m deep. If the heater is properly calibrated, local melting is observed, which yields maximum Fr production for a few hours without damaging the target. Under these conditions, the extraction efficiency can reach 40%. However, most of the time we have operated in a safer regime. In our experience, the target can be used for several days at 1200 K before a replacement is required.

The yield is proportional to the beam flux up to $j = 1 \times 10^{12}$ Hz. At higher fluxes, there appears to be a systematic increase in the slope, possibly due to beam-induced local melting. On the other hand, looking at bulk temperature and lower fluxes ($j \leq 10^{12}$ Hz) in the same energy range, the yield shows a sharp increase above 1100 K.

The primary beam power does not exceed 25 W. Therefore, the design of the source is kept simple and relatively inexpensive. Yields are reproducible within a factor of two, with a few targets being particularly good or bad. Possible reasons include mechanical and thermal nonuniformity, bulk or surface impurities, and primary beam features, but their contributions cannot be disentangled with the present setup.

References: