PRODUCTION AND TRANSPORT OF RADIOACTIVE FRANCIUM FOR MAGNETO-OPTICAL TRAPPING

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Abstract

The goal of our experiment is to collect alkali atoms in a magneto-optical trap (MOT) for high-precision spectroscopy and for the study of parity violation in atomic systems. We are focusing on francium isotopes, which are particularly suitable for these purposes. The production of francium is achieved by sending a 100-MeV ^{18}O beam from the Tandem-XTU accelerator on a thick gold target. The extraction of Fr^+ is enhanced by heating the target to 1200 K and by biasing it at $+3$ kV. The ions are transported to the magneto-optical trap (MOT) through an 8-m electrostatic beam line. The diagnostic systems for monitoring the beam intensity ($\sim 10^5$ ions/s) are based on silicon surface-barrier detectors sensitive to the α particles from Fr decays. Beams of stable Rb^+ can also be used for optimizing the transport and trapping processes. At injection into the MOT cell, the beam is neutralized and released in atomic form by a heated yttrium foil. Details on Fr production, transport and neutralization are presented.

INTRODUCTION

An innovative facility for the production and trapping of radioactive francium isotopes is operating at the INFN laboratories in Legnaro, Italy. The goal is to obtain a dense cloud of cold and possibly polarized radioactive atoms for a wide range of fundamental studies. Among them are high-resolution laser spectroscopy, α-decay asymmetries from deformed nuclei, and tests of the standard model at low transferred momenta. Francium is particularly interesting because it is the alkali metal with the highest atomic number and it has several radioactive isotopes with relatively long lifetimes (10^2–10^3 s). Reviews of this field can be found in Refs. [1, 2].

FRANCIUM PRODUCTION

The experimental setup is located in Hall II of the Tandem-XTU complex at INFN's laboratories in Legnaro, Italy.

^{18}O is accelerated to ~ 100 MeV by the Van-de-Graaff tandem accelerator. After the analyzing dipole, the beam can be adjusted with a quadrupole doublet and a steerer. Four movable tantalum scrapers define a window through which the beam has to pass before entering the target chamber, where its position and shape are visible through the fluorescence induced on a retractable quartz or Macor disk, positioned a few centimeters upstream of the target assembly.

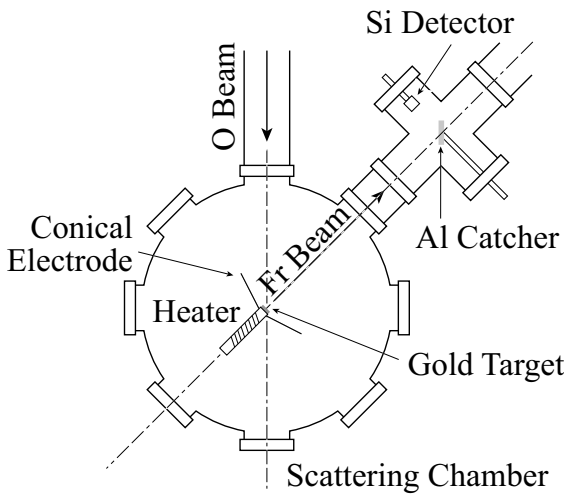

Figure 1: Schematic diagram of the target area.

The target itself is a 8-mm-diameter ^{197}Au disk with a thickness of about 2 mm. The gold is mechanically mounted on a 81-mm-long tungsten rod of the same diameter, which is kept at a potential of $+3$ kV. The beam impinges on the target surface at 45° with respect to the surface normal so that the extraction of the reaction products can be perpendicular to the surface itself (Fig. 1).

Francium nuclei are produced via the fusion-evaporation reaction

$$^{18}\mathrm{O} + {}^{197}\mathrm{Au} \rightarrow {}^{215-k}\mathrm{Fr} + k\mathrm{n}$$

within a target depth of about 10 μm. The kinetic energy of the projectile determines the average production depth. It also influences the relative and absolute yield of each isotope. An optimum for ^{210}Fr was found empirically around 102 MeV.

To facilitate the drift of Fr towards the gold surface, the target temperature is kept near the melting point of gold by means of a heater providing approximately 60 W

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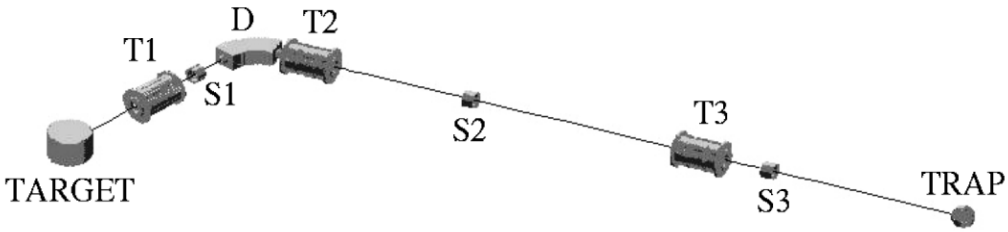

Figure 2: 3-keV francium beam line.

of power. The heater consists of a current-carrying wire wound around a cylindrical ceramic sleeve containing the support rod. The ceramic sleeve electrically insulates the heating wire from the target, and it is chosen to have a good thermal conductivity. The whole assembly lies inside a molibdenum heat shield. The temperature of the gold surface is monitored by an optical pyrometer. The pyrometer readings are calibrated with a thermocouple, which can be put in thermal contact with the gold when the high voltage is turned off.

Since the work function of Au (5.1 eV) exceeds the ionization energy of Fr (3.8 eV), the atoms that reach the surface are ionized and expelled by the positive potential. A conical extraction electrode fits on the gold end of the support rod, in electrical contact with it. Its outer diameter (68.7 mm) and half-aperture angle (75°) are designed to minimize the beam divergence and guarantee that all ions are collected, independent of where on the gold surface they are generated.

The production of francium is monitored by identifying its α decays, collected on a silicon surface-barrier detector. An aluminum catcher plate is inserted to intercept ion trajectories 60 cm downstream of the target; the detector is positioned so that it can see the exposed catcher surface.

Typical rates at the catcher are 0.7×10^6 (^{210}Fr ions)/s for a $^{18}O^{6+}$ beam flux of 10^{12} particles/s (corresponding to 1 μA), at a target temperature of 1200 K. Taking into account the energy loss of oxygen in gold and the Fr excitation functions recently measured with the PISOLO apparatus in Legnaro [3], one would expect a total production rate for ^{210}Fr of 3.4 MHz. There is a diffusion inefficiency intrinsic in this kind of target, since about half of the atoms produced in the bulk diffuse away from the gold surface. The remaining inefficiency ($\sim$60%) is a combination of diffusion time, chemical bonds with impurities, desorption from the surface and transport to the catcher.

BEAM TRANSPORT LINE

The main function of the beam line is to separate the MOT from the radioactive target area. It is also used to decouple the ultra-high-vacuum MOT region ($< 10^{-8}$ mbar) from the target chamber (10^{-7} –10^{-6} mbar). The arrangement of elements is partly constrained by the layout of the experimental hall.

The beam line contains a series of electrostatic bending and focusing elements (Fig. 2): three quadrupole triplets (T1, T2 and T3), one deflector (D), and three steerers (S1, S2 and S3). Besides its lower cost in the keV energy range, an electrostatic beam line is chosen so that stable Rb can be transported for tuning of the line itself and for tests of the trapping system. A drawback is that the thermionic current from the target ($\sim$ 10 nA) is also injected into the MOT cell, possibly degrading vacuum and contaminating the cell coating. For this reason we are planning to install a Wien filter for velocity selection.

The beam optics is designed with the aid of two computer programs: TRACE 3-D (within the PBO Lab environment) [4, 5], a beam dynamics software for envelope calculations based upon matrix multiplication; and SIMION 3D [6], which calculates potentials (relaxation method) and ion trajectories, starting from the electrode shapes defined on a discrete grid. The initial beam emittance and the Courant-Snyder α and β functions are calculated with SIMION. Ions are generated on the gold surface and their positions and velocities recorded after the acceleration stage, at the exit of the target chamber. The beam envelope is designed with TRACE 3-D; it is kept below a radius of 12 mm along the line; at the MOT, the calculated beam radius is 5 mm. SIMION is also used for optimizing the geometry and the fields of each electrostatic element.

Each quadrupole triplet consists of twelve cylindrical electrodes mounted on 4 Stesalit bars. Each group of 4 electrodes is separated from the next one by a round aluminum plate for better control of fringe fields. Electrode potentials range between 70 V and 150 V. In the deflector, two aluminum electrodes (68° bend, radius of curvature 315 mm and 345 mm, respectively), operating at $\pm$270 V, are housed in a case obtained from a single solid block of aluminum. The three steerers are used for orbit correction in the horizontal and vertical planes; each one of them consists of two pairs of parallel copper plates.

All beam-line elements were built at the machine shops of INFN in Legnaro and Ferrara. The line has been operational since June 2002.

DIAGNOSTICS

As in the case of the production yield, the presence of francium ions along the beam line is detected by identify-

ing its α decays, observed on 4 silicon surface-barrier detectors (SSBD) placed on movable supports. The first detector is the one used in conjunction with the catcher plate to measure production rates. Two other detectors are placed before and after the bend, respectively. A fourth SSBD is located just downstream of steerer S3 to monitor the ion flux into the MOT. We have so far obtained overall transmission efficiencies around 40%.

The beam profile can be probed by sliding the SSBDs across the beam and recording count rates as a function of position. This method indicates a transverse emittance close to the calculated value of 45π mm $\cdot$ mrad. These measurements are time consuming, due to the relatively long half-life of ^{210}Fr ($T_{1/2} = 191$ s).

Both the deflector's outer electrode and the neutralizer can be used as ion current monitors. The thermionic current from the target is used for rough tuning of the steering optics in the absence of a francium beam.

The line is set up so that rubidium ions can also be transported. A dispenser of a Rb natural-mixture is placed inside the target chamber; the release of atoms can be controlled with a power supply located in the MOT area. Atoms from the vapor which come into contact with the hot gold surface are ionized and accelerated to the same kinetic energy of francium. Rb^+ currents of 30 nA can be obtained. With this diagnostic tool one can set up some of the transport, neutralization and trapping parameters when the primary ^{18}O beam is not available.

BEAM NEUTRALIZATION

At the end of the beam line, the ions enter the MOT Pyrex cell. Inside they hit the neutralizer, which is designed to intercept the ion beam and to release Fr atoms. The neutralizer is a rectangular yttrium foil (11 mm by 9 mm, thickness 25 μm, work function 3.1 eV). On its short sides, the electrical contacts for heating (about 4 A at 0.5 V) are attached.

The neutralization and release efficiencies are measured with a dedicated setup. A test neutralizer is installed on the beam line between triplet T2 and triplet T3. The test neutralizer is irradiated with francium ions for a known amount of time. Its residual α activity is then measured. A large residual activity corresponds to large escape times, which describe the processes of bulk diffusion and release from the surface.

From these measurements, it is possible to determine the Fr escape times as a function of neutralizer temperature with good accuracy ($\sim$15%). Over a wide interval of temperatures, the escape times range between 10 s and 30 s, corresponding to a release efficiency $>$90% for ^{210}Fr. By biasing the neutralizer with positive and negative potentials the escape times are not affected, implying that Fr leaves the neutralizer in neutral form. With different techniques, the group at SUNY Stony Brook found similar results for stable rubidium [7] and for francium [8].

MAGNETO-OPTICAL TRAPPING

In the MOT cell, a siloxane coating reduces the adsorption coefficient of the cell walls. A fraction of the atoms is trapped by the combined cooling and confining action of twelve laser beams and a constant-gradient magnetic field. The basic principle of the magneto-optical trap is illustrated in Ref. [9].

Trap signals are still unstable and weaker than expected. Studies are under way to improve the laser trapping techniques, the cell coating and the light detection system [10].

CONCLUSIONS AND OUTLOOK

We have built a facility for the production of francium isotopes in the mass range 208–211 with typical intensities of 0.7×10^6 ions/s for ^{210}Fr. Fr ions are delivered to a magneto-optical cell, where they are neutralized and trapped. After completing the technological development, we plan to start our interdisciplinary physics program.

REFERENCES

[1] G. D. Sprouse and L. A. Orozco, Annu. Rev. Nucl. Part. Sci. **47**, 429 (1997).

[2] W. C. Haxton and C. E. Wieman, Annu. Rev. Nucl. Part. Sci. **51**, 261 (2001).

[3] L. Corradi et al., "Excitation functions for $^{208-211}$Fr produced in ^{18}O + ^{197} Au," submitted to Phys. Rev. A.

[4] K. R. Crandall and D. P. Rusthoi, TRACE 3-D Documentation, 3rd ed., Los Alamos National Laboratory Rep. LA-UR-97-886 (1997).

[5] G. H. Gillespie, PBO Lab 2.0 User Manual (Accelsoft Inc., San Diego, 1999).

[6] D. A. Dahl, SIMION 3D Version 6.0, 43rd ASMS Conference on Mass Spectrometry and Allied Topics, May 21–26 1995, Atlanta, Georgia, p. 717.

[7] J. A. Behr et al., Nucl. Instrum. Methods A **351**, 256 (1994).

[8] S. Aubin et al., Rev. Sci. Instrum. **74**, 4342 (2003).

[9] E. L. Raab et al., Phys. Rev. Lett. **59**, 2631 (1987).

[10] S. N. Atutov et al., Physica Scripta **T105**, 15 (2003); J. Opt. Soc. Am. B **20**, 953 (2003); Hyperfine Interact. **146**/**147**, 83 (2003).