ELSEVIER

A low-energy ion beam from alkali heavy-ion reaction products

J.A. Behr *, S.B. Cahn, S.B. Dutta, A. Ghosh, G. Gwinner, C.H. Holbrow [1],
L.A. Orozco, G.D. Sprouse, J. Urayama, F. Xu

Physics Department, State University of New York, Stony Brook, NY 11794-3800, USA

Abstract

We have tested and developed an ion beam apparatus for transporting alkali atoms made in heavy-ion reactions. Stopped recoils diffuse out of a hot thick target, are surface ionized, and extracted into a low-energy ion beam with efficiencies of approximately 20%. The ions are then neutralized for injection into a magneto-optic trap.

1. Introduction

It is often useful to separate the regions where a nuclear reaction takes place and where the products can be studied. In most experiments this is required to suppress radioactivity backgrounds. In our application we are mainly concerned with having high vacuum in the region of study where we utilize a magneto-optical trap (MOT) [1].

A MOT provides a source of atoms well-confined in phase space. It is therefore ideal for studies of small numbers of atoms using atomic techniques, such as the limited quantities of short-lived radioactive atoms that can be produced on-line at accelerators. It can also provide a cold sample of atoms that can be spin-aligned for beta decay experiments. Atoms with a cycling transition are easily trapped, so alkali atoms are ideal. Once captured, the mean time for atoms to remain trapped is determined by collisions with residual background gas, so the trap region must have good vacuum.

We have developed an apparatus to convert recoil alkali products from nuclear reaction into a low-energy ion beam. We then transport the alkalis as ions far from the target/accelerator region to a neutralizer which injects the alkalis as atoms into a magneto-optic trap. Success of this apparatus in trapping radioactive ^{79}Rb is reported in Ref. [2]; we will describe here the technical details of the ion transport system.

The device has been designed for the production of Fr isotopes. We have also tested it with radioactive Rb. We can sustain 1×10^5 ^{210}Fr/s and 7×10^4 ^{79}Rb/s in the form of an ion beam with energies variable from 10 to 300 eV. The lifetimes are limited by diffusion times in the target, which are ≤ 10 s.

We have made use of the well-known property of the low ionization potential of the heavier alkalis. Metals exist with work functions both higher and lower than these ionization potentials, making it straightforward to first ionize and then neutralize them on different surfaces [3].

2. Apparatus

The geometry is kept quite simple (see Fig 1.) For Fr production, a thick Au target is held at 45° to the direction of the ^{18}O beam from the Stony Brook superconducting linac. The Au target is supported by a 6 mm diameter tungsten cylindrical rod, heated indirectly by a tantalum-aluminum oxide coaxial heater [4]. We chose tungsten, despite fabrication difficulties, because we found that it did not alloy with gold (in contrast with tantalum and molybdenum). Recoils from the reaction ^{197}Au(^{18}O,xn)$^{215-x}$Fr stop in the thick target. The target is heated to $\approx 850°C$, close to its melting point (1063°), and the Fr diffuses to the surface.

Au was chosen for its relatively inert chemistry and lack of an oxide layer; our earlier experiments with Tl as a target failed to evolve Fr, possibly for this reason. Au also has a relatively high melting point compared to heavier targets in this mass region, so it can withstand larger beam currents. It is also, of course, monoisotopic. The ^{18}O projectile is light enough that fusion competes favorably with fission. Ta and W targets could also be used to make lighter Fr isotopes and should made suitable ionizers, but with the higher angular momentum carried in by the heavier projectiles needed, fission predominates over fusion.

* Corresponding author. Present address: TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3, Canada.

[1] Permanent address: Colgate University, Hamilton, New York, USA.

For radioactive Rb production, a 1.4 mg/cm² vanadium target was held 2 cm from the Au ionizer. The recoils that ranged out of the target were then stopped in the Au. Cu would be the chemically obvious choice for an ionizer to make Rb directly, but our attempts to extract Rb from Cu failed, possibly because of chemcial problems; also, the vapor pressure of Cu is an order of magnitude higher than that of Au at the temperatures of interest. The Fr recoils have low energy and thus a shorter range, so use of a thin foil and recoils into the ionizer would lose about a factor of 5 in atoms compared to direct production in the thick ionizer.

The range of the Fr recoils is only ≈ 1 mg/cm², so the Fr recoils are implanted in the Au at a maximum depth given by the range of the ^{18}O beam while the beam is above the Coulomb barrier, ≈ 30 mg/cm². We have solved the diffusion equation for the problem, using the Green's function for a point source implanted 30 mg/cm² into a semi-infinite slab and then using a series of 'image' sources to construct the proper boundary conditions for the target/ionizer, modeled as a thick slab. For the 500 mg/cm² thick Au target/ionizer used it is clear that the Fr escapes predominantly out the front of the ionizer and not the back.

The work function of Au is nominally 4.8–5.1 eV, higher than the ionization potentials of Fr and Rb (4.07 eV [5] and 4.177 eV, respectively). Thus the Fr and Rb should release from the Au surface as ions, depending on the cleanliness of the surface, and we find this to be qualitatively true. The resulting ions are then extracted into a low-energy beam with electrostatic potentials (Fig. 1). The apparatus uses commercially available prefabricated parts [6] with stainless steel electrodes supported on aluminum oxide insulators. Cylindrical symmetry of the fields at the ionizer is partially restored by the use of a tungsten mesh wrapped in a cylinder around the tip of the ionizer; this increases the ion transport efficiency by an order of magnitude. The target was elevated by between +8 and +300 V with respect to ground. The upper limit is determined by the isolation of the high-current heater supply and could be increased by use of an isolation transformer. Efficiency of transport of the ion system is not lost down to 8 eV beam energy. A series of einzel lenses and steerers then tranports the beam about 1 m away. Ion trajectories calculated using the Los Alamos POISSON package were used for the design. The target was assumed to have cylindrical symmetry; since various target geometries did not make large changes in the calculated trajectories, this approximation was adequate for planning purposes. The system is complex enough to allow several solutions; trajectories for the most efficient mode are shown in Fig. 1. A 1 cm aperture through which the beam is focussed provides vacuum isolation of the target and trap regions.

A rubidium dispenser [7], which evolves Rb from RbCrO₄ in a Zr–Al alloy getter host when heated directly by a current, is installed near the ionizer. When heated, Rb
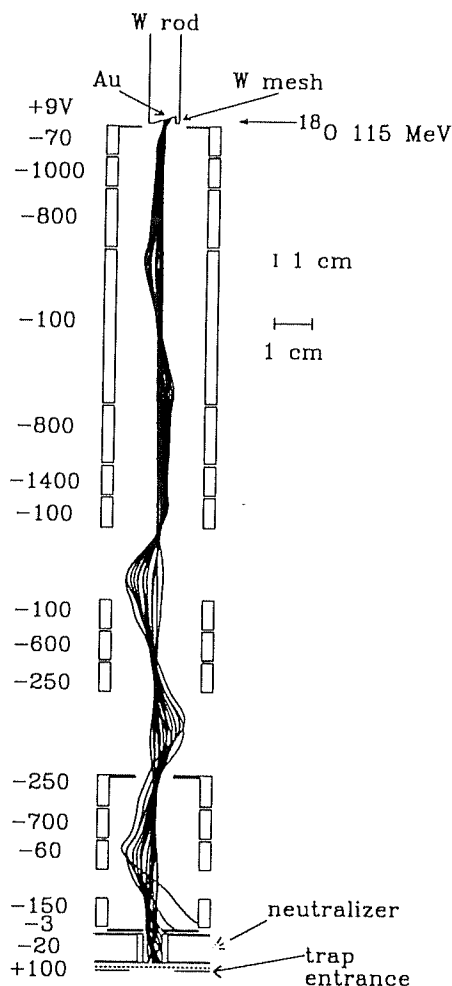

Fig. 1. Top view of Au target/ionizer, ion optics, and neutralizer, with ion trajectories from POISSON. Aspect ratio is $x : y = 3.4 : 1$.

is sprayed onto the ionizer; the resulting current of Rb ions can be read on the neutralizer electrode when it is cold, allowing initial tuneup of the system.

The neutralizer design is simple for ease of alignment. It is a cylinder of tantalum, lined by a thin Y foil, heated by a tantalum–aluminum oxide coaxial heater [4] to 700–1000°C. The beam is focussed through the neutralizer tube, and a deflector grid after the neutralizer returns ions to the far end. The idea is that the atoms should preferentially diffuse out of the neutralizer in the direction of the trap cell entrance. The neutral Rb atoms produced after the neutralizer are trapped in the magneto-optic trap, and the potentials near the neutralizer are tuned to optimize the number of trapped atoms.

The ion beam energy and the neutralizer negative potential were kept low to minimize the implantation depth in the neutralizer and thus the time to diffuse out. Escape times (i.e. diffusion convoluted with surface release times) were measured by the decay of resonant fluorescence of
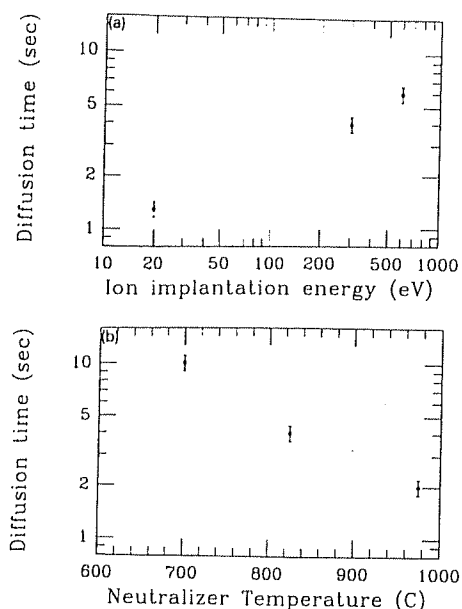
Fig. 2. Time for 1/3 of Rb in Y neutralizer to escape, as a function of: (a) ion implantation energy at $T = 800°C$; (b) temperature at ion implantation energy 300 eV.

the neutral Rb atomic beam leaving the neutralizer after the ion beam is turned off. Fig. 2 shows the dependence of the escape time on the ion beam implantation energy and the neutralizer temperature. These escape times are small compared to the half-lives of the Fr isotopes of interest.

The ion system before the 1 cm differential pumping aperture is pumped by a 60 l/s turbo, a Ti sublimation pump, and a LN_2 trap. A pressure of 4×10^{-8} Torr in this region can be sustained when open to the accelerator. The trap region after the 1 cm aperture is pumped by a 100 l/s ion pump and by a nonevaporable Zr-Al getter pump (1000 l/s for H_2) [7]; the result is $\approx 5 \times 10^{-10}$ Torr when isolated from the ion system and 4×10^{-9} Torr when open all the way to the accelerator.

3. Efficiency tests

Efficiencies for the production of Rb and Fr were measured in separate geometries. Initial tests were done by implanting a ^{85}Rb beam produced from the Stony Brook Tandem Van de Graff into the Au ionizer; the atomic beam produced after the neutralizer was measured by resonant fluorescence in the D_2 line. Production of Fr was tested by stopping the ion beam both in a catcher at the neutralizer position and also by placing a catcher after the neutralizer; the alpha activity of the Fr was then measured in a surface barrier detector. By appropriate biasing of the electrode after the neutralizer, the Fr evolved from the neutralizer tube was found to be > 90% neutral, in agreement with the similar scheme used by the Orsay group at

ISOLDE [3]. Rb radioactives were produced and similarly monitored with a Ge detector. We trapped ^{79}Rb in the MOT, and measured the number of atoms by their fluorescence.

The statistical model code CASCADE with a modified level density [8] was used to estimate the nuclear production in the target, and from this the efficiency of extraction of the reaction products was deduced. In all cases literature data for similar reactions were used to test the code's calculation of evaporation residues, and a conservative error of $\pm 50\%$ is in order.

We have made $^{209-211}$Fr with ^{18}O + ^{197}Au, using ^{18}O beam energies of 110–115 MeV. A catcher was placed at the neutralizer position and viewed with a silicon surface-barrier detector covered with a 2 mg/cm^2 Ni foil. A typical alpha spectrum is shown in Fig. 3. ^{209}Fr could be distinguished from ^{210}Fr and ^{211}Fr by the half-life and energy of the alpha activity. It was determined that $\approx 25\%$ of the Fr was ^{209}Fr, the rest ^{210}Fr and ^{211}Fr; this is consistent with the statistical model calculations. Data from the literature indicates that we could make $^{206-208}$Fr with a ^{16}O beam [9]. It would be useful to make ^{212}Fr, which has a 20 minute half-life, but we find negligibly small production of it. A thin ^{198}Pt isotopically enriched foil is a possibility for ^{212}Fr, using ^{19}F + ^{198}Pt as the reaction.

Fig. 4 shows the yield of Fr isotopes as a function of beam current, i.e. target temperature. With the beam off, the target was heated to 820°C. The factor of two increase in efficiency at the low beam currents can be attributed to an increased diffusion coefficient as a function of tempera-
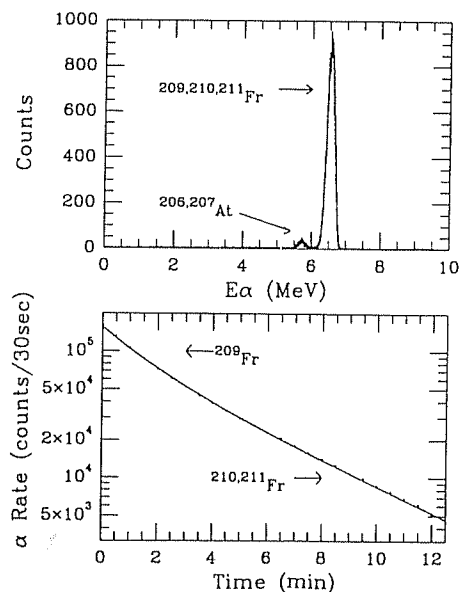

Fig. 3. Alpha-particle spectrum from Fr produced via 115 MeV ^{18}O + ^{197}Au, along with At daughter decay products. Decay curve after ion beam off; ^{209}Fr has $t_{1/2} = 50$ s, ^{210,211}Fr have $t_{1/2} = 3.2$ and 3.1 min.

ture as the beam heats the target. This is consistent with diffusion times for natural Rb in gold measured in tests with beams injected from the Stony Brook tandem. Above this beam current the yield is independent of target temperature over a wide range, indicating that diffusion times are much shorter than the 3 min half-life of ^{210}Fr and ^{211}Fr. The sudden rise in efficiency just before the melting and destruction of the target is unexplained, and is most likely a cleaning of the target resulting in improved ionization efficiency.

The highest sustainable production rate is 1×10^5 ^{210}Fr/s at the neutralizer. For 60 p-nA of ^{18}O beam and a calculated average production cross-section of 80 ± 40 mb, the production in the target is $1.0 \pm 0.5 \times 10^6$/s. Thus the sustainable efficiency of extraction into the useful ion beam is $10 \pm 5\%$. This efficiency increases to 40% just before the target melts, and it would obviously be useful to harness this.

To test the magneto-optic trapping of radioactives, we produced ^{79}Rb ($t_{1/2} = 23$ min) using the ^{51}V (^{31}P,2pn) and ^{51}V(^{32}S,2p2n) reactions, with beam energies of 90 MeV for ^{31}P and 145 MeV for ^{32}S. The V target was held 2 cm from the same Au target-ionizer used for the Fr production, and recoiling Rb isotopes stopped in the Au. A germanium detector looked at gamma-rays produced in the beta decay of isotopes collected at the neutralizer. An example of such a spectrum for the (^{31}P,2pn) reaction is shown in Fig. 5. The ^{31}P beam was on target for 45 min, allowing the ^{79}Rb and shorter-lived activities to reach equilibrium; the spectrum in Fig. 5 was accumulated for 5 min, immediately after the beam was turned off. All lines can be identified with ^{79}Rb and 5–10% as much ^{80}Rb, ^{78}Rb and ^{78}Rb^m, consistent with the CASCADE calculation. For the average calculated 80 ± 40 mb cross-section in the 1.4 mg/cm^2 V target, the 40 particle-nA of ^{31}P produced $3.6 \pm 1.8 \times 10^5$ ^{79}Rb/s in the target. The measured decay rate (together with the measured germanium detector efficiency) implied a production rate at the neu-
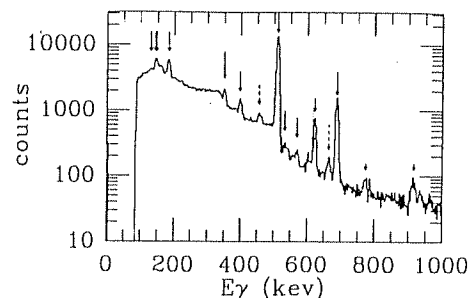
Fig. 5. Germanium detector gamma-ray spectrum of Rb isotopes produced via 90 MeV ^{31}P + ^{51}V. Solid arrows are ^{79}Rb, dashed ^{78}Rb and ^{78}Rb^m, dot ^{80}Rb.

tralizer of 7.1×10^4 ^{79}Rb/s. The resulting efficiency for extraction into the useful ion beam is $20 \pm 10\%$, a number not inconsistent with the Fr production.

The beam heats the vanadium target to $> 1200°$C, which makes a self-cleaning target. Approximately 50 μg/cm^2 per day of Au was deposited on the parts of the V target not heated by the beam; this would eventually stop the recoiling products. In principle, a sintered W ionizer would avoid the evaporation problems of Au, and still could be practically heated hot enough to yield short diffusion times.

4. Conclusion

The present design conservatively kept the neutralizer outside the trap cell to ensure good vacuum. The MOT cell is also coated with a non-stick Dryfilm coating which is known to be damaged by temperatures above 300°C [10]. Some neutral atoms are lost by diffusing back out the entrance end. A neutralizer design like that used by the Orsay group at ISOLDE Ref. [3] seals the entrance end by using an ionizing tantalum surface as the entrance; the thin tantalum is heated by direct current to maintain a potential gradient that confines the ions. They heat the Ta to 1300°C, presumably to insure a clean surface for good ionization efficiency; we have found similar high temperatures to be necessary in similar geometries with Mo ionizers; this may be incompatible with the MOT. We are exploring possibilities for moving the neutralization process entirely into the trap cell.

This device is essentially a separator for different ionization potentials with reasonably high efficiency of 10–20%. Only the alkalis heavier than Na, and possibly some alkali earths and rare earths, have ionization potentials low enough to ensure ionization by Au; all other elements have higher ionization potentials than the work function of Au, and so will not be surface ionized, as least not in a simple one-step process. The alpha spectra in the ^{18}O + Au reaction and the gamma-ray spectrum for the ^{31}P + V reaction show only the alkalis and their daughters formed by radioactivity; they are quite clean of beam-related radia-
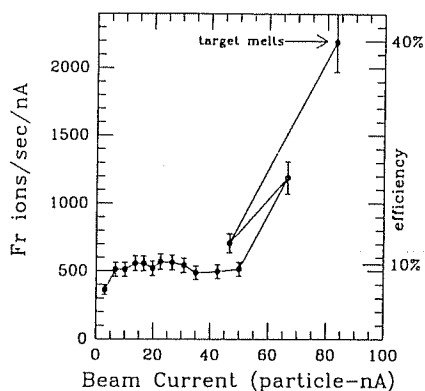
Fig. 4. Yield of Fr isotopes as a function of beam current. Line is time-ordering, so the point at 47 particle nA indicates sustainable improvement in efficiency after target partially melted.

tion. However, the heavy-ion reactions we have used specifically make the alkalis desired and very little else, so setting meaningful limits on, e.g., Sr ionization would require use of another reaction. Possible uses of this device include the study of nuclear decays of neutron-rich alkalis produced in fission reactions-depending on how close to the Au melting point the apparatus could be reliably run to produce short enough diffusion times.

Acknowledgements

References

[1] E.L. Raab, M. Prentiss, A. Cable, S. Chu and D.E. Pritchard, Phys. Rev. Lett. 59 (1987) 2631.

[2] G. Gwinner, J.A. Behr, S.B. Cahn, A. Ghosh, L.A. Orozco, G.D. Sprouse and F. Xu, Phys. Rev. Lett. 72 (1994) 3795.

[3] F. Touchard, J. Biderman, M. de Saint Simon, C. Thibault, G. Huber, M. Epherre and R. Klapisch, Nucl. Instr. and Meth. 186 (1981) 329.

[4] Temptron Engineering, Inc., 7823 Deering Ave., Canoga Park, CA 91304, (818) 346–4900.

[5] S.V. Andreev, V.I. Mishin and V.S. Letokhov, J. Opt. Soc. Am. B 5 (1988) 2190.

[6] eV parts, Kimball Physics Inc., Kimball Hill Road, Wilton, NH 03086–9742, (603) 878–1616.

[7] SAES Getters/USA Inc., Colorado Springs, CO, USA.

[8] F. Pühlhofer, Nuclear Physics A280 267 (1977); M. Kicińka-Habior, K.A. Snover, J.A. Behr, G. Feldman, C.A. Gossett and J.H. Gundlach, Phys. Rev. C 41 (1990) 2075.

[9] S. Baba, K. Hata, S. Ichikawa, T. Sekine, Y. Nagame, A. Yokoyama, M. Shoji, T. Saito, N. Takahashi, H. Baba and I. Fujiwara, Z. Phys. A 331 (1988) 53.

[10] D.R. Swenson and L.W. Anderson, Nucl. Instr. and Meth. B 29 (1988) 627.