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### An Orthotropic Source of Thermal Atoms

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## **An Orthotropic Source of Thermal Atoms**

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# AN ORTHOTROPIC SOURCE OF THERMAL ATOMS

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A highly efficient source that produces a narrow beam of neutral atoms at thermal velocity with small angular divergence is described. It uses a high work function interior surface to evaporate alkali atoms as ions and a low work function neutralizer, biased to collect the ions and evaporated them as neutral atoms. The neutralizer is located opposite an exit aperture so that the beam characteristics are determined by the geometry of the neutralizer and aperture. The orthotropic source is especially well suited for atomic clocks and for efficient loading of short lived radioactive alkali atoms into an optical trap.

## I. INTRODUCTION

We describe the principle, the operation of a prototype, and applications of an orthotropic source - a thermal source of neutral alkali atoms that emits all of the atoms in a narrow beam with small angular divergence (small emittance).

## II. PRINCIPLE OF OPERATION

A schematic of the orthotropic source is shown in Fig. 1. The interior surface is a high work function metal which, when hot, evaporates alkali atoms as positive ions. The ions are attracted to a negatively biased neutralizer located opposite the exit aperture. The neutralizer is a low work function metal (also hot) from which the ions re evaporate as neutral atoms. The neutral atoms must either leave through the exit aperture or strike the walls. If the atoms strike the walls they are again ionized and returned to the biased neutralizer. If they leave through the exit aperture, they form a beam whose size and divergence is defined solely by the geometry of the neutralizer and aperture.

Since the orthotropic source requires that the atoms be ionized on the walls, its use is generally limited to atoms that can be efficiently surface ionized (an important exception is discussed later). Platinum has a work function<sup>1</sup> of 5.65 eV, which will efficiently ionize all of the alkalis, Ba, Ra, Ac and a few lanthanides. Tungsten oxide has an even higher work function and has been used to efficiently ionize thallium<sup>2</sup> (ionization potential 6.1 eV). There are many elements with low work functions that may be used as neutralizing collectors. Yttrium has a work function of 3.4 eV, a melting point of 1800 °C and good mechanical properties.

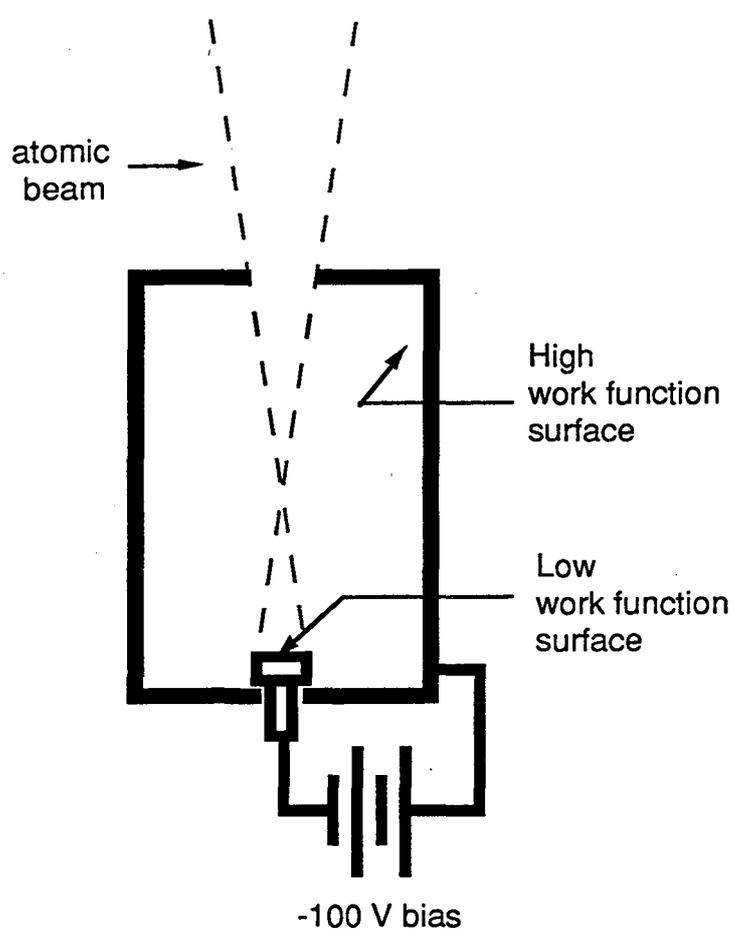


Fig. 1. Schematic of an orthotropic source. The interior surface is a high work function metal except for a neutralizer made from a low work function metal. The neutralizer is electrically insulated and at a negative potential with respect to the walls. A source of this design and scale is used for tests described in this paper. The interior cavity is 2.5 cm long by 1.9 cm dia., and the overall size is a 3.8 cm cube. A small aspect ratio is used to ensure that the electric field from the neutralizer penetrates the full volume. The source is heated by passing current through 0.05 cm dia. Ta wires threaded through insulators placed in cavities in the source body. The temperature is monitored by chromel-alumel thermocouples also placed in cavities in the source body. The orthotropic source is loaded by removing a tapered cap that fit flush on the bottom. The neutralizer is also attached to this cap.

### III. PROTOTYPE ORTHOTROPIC SOURCE

#### A. design and measurement technique

To test the principle of the orthotropic source we built a prototype to the same scale as shown in Fig 1. It has a 0.48 cm dia exit aperture, a 0.28 cm dia neutralizer and a neutralizer to exit aperture distance of 2.3 cm, to produce a beam with an expected 150 mR divergence. The body is made from stainless steel with platinum sputtered on the inside surfaces. The neutralizer is made of yttrium and rests slightly above the rear surface of the source on an aluminum oxide spacer. The source can be heated to a maximum of 950 °C. Its temperature was limited by size of the heating elements.

The orthotropic source was tested using francium. We obtained  $^{221}\text{Fr}$  ( $t_{1/2} = 5$  m), continuously from the alpha decay of  $^{225}\text{Ac}$ , which was prepared by electrostatic collection of  $^{225}\text{Ra}$  recoils<sup>3</sup> from a thin  $^{229}\text{Th}$  ( $t_{1/2} = 7300\text{Y}$ ) source<sup>4</sup>.  $^{225}\text{Ra}$  beta decays ( $t_{1/2} = 15\text{d}$ ) to  $^{225}\text{Ac}$  ( $t_{1/2} = 10$  d). The Ra/Ac source was collected on a nickel foil disk. The disk, which had a hole in its center, was mounted in the rear of the orthotropic source surrounding the neutralizer assembly. The Ra/Ac source, as used in our measurement, produced approximately  $10^4$  Fr atoms/s with the combined Ra/Ac half lives.

Francium atoms, emitted from the orthotropic source, were collected on metal catchers located 10 cm from the output aperture. The 6.36 MeV alpha from the decay of the  $^{221}\text{Fr}$  along with the subsequent 7.07 MeV alpha from the ( $t_{1/2} = 32$  ms) decay from  $^{217}\text{At}$  were counted for 100 seconds. Corrections were applied for the francium lifetime and francium collection time. The 6.36 MeV and 7.07 MeV alphas are completely resolved from the 5.75 MeV alpha from  $^{225}\text{Ac}$ , (the 4.86 MeV alpha from  $^{229}\text{Th}$ ) and the alphas from all of the  $^{217}\text{At}$  daughters.

#### B. angular distribution

To measure the angular distribution shown in Fig. 2, the orthotropic source was heated to 750 °C and the emitted francium atoms allowed to accumulate on the catcher for 45 minutes. The collected francium decays  $^{221}\text{Fr} \rightarrow ^{217}\text{At} \rightarrow ^{213}\text{Bi}$ , the latter having a 45 minute half-life which allows a large buildup of bismuth. After the 45 minute collection period the orthotropic source was turned off and the apparatus allowed to cool. The  $^{213}\text{Bi}$  atoms were detected by the 8.38 MeV alpha from the decay of  $^{213}\text{Po}$  ( $t_{1/2} = 160$  us) following the beta decay of  $^{213}\text{Bi}$ . The catcher was stepped over the collimated surface barrier detector.

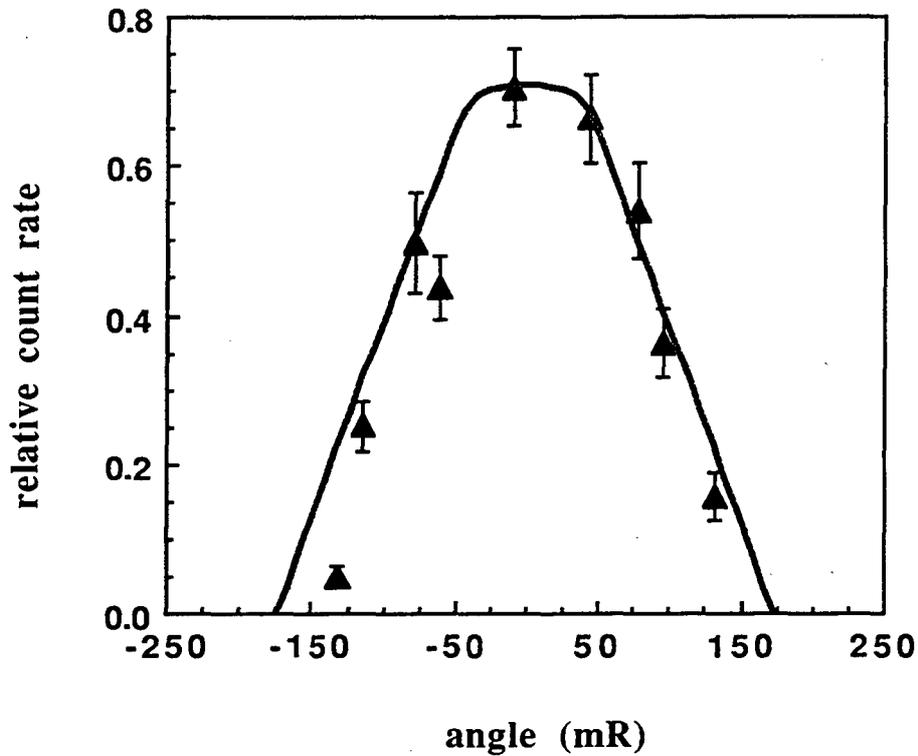


Fig. 2 Angular distribution of francium atoms from a 150 mR orthotropic source. The solid line is an overlay of the expected angular distribution based upon the dimensions of the orthotropic source.

Fig. 2 demonstrates that a low divergence francium beam is emerging from the orthotropic source. A comparison between the orthotropic source, a channeled source of similar dimensions, and an effusive source is shown in Fig. 3. Utilization of the atoms by this 150 mR orthotropic source is a factor of 10 more efficient than for a channeled source and a factor of 100 more efficient than for an effusive source. Since the efficiency scales inversely as the square of the divergence angle, we expect to realize tremendous gains in a source with a far smaller divergence.

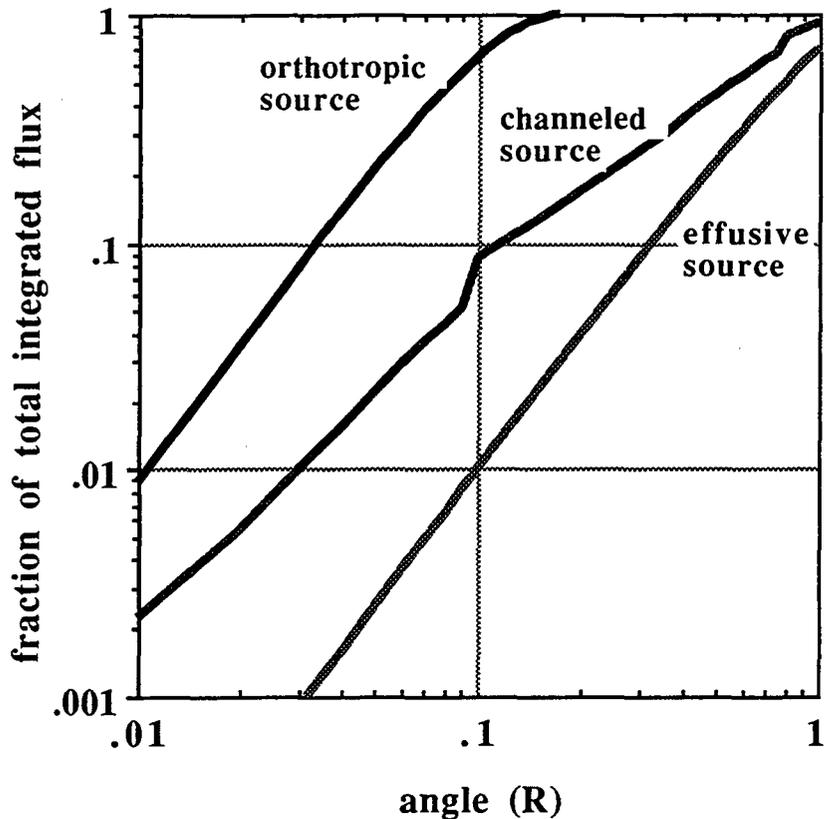


Fig. 3 Normalized integrated angular flux versus angle calculated for our prototype orthotropic source, a channeled source of similar dimensions and an effusive source. An orthotropic source can be designed to put all of its flux into a smaller solid angle than does our prototype. For details see below.

### C. flux measurement

The total flux of neutral atoms was calculated by measuring the flux in the central peak (as a function of temperature) and combining it with the angular distribution measurements. A catcher accumulated francium atoms for 60 s, was rotated away from the orthotropic source to cool for 60 s, and then rotated to face a collimated surface barrier detector which counted alpha particles from the decay of the francium atoms.

For each francium collection we measured the activity on the catcher at its center and verified the angular distribution by also measuring the activity at a single position corresponding to an angular divergence of  $>150$  mR. (The  $^{221}\text{Fr}$  half-life is too short to permit a complete scan for each data point.) At all temperatures no francium was seen beyond 150 mR. The experiment was repeated with both positive and negative bias on the catcher with identical results, indicating that the beam is entirely neutral. We also applied a positive bias to the yttrium neutralizing collector to prevent ions from evaporating from the oven walls, and under these conditions no flux was seen.

The measured central flux is shown in Fig. 4. It can be seen that the flux is still increasing rapidly with temperature at 950 °C indicating that our prototype orthotropic source is below the optimal temperature. Combining the data in Fig. 4 with the angular distribution data of Fig. 2 we find that at 950 °C, about 15% of the all the francium atoms generated in the orthotropic source were emitted in steady state operation. A far larger flux should be available with higher temperature design.

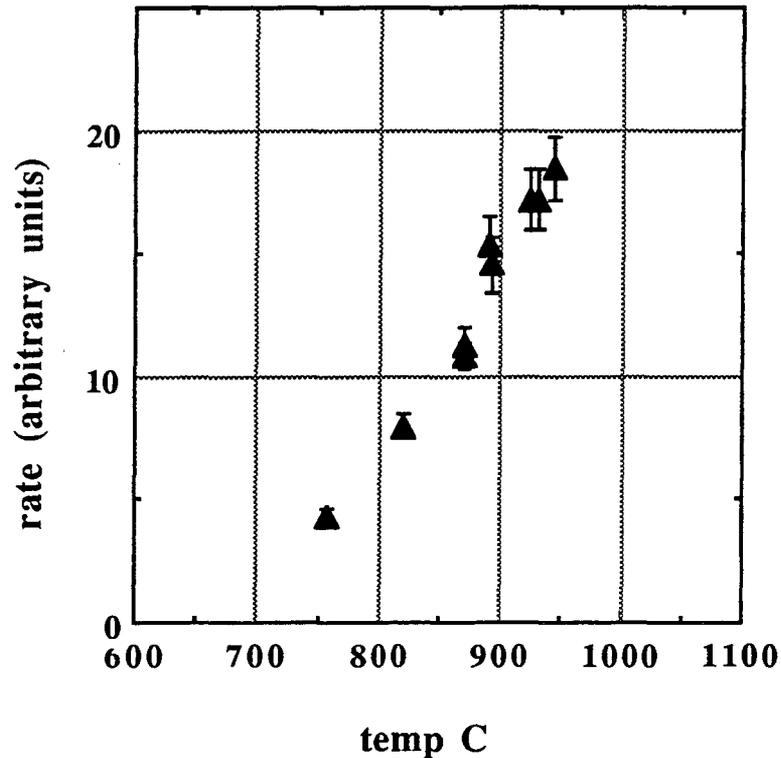


Fig 4. Temperature dependence of flux for prototype orthotropic source. Possible sources of error in the flux calculation arise from uncertainties in the detector calibration, actinium source activity, and the ability of francium to stick to the room temperature catcher. (Collection times were varied from 30 seconds to 3 minutes and compared with the 1 minute collection. No effects were seen indicating that heating of the catcher was not a problem for collection times of one minute.)

The 15% yield suggests that most of the francium atoms decay before having a chance to exit the orthotropic source. In the present (prototype) design an atom must make an average of 100 attempts to leave the source. In addition, the francium is formed by the alpha decay of  $^{225}\text{Ac}$ . The recoil energy of the francium daughter gives it a range of about  $400\text{\AA}$  so that the francium must first diffuse out from either the Ni backing or the Pt coating on the walls. Since only about half the francium atoms diffuse out (rather than in) only about 50% of the francium will be available.

To better understand how diffusion might be affecting our yield we did tests with foils of Pt, Ni and other metals upon which a  $^{225}\text{Ra}/^{225}\text{Ac}$  source had been grown. The foils were heated and the yield of francium was measured as a function of temperature. The alpha particles from the  $^{225}\text{Ac}$  and  $^{221}\text{Fr}$  decays, which easily penetrate  $400\text{\AA}$ , give an accurate measure of the amount of francium in the foil. (And since the  $^{221}\text{Fr}$  grows back into the foil after evaporation with a 5 minute half life, we had reproducible conditions for the same foil at different temperatures.) These tests showed that at a given temperature some of the francium would escape rapidly but after 10-30 s very little additional francium would escape. As the temperature was increased more francium escaped but always with a similar time constant. At  $950\text{ }^\circ\text{C}$  we found that about 25% of the francium escaped from a Pt foil and about 35% escaped from a Ni foil. Thus if diffusion were the only limitation on the prototype orthotropic source, we would have expected about a 30% yield.

Other limitations are being investigated. They include a possible defect in the aperture design and the possibility of long sitting times for francium atoms on the aluminum oxide insulator that supports the neutralizing collector. Aluminum oxide has a high work function and the bias voltage may be holding francium ions on the insulator.

#### **IV. USES OF THE ORTHOTROPIC SOURCE**

##### **A. efficient use of material**

The orthotropic source can be exploited for experiments in nuclear, atomic and chemical physics. Its efficient use of material makes it ideal for use with radioactive atoms, separated isotopes, and applications where it is important to limit the amount of beam scattered or deposited in the apparatus. Compared to an effusive source, an orthotropic source in a 2 meter long atomic beam apparatus with a 1 cm detector (such as an atomic clock) could deliver the same flux to the detector with a factor of  $10^5$  less total output. It should be possible to collect and recycle most of the output beam by using a beam dump. The beam could even be shuttled between two orthotropic sources having variable apertures by alternating the use of each as a beam dump (large aperture and cold) and oven (small aperture and hot) and then reversing their configurations.

##### **B. laser trapping of radioactive alkalis**

The orthotropic source is uniquely suited for efficiently loading short lived radioactive atoms into an optical trap for laser trapping and cooling. A thermal beam from an orthotropic source with a 10 mR to 30 mR divergence could be laser slowed to 10 m/s with most of the beam preserved. With a Zeeman slowing section we would expect the slowest 20% of the atoms leaving the orthotropic source to be captured into a magneto optic trap. With an effusive source only about  $10^{-5}$  to  $10^{-4}$  of the atoms leaving the oven are captured. At present no more than a few thousand short-lived radioactive alkalis have been trapped at any one time<sup>5</sup>. The orthotropic source will allow traps to be filled to capacity ( $>10^8$  atoms) with short lived radioactive atoms and makes feasible, experiments using radioactive alkali atoms to study parity non-conservation, beta decay asymmetry and to search for a permanent electron electric dipole moment.

### C. high flux beams

By adding a second stage as a reservoir, the orthotropic source could be used to make high flux beams. The reservoir is needed to provide the large numbers of atoms without the atoms coating the high work function walls of the orthotropic source. (Alkali atoms have extremely low work functions). For example, if in a 150 mR divergence orthotropic source, it takes an of average 100 tries before an atom exits the source, then it is desirable to have no more than about 0.01 alkali atoms/Å<sup>2</sup> (10<sup>14</sup> atoms/cm<sup>2</sup>) on the walls. A 10 cm<sup>2</sup> source at a temperature that gave an atom sitting time of 1 ms would allow a flux of 10<sup>15</sup>/s into 150 mR; which compares favorably with a standard effusive source of 5 x 10<sup>16</sup> molecule sr<sup>-1</sup> s<sup>-1</sup>.

The collection of beam atoms on the neutralizer should not impair and may improve the source operation because alkali atoms have low work functions. And, once a monolayer forms, evaporation may be enhanced. Ionization of the neutral atoms leaving the neutralizer by ions attracted to the neutralizer is expected to be less of a limitation than the surface considerations.

### D. high ionization potential atoms

We have so far considered only orthotropic sources with very high ionization efficiencies. However even a low ionization efficiency can significant enhance a low-divergence beam when there are a limited number of atoms available. Since only wall collisions are important in these ovens, then atoms which leave in the desired direction can only come from one location on the walls within the oven. Any process that can increase the flux of atoms arriving (and departing) from this location will enhance the output in the desired direction. For example, in a simple oven source a small spot inside the oven that subtends 10 mR to the exit aperture will produce 10<sup>-4</sup> of the total output beam within the same angle. If we now make this spot the neutralizer for an orthotropic source and the remaining walls ionize only 1% of the atoms, then 1% of the flux will arise from this collector and will provide 1% of the total output within 10 mR - an increase of two orders of magnitude.

The example here corresponds to a situation where, at 950 °C, the ionization potential of the atom is 0.4 eV *greater* than the work function of the wall surface. The ratio,  $n_+/n_0$  of ions to atoms evaporated from a surface of work function  $\Phi$  at a temperature,  $T$  (°K) where the atoms have an ionization potential,  $I$  is given by the Langmuir Saha eq<sup>6</sup>:

$$n_+/n_0 = \omega_+/\omega_0 \exp[\epsilon (\Phi - I)/kT] \quad (1)$$

where  $\omega_+/\omega_0$  is the ratio of statistical weights, which for alkali atoms is equal to 1/2 and  $\epsilon$  is the charge on the electron. Fig. 5 shows  $n_+/n_0$  as a function of  $\Phi - I$  at 700 °C, 950 °C and 1200 °C. The 1% ionization fraction extends the range of atoms for which an orthotropic source with platinum coated walls is useful to those with ionization potentials up to 6.1 eV or higher and includes Al, Ca, Ga, Sr, In, most of the lanthanides, Tl, Th, Pa, Pu, Am, and Cm. A tungsten<sup>7</sup> oxide surface would ionize all of these with much higher efficiency and has been used for extended periods<sup>2</sup> at 900 °C - 1000 °C. However,

many of these elements evaporate only at high temperatures where the tungsten oxide may decompose rapidly. A solution might be to continuously leak oxygen into a tungsten coated source.

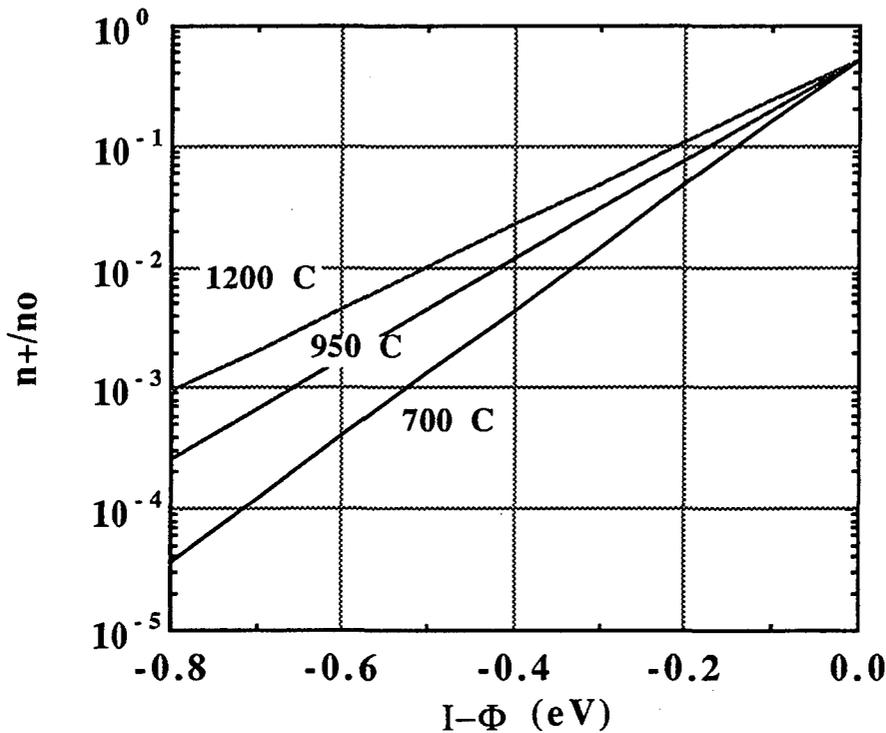


Fig 5. - Ratio of alkali ions to neutral atoms evaporating from surfaces at 700 °C 950 °C and 1200 °C as a function of the difference between the work function and the ionization potential. For other atoms, the curves may be scaled by the relative statistical weights.

### E. pulsed orthotropic source

A very useful feature (and diagnostic) for the orthotropic source is to operate in pulsed mode. The source can be turned off by simply reversing the polarity of the bias on the neutralizer. The alkali atoms become pinned to the oven walls and the recycling action is brought to a halt. Two very useful applications result: In situations where a radioactive isotope is produced continuously, a large number of atoms can be accumulated in the oven and then quickly pulsed out. This is very appealing for laser trapping and cooling of rare atoms where pulse times could be much shorter than the trap loss times, thus improving the number of atoms trapped. Another application is for chopped beams. With the orthotropic source chopping can be done electronically, with the pulse duration and repetition period varied from pulse to pulse. And, the beam material is conserved between pulses. There are

two limitations however. First, the atoms that are pinned to the surface may diffuse into the walls. When the bias is restored it will take some time for those atoms to return to the surface. This limits how sharp a turn-on pulse can be produced. In addition some of the atoms may take too long to return to the surface and will effectively be lost. Second, the atoms may not remain ionized for long times (and so may leak out effusively) unless the ionization fraction is high and/or the sticking time is long.

## V. OTHER ORTHOTROPIC SOURCES

It may be possible to construct an orthotropic source using other recycling mechanisms. One possibility is a low mass source whose walls and collector can be rapidly heated and cooled. A hot collector and cold walls are used to launch the atoms and then hot walls and a cold collector are used to return the atoms to the collector. This arrangement would work best at very high temperatures where radiative cooling can rapidly drop the temperature. A shuttered aperture (or very large ratio of collector area to aperture area) is also needed to maintain high efficiency.

## VI ACKNOWLEDGMENTS

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