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A PIG SPUTTER SOURCE FOR NEGATIVE IONS

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Summary

A PIG discharge with radial extraction and a separate sputtering cathode placed opposite to the outlet has been built. To increase the yield of negatively sputtered ions, cesium is vapourized into the discharge. Magnetically analyzed spectra of the extracted beams prove, together with other evidence, that the extracted ions are those directly sputtered. Among others, the following analyzed beams have been obtained: C^- - 7 μA, F^- - 15 μA, Al^- - 1 μA, Al_2^- - 2.0 μA, Cl^- - 30 μA, Ta^- - 3 μA, and Au^- - 56 μA. With 10 μA injected into our tandem accelerator, a 2.4 μA Au^{++} beam was obtained.

Introduction

The tandem laboratory of the Institute of Physics, University of Aarhus, was planned to be an extension to higher energies of the wide range of heavy-ion accelerating facilities for atomic physics already existing at the Institute. Hence, development of sources for a wide range of negative ions was a vital part of the program. When our ion-source program started three years ago, the natural starting points were the Penning source of Heinicke et al.[1,2] and the rotating-wheel sputter source of Hortig et al.[3,4]. The Penning source[1] was designed for gases and evaporated metals only, but it was known that tantalum originating from the heavy sputtering of the cathode could be extracted as negative ions from the plasma. Hence it was planned to introduce atoms of a wide variety of solids into the discharge by sputtering. To eliminate the heavy sputtering wear of the discharge cathodes, we chose not to use the cold-cathode PIG discharge but rather to employ a filament for introducing electrons into the discharge. A special sputtering cathode of the desired material was utilized, and when this cathode was placed close to the radial extraction opening, beams of low-intensity, negative ions could be extracted. A natural addition was to use cesium to increase the yield of sputtered negative ions along the lines of Hortig et al.[3,4], but this development was first triggered off by the news about the UNIS source[5,6] from the University of Pennsylvania.

Source Description

The present version of our source is shown in Fig. 1. A preliminary report has been presented earlier[7]. Parallel to developments here, which have aimed at maximizing the negative current of directly sputtered ions, Smith and Richards[8,9] worked on a source with a similar geometry but concentrated on the extraction of negative ions from the plasma. The source consists of a 15-mm-diameter and 50-mm long stainless-steel cylinder. The cathodes (graphite) at the ends are usually kept at -150 V, and the cathode current is typically 0.15 A. Boron nitride is used for electrical insulation. Electrons for the discharge are supplied by a 1-mm-diameter tungsten filament, which also heats the chamber to app. 500°C, and thus prevents cesium from condensing on the chamber surfaces. Opposite the 1.5-mm-diameter beam outlet is placed the sputtering cathode, the voltage of which may at present be varied from 0 to -2 kV. A typical sputter current is 10 mA. Secondary electrons and negatively sputtered ions constitute a large fraction of this. The end of the cathode is shaped as the inside of a sphere with its center in the outlet opening. The sputtering cathode

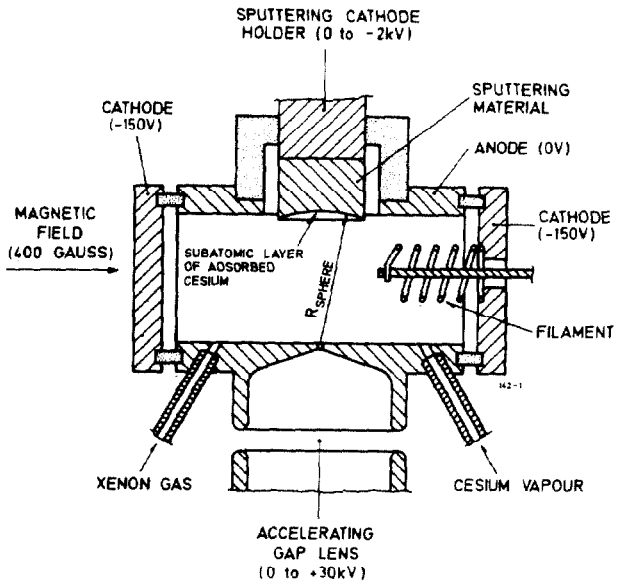

Fig. 1. Schematic drawing of the ion source.

may be water-cooled. Furthermore, the source is equipped with inlets for support gas (usually xenon) and for cesium vapour from a small oven. The cesium consumption is ~ 10 mg/hr. A magnet (not shown) gives an axial field of ~ 400 gauss. Two different geometries may be used for the optics of the extraction region. In the model shown here, an accelerating gap lens is included. This geometry suppresses extraction of negative ions from the plasma and heavy electron-current loading. Hence, space-charge effects in the extraction region are, to a large extent, avoided. The older version used a conventional extraction electrode which drew electron currents of the order of 2 mA.

The operational experience with the ion source is not sufficient for an accurate estimation of those critical components limiting its life. One one occasion, the source was mounted and dismounted for several runs without being opened. After a little over 200 hrs of operation, the filament wore out and the sputtering cathode was short-circuited by flakes of sputtered material that had come loose from the source walls. Until the present moment, the filament only failed once. The above failures are expected to occur only after longer running times when the source is not being handled mechanically.

Mechanism for Obtaining Negative Ions

The recognition that the source utilizes the directly sputtered ions is crucial for its optimization. Three independent pieces of evidence exist. The first one is presented in Figs. 2 and 3, displaying magnetically analyzed spectra obtained at our ion-source test bench, i.e., obtained with the source version utilizing an extraction electrode. Figure 2 depicts gold beams obtained with two different sputtering voltages. We see that the main peak, moving as it does with the sputtering voltage, must originate at the cathode. The weaker beam is independent of sputtering voltage and

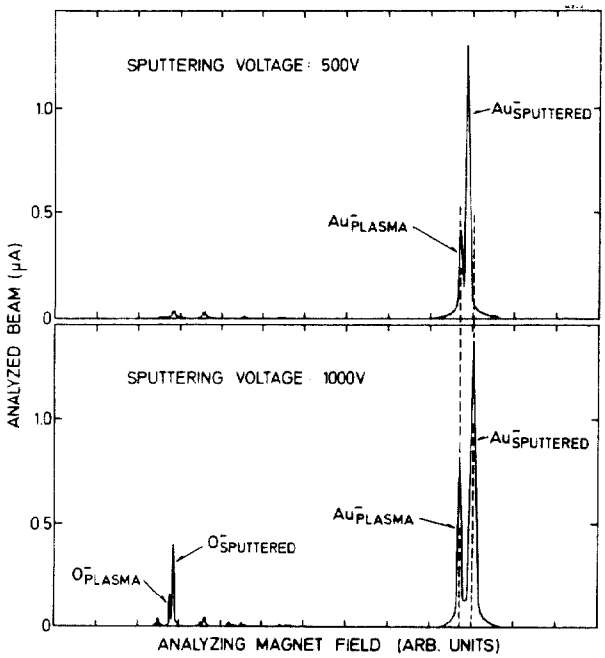

Fig. 2. Magnetically analyzed gold beams displaying directly sputtered negative gold ions as well as some extracted from the plasma. The discharge support gas was xenon, and the cesium oven was kept at 100°C.

originates in the plasma. In the extraction optics of Fig. 1, this beam is entirely suppressed. Similar evidence is obtained from Fig. 3, where we see that even most of the O^- beam stems from the sputtering cathode.

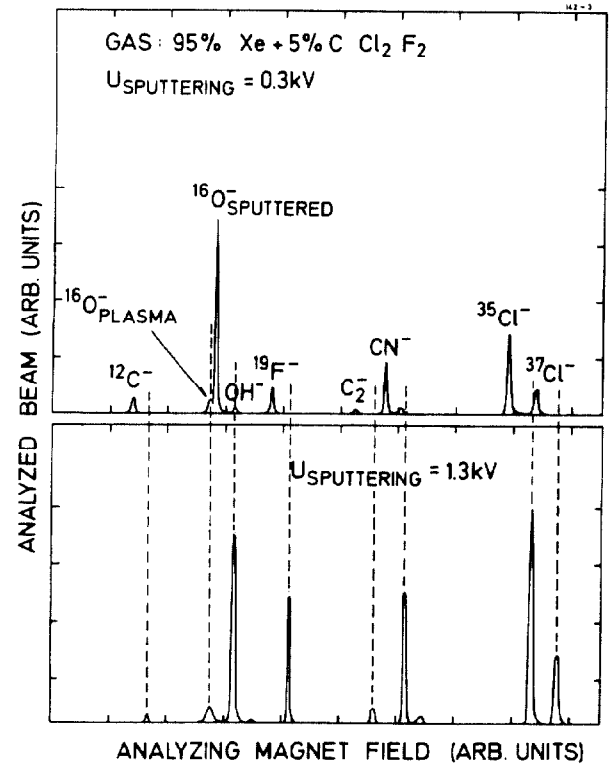

Fig. 3. Magnetically analyzed oxygen (from the rest gas), fluorine, and chlorine beams originating from the sputtering cathode.

The cathode was designed so as to let the plasma penetrate into the spherical depression where negatively charged, sputtered ions will be accelerated across the thin plasma boundary sheath and thus focused on the outlet opening if the distance from the sphere to the opening corresponds to the radius of the sphere. Figure 4 shows unambiguous evidence of this mechanism. Three different copper cathodes with radii 9, 12, and 15 mm have been used, and the source output as a function of distance from cathode to outlet has been measured. The ratio between sphere radius and cathode diameter was the same for all three cathodes. When the distance from cathode to outlet corresponds to the radius, all three cathodes are seen under the same solid angle from the outlet, and the current would be expected to grow as the radius squared. This effect is counterbalanced by charge exchange in the plasma, which causes an exponential attenuation with distance of the negative beam. The combination of these two mechanisms causes the maxima in the current versus distance to be displaced slightly in the direction of the outlet. A mean-free path λ of 3.6 mm for negative copper ions in the plasma may be deduced from the curves. This value refers only to the plasma densities considered here, λ being inversely proportional to the density. From the deduced value of λ, an optimum sphere radius of 7.2 mm may be calculated but will yield a current only 5% higher than that of the 9-mm radius. A better utilization of the sputtered ions will, however, be obtained by going to small cathodes and closer distances. This may be of importance if a current of rare isotopes is needed but will probably necessitate the whole chamber to be built smaller. The source may also work in a different, not as fully understood, mode. Here, the plasma burns on the cesium vapour only. Hence the plasma is much less dense. In this way, 20-μA currents may be obtained with a 12-mm-radius cathode but for a distance of 18 mm. We imagine that here the plasma does not penetrate completely into the sphere. Hence the plasma will have a larger radius than the sphere, yielding the best focusing for distances longer than the sphere radius.

The third piece of evidence for the sputtering mechanism will not be presented here as it requires a colour reproduction. With a 10-mm-diameter cathode, the region around the outlet showed the following features after a prolonged copper run: The entire chamber wall was covered with copper except for a narrow region around the 1.5-mm-diameter opening. A region less than 3 mm in diameter showed the stainless-steel surface without any visual trace of copper. The

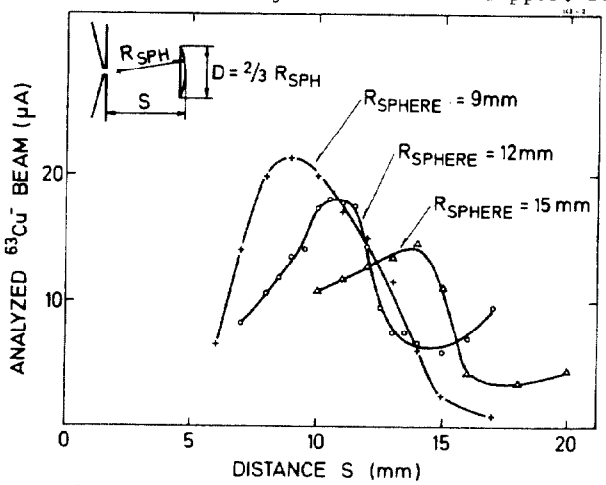

Fig. 4. The dependence of the intensity of analyzed $^{63}Cu^-$ beams on sputtering-cathode curvature and distance from extraction opening.

self-sputtering yield of 1-keV copper is approximately three. If the ratio between the flux of 1-keV atoms to thermalized atoms deposited from the plasma is less than 1:2, the surface will be kept clean. As the area of the cleaned spot is a factor of 20 smaller than the cathode area, this also proves that focusing occurs.

Emittance, Brightness, Energy Spread

The demonstrated understanding of the detailed working mechanism of the source in principle allows not only the source emittance but also the brightness contours in the emittance diagram to be calculated. All the necessary information is contained in the distribution of sputtered-particle momenta parallel to the surface at the sputtering cathode. Such information is not directly available. One may, however, safely assume a cosine distribution of the intensity of the negatively sputtered ions. Energy distributions of negative ions have been measured for uncovered surfaces only[10]. Doucas and Hyder[11] cite mean energies of the order of 200 eV. First, owing to the extreme skewness of the energy distribution of sputtered particles, mean energies are not physically very relevant; second, energy distributions of negative ions from a cesium-covered surface will presumably be much more like distributions of neutrals from uncovered surfaces and thus be shifted to lower energies. A simple formula for the energy spectrum like that proposed by Thompson[12] might be sufficient for calculations. Easily sputtered materials will have more intensity in the low-energy part of the spectrum than those more difficult to sputter. Hence, the large beams from easily sputtered materials might have a better emittance than smaller beams from a more difficult material. For a recent review on sputtering in general and energy spectra in particular, see Ref. 13.

The energy spread in the obtained beams corresponds to the component of the energy distribution perpendicular to the cathode of the sputtered particles. Hence, the half-width will be less than that of the sputtering-energy distributions, i.e., less than 10 eV[13].

Emittance measurements have not been performed on the source. In the abscense of these, some very simple geometrical arguments may be used to set an upper limit to the emittance, E_m. Disregarding the focusing mechanism discussed above but bearing in mind that the particles move in straight lines from the plasma boundary to the outlet opening, we may estimate the emittance containing 100% of the beam to be $E_m \sim dDR_{sph}^{-1}E^{1/2}$, where d is the outlet diameter, D the cathode diameter, R_{sph} the cathode-outlet distance, and E the sputtering energy (see the sketch of the geometry in the insert of Fig. 4). For the dense-plasma-burning-mode, this upper limit is 32 mm mrad × ×MeV$^{1/2}$, for the thin-plasma mode 21 mm mrad×MeV$^{1/2}$. The focusing mechanism will cause the main fraction of the beam to be contained within a smaller emittance. Hence, the emittance is expected to compare favourably with the UNIS[11] as well as with the Smith and Richards source[9].

Tandem Transmission Measurements

Information on the beam quality is also contained in the transmissions measured with our HVEC EN tandem. The injector system being crucial for transmission, our injector is shown in Fig. 5. (The injector is designed and built by DANFYSIK.) Two different types of transmission experiments were performed. The tandem acceptance is determined by the stripper canal; hence, a negative beam was transmitted through the tandem with the terminal at 1.6 - 3.6 MeV but without stripper gas. The transmission of the negative beams was found to be higher than 50%, independent of projectile mass. The loss includes the part of the beam not within the tandem acceptance, imperfect matching between source and tandem, and charge-exchange through collisions with rest gas in the beam tubes. In the other quantitative transmission study, the analyzed beams that could be obtained in each charge state by optimizing the stripper-gas pressure were determined. The transmitted currents (electrical) are shown in Table I [$(ME/Z^2)_{max}$ = 240 amu MeV].

Further, for 10 μA Au^- injected, an analyzed beam of 2.4 μA Au^{++} was obtained. For carbon, a foil stripper was also used at 3.6 MV. Summation of the particle currents over all charge states yielded a total transmission of 47% in the analyzed beams, for 4.3 μA C^- injected.

Tested Materials

No extensive survey of the beams obtainable from the source has been performed, but we have tried easily-sputtered materials (copper, gold) as well as more difficult ones (aluminum, tantalum) and materials

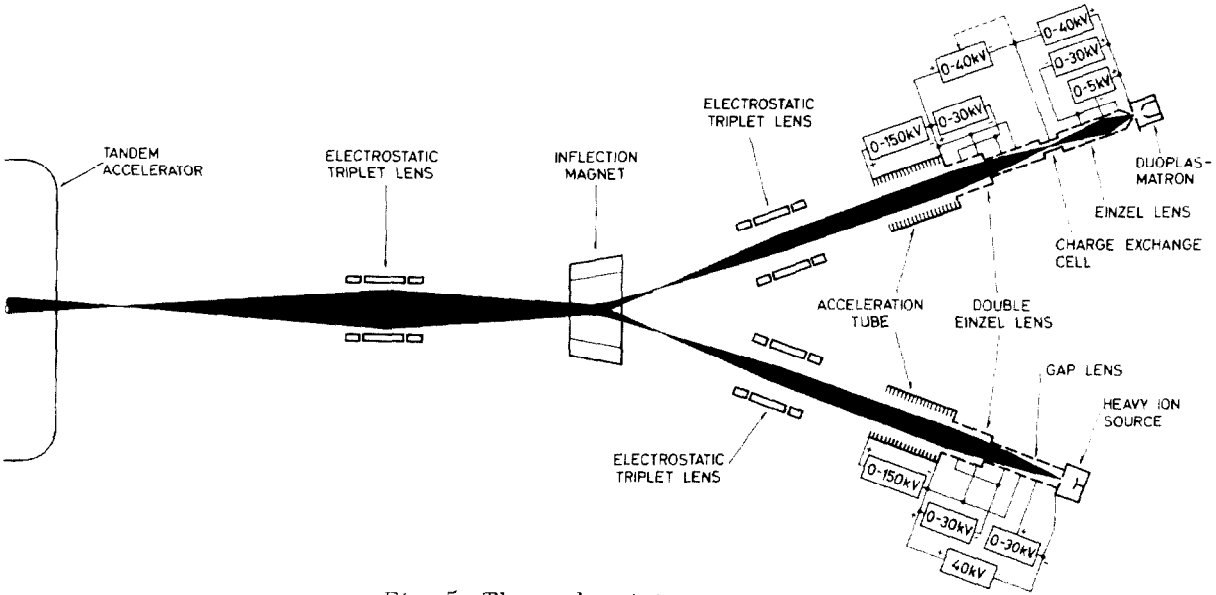

Fig. 5. The tandem-injector system

Table I

	Gold V_{term}=1.6MV		Gold V_{term}=2.6MV		Carbon V_{term}=3.6MV	
Charge state	I_{LE} μA	I_{anal} nA	I_{LE} μA	I_{anal} nA	I_{LE} μA	I_{anal} nA
+1					4.3	1000
+2	3.4	1240			4.3	1570
+3	3.5	715	2.9	1000	4.3	1900
+4	3.5	230	3.2	470	4.3	815
+5	3.6	66	3.3	190	4.3	50
+6			3.4	30		

with low electron affinity (titanium, iron). Furthermore, some experience on the sputtering of adsorbed or chemically bound gases has been gathered (oxygen, fluorine, chlorine). Maximum analyzed currents are listed in Table II. For materials consisting of more

Table II

Beam	I_{anal} μA	Attempts	Beam	I_{anal} μA	Attempts
BeH^-	0.8	few	Al_2^-	2	few
BeO^-	0.9	few	Al_3^-	0.2	one
C^-	7	many	Cl^-	50	few
C_2^-	12	many	Ti^-	0.9	one
C_2^-	1	many	Fe^-	0.7	one
CN^-	5	few	Ni^-	6	one
O^-	4	many	Cu^-	30	many
F^-	15	few	Ta^-	3	one
Al^-	1	few	Au^-	56	many
AlO^-	1	few			

than one isotope, the intensity of those most abundant is listed. As the currents obtained to a large extent depend on the amount of work devoted to a particular material, we have also roughly classified the number of attempts. We shall now briefly comment on each of the investigated materials.

Beryllium: A sputtering cathode of beryllium was used. The best results were obtained with new sputtering cathodes. On such an occasion, BeH^- and BeO^- beams of nearly 1 μA were obtained once, but until now we have been unable to reproduce this result. Adding hydrogen or water vapour to the discharge had no effect. It is planned to try loading the beryllium cathode heavily with implanted hydrogen to improve the yield of BeH^- ions.

Carbon: The C^- beam was produced with a sputtering cathode of graphite. In spite of the low sputtering yield and the low electron affinity of carbon, rather high intensities were obtained. As is usually the case[6], the C_2^- beam was more abundant than the C^- beam.

Nitrogen: Each time the cesium was loaded, a CN^- beam of high intensity was obtained from rest gases of kerosene, which was used to protect the cesium from oxidation.

Oxygen: A good O^- beam was obtained each time the source was exposed to air. By adding air to the discharge, the beam could also be obtained at later stages. In practice, we often had to alternate between a gold and an oxygen beam, and the above method was found to be feasible.

Fluorine: Prolific beams of fluorine sputtered off the cathodes of aluminum or copper were obtained by adding 5% CCl_2F_2 (freon 12) to the xenon gas and with no cesium evaporation into the discharge. Very small intensities of fluorine were observed with a sputtering cathode of gold. The beams were, however, not very reproducible, and apparently the mechanism requires the cathode to have been loaded with cesium by prolonged sputtering. A continuous evaporation of cesium into the discharge will probably improve the reproducibility.

Aluminum: Sputtering cathodes of aluminum were used, but this material is difficult to sputter owing to the unavoidable oxide layer. Due to pitting where the oxide layer was first sputtered, the surface may become very rough[13]. Note that where the intensity is more important than energy, four times more aluminum is contained in the Al_2^- beam than in the Al^- beam.

Chlorine: See fluorine. Note that small intensities of Cl^- sputtered off metal surfaces were originally detected by Campbell and Cooper[14].

Titanium: The sputtering yield as well as the electron affinity being very low for titanium, the intensity of the obtained beam is low. A titanium sputtering cathode was used.

Nickel: Prolific beams of nickel were obtained with a sputtering cathode made of stainless steel. A cathode of pure nickel was avoided in order not to disturb the axial magnetic field.

Iron: For the same reason that applies to nickel, a stainless-steel cathode was used. The electron affinity for iron being very low, the intensity of the beam obtained is very low too.

Copper: As very prolific Cu^- beams of high reproducibility were obtained with a copper cathode, most of the tests on the bench were carried out with this material.

Tantalum: This material is often used as apertures, etc., in heavy-ion work due to its very low sputtering yield. In spite of this, and in spite of its low electron affinity, good beams were obtained.

Gold: This constituted our most intense and reliable beam due probably to the fact that the beam has been studied extensively as it is heavily utilized for sputtering as well as for multiple- and single-scattering studies at the tandem.

The results obtained for the materials studied makes us confident that usable beams of all metals and semiconducting elements could be obtained provided the electron affinity is positive. Beams in excess of 10 μA are expected for easily sputtered materials and in excess of 1 μA for materials more difficult to sputter.

Conclusion

We conclude that the source discussed here will yield negative beams of most elements. For metals, the intensity compares favourably with other recently published sources[5,8]. This is also expected to be the case for the emittance. The source may be in operation unserviced for more than 200 hrs. To change the beam, it is necessary to change the sputtering cathode through

an air-lock. The main virtue of the source may well it requires no special material or materials that are difficult to machine. Hence, the source can be built in most nuclear- or atomic-physics laboratories.

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