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HIGH PERFORMANCE HEAVY-ION SOURCE FOR CYCLOTRONS

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HIGH PERFORMANCE HEAVY-ION SOURCE FOR CYCLOTRONS*

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Summary

A cold cathode Penning discharge ion source,[1,2] power supply, and its performance in the Oak Ridge Isochronous Cyclotron (ORIC) are described. The ion source has operated at power levels as high as 8 kW and has produced a variety of particle beams, ranging from deuterium to xenon and with charge states up to +12. In particular, 20 eμA (electrical microampere) of $^{16,18}O^{5+}$, 5 x 10^4 p/sec (particle per second) of $^{40}Ar^{10+}$, and 10^7 p/sec of $^{132}Xe^{12+}$ have been extracted from ORIC. From the known intensities of accelerated ions and the calculated total ionization potential, a means of predicting particle intensity for a given charge state has been developed.

Penning Source Design

At Oak Ridge we have recently constructed a very compact Penning source for ORIC. A schematic drawing of the source is shown in Figure 1. The source is 5-1/4 in. long and is mounted on a single radial arm. The mid-plane diameter of the source, the dimension that particles must clear in their first cyclotron orbit, is designed so that a beam with an initial starting radius of 3/4 in. will clear the chimney. The mid-plane schematic (Section AA, Fig. 1) shows two circular areas contained within the ground shell of the chimney. The smaller area is the plasma chamber and is 5/16 in. in diameter. The larger area contains a water-cooled rod having 1/8 in. clearance from the grounded shell. This rod supports the left cathode holder and provides cooling water and the electrical connection to the high voltage manifold. The right cathode holder is water cooled and is mounted directly on the water manifold at high voltage. The easily replaceable cathodes are 1/2 in. sections cut from 1/2 in. dia. tantalum rod. The 3/16 by 5/8 in. beam aperture is defined by a replaceable tantalum slit centered on the 3-1/2 in. long plasma chamber. Figure 2 is a photograph of the source.

Removable tantalum covers, which allow access for maintenance, are provided at the right and left ends of the arc chamber. Gas lines, water cooling lines, the electrical lead and a source adjustment rod are housed in the support stem. The gas is fed in above the right cathode. Two concentric copper tubes for water cooling the cathodes are contained in a nylon tube; they also serve as the electrical lead. The cathode cooling water temperature increases 40°C for 10 kW cathode power dissipation. The source adjustment rod allows the chimney to be rotated ±2° about the cathodes. To align the axis of the arc plasma with the magnetic field the chimney can be rotated (tilted) ±2° with respect to the supporting stem and the stem can be rotated ±5°. All vacuum seals are made at the faceplate end of the source stem.

*Work sponsored by US AEC under contract with Union Carbide Corporation.

Power Supply

Potentials of up to 6 kV are required for striking the discharge (arc) and currents up to 12A at 0.5 to 2.5 kV are required to sustain the arc. Figure 3 is a schematic of the arc power regulator used at ORIC. A series regulator was added to an existing 75 kVA (12 A at 6.2 kV) dc power supply and the regulator is operated in a current-source mode. Series resistance in the screen circuit protects the 4CW25000A tubes from excessive screen current. The grid bias controls the arc current from 0 to 12 A. The tubes are able to withstand the full output of the power supply when a short circuit or very low arc impedance occurs.

DC Test Stand Results

An early version of the source was constructed and tested in a dc source test stand. A procedure to align the arc with the magnetic field was developed as follows. The arc current control is set at zero and a high gas flow (10 cc/min) is maintained. The voltage supply is turned on at 6 kV and the source stem is rotated until a minimum in the arc voltage occurs; this indicates optimum alignment with the magnetic field.

Ion outputs for various ion charge states were measured. A typical result for oxygen is 17 μA of 5+, 210 μA of 4+, 1300 μA of 3+, 1400 μA of 2+ and 800 μA of 1+. A detailed systematic evaluation of various source parameters[3,4] (gas flow, arc current, and arc voltage) has not been made. However, we find that an "optimum" source condition can be arrived at quickly in cyclotron operation.

Operation of Source in Cyclotron

A typical set of peaked source condition on the cyclotron is 600 V at 3 to 8 A. Even for the high charge states such as $^{40}Ar^{10+}$ or $^{132}Xe^{12+}$, the beam current peaks at ∿600 V. The output of the higher charge states is extremely sensitive to gas flow (∿2cc/min). The lower the gas flow, the higher the output, except there is a minimum flow that the arc must have to operate in the high current mode (>2 A).

The cathode lifetime is a function of ion species and source power. For carbon and nitrogen ions, lifetimes of 8 to 12 hours are usual. For oxygen and argon ions, 2 to 4 hours are typical. Fortunately, changing of cathodes is a relatively simple procedure and requires only 15 to 30 minutes. Source failure is due to erosion of the cathodes by positive ions draining from the arc plasma. Figure 4 shows some typical eroded cathodes; the erosion rate for tantalum is about one gram per hour. As the depth of the crater in the cathodes increases, it is increasingly difficult to restrike the arc. When the crater depth equals the crater diameter (∿1/4 in.) the full 6 kV is inadequate to strike the arc. The arc is easier to restrike if the cyclotron rf is turned off, the gas flow is increased, and the cathodes have not yet cooled appreciably. A fast acting bypass valve on the gas line permits a rapid increase of the gas flow.

Erosion of the chimney from bombardment by accelerated ions that do not gain enough energy to clear the source erodes 1/16 in. of copper in about a month's operation. Erosion in another region can only be attributed to negative ions accelerated off phase. All water and gas lines that cross the median plane are protected by additional copper shields. An increase in beam intensity of the high charge states was noticed as a hole was eroded in the plasma chamber. When this hole into the cyclotron vacuum was enlarged the beam intensity of the high charge states ($^{40}Ar^{9+}$) increased but the beam intensity of the low charge states ($^{16}O^{4+}$) decreased. This indicates that the optimum pressure at the source mid-plane depends on the charge state desired.

Only a few runs have been made with light ions (D, He) in the heavy ion source. This source puts out great quantities of light ions and is difficult to control. A reduced slit aperture (1/16 diameter), an excessive gas flow (to quench the arc), and a reduced rf voltage was used to limit the light-ion beam current from the source to safe levels. The brightness of this source is apparently greater than that of the ORIC hot cathode source. It appears that cyclotrons with hot cathode[5] sources and limited source brightness may increase their beam intensity substantially with a cold cathode source.

ORIC Beams

The use of the "analogue beam"[6] technique (the use of equivalent q/m ions) in developing new beams permits the separate treatment of cyclotron parameters and source parameters. The identification of a new beam is accomplished by measuring the extracted beam energy via elastic scattering (15°) from a (1.5 mg/cm²) gold foil onto a surface-barrier detector. The analogue beam is used to calibrate the measuring system. Figure 5 is an energy measurement for $^{132}Xe^{12+}$. The analogue beam was $^{22}Ne^{2+}$ (q/m = 1/11). The width of the $^{132}Xe^{12+}$ energy peak and the shift in energy from 98 MeV to 60 MeV is due to the thickness of the gold scattering foil.[7] The central peak has been identified as $^{66}Zn^{6+}$ and its origin is attributed to vaporization of brass components in the source.

More than twenty heavy ion beams (mass >12) have now been extracted from ORIC, see Table 1. The maximum energy from ORIC in MeV, is ≈90 q^2/A. The external beam currents are also listed in Table 1. Extracted beam currents for particles with currents above 1 eμA do not represent the maximum source output since greater intensities were not required for the experiments.

Within recent years many machines[8] have been designed to accelerate heavy ions up to 10 MeV/nucleon. A crucial parameter in almost all proposed designs is the assumed intensity of the Penning ion source for a given particle and charge state. Figure 6 is the calculated ionization potential[9] versus mass number. The small numbers are the charge state for a given mass and are located at the calculated ionization potential for that charge state. The geometric symbols indicate the measured intensities of heavy-ion beams that have been extracted from ORIC. Figure 7 is the total ionization potential versus charge state calculated for several elements from carbon to uranium. The experimental intensities are shown and the symbols are the same as in Figure 6. In predicting intensities of new beams, the total ionization potential versus charge state is amazingly reliable. That is, all charge states below 600 V are produced in eμA quantities from the present source. An interesting check would be to measure the intensities of the various charge states of uranium; we would expect eμA quantities of U^{10+}, and lower charge states and enA quantities of U^{11+}, $^{12+}$, $^{13+}$.

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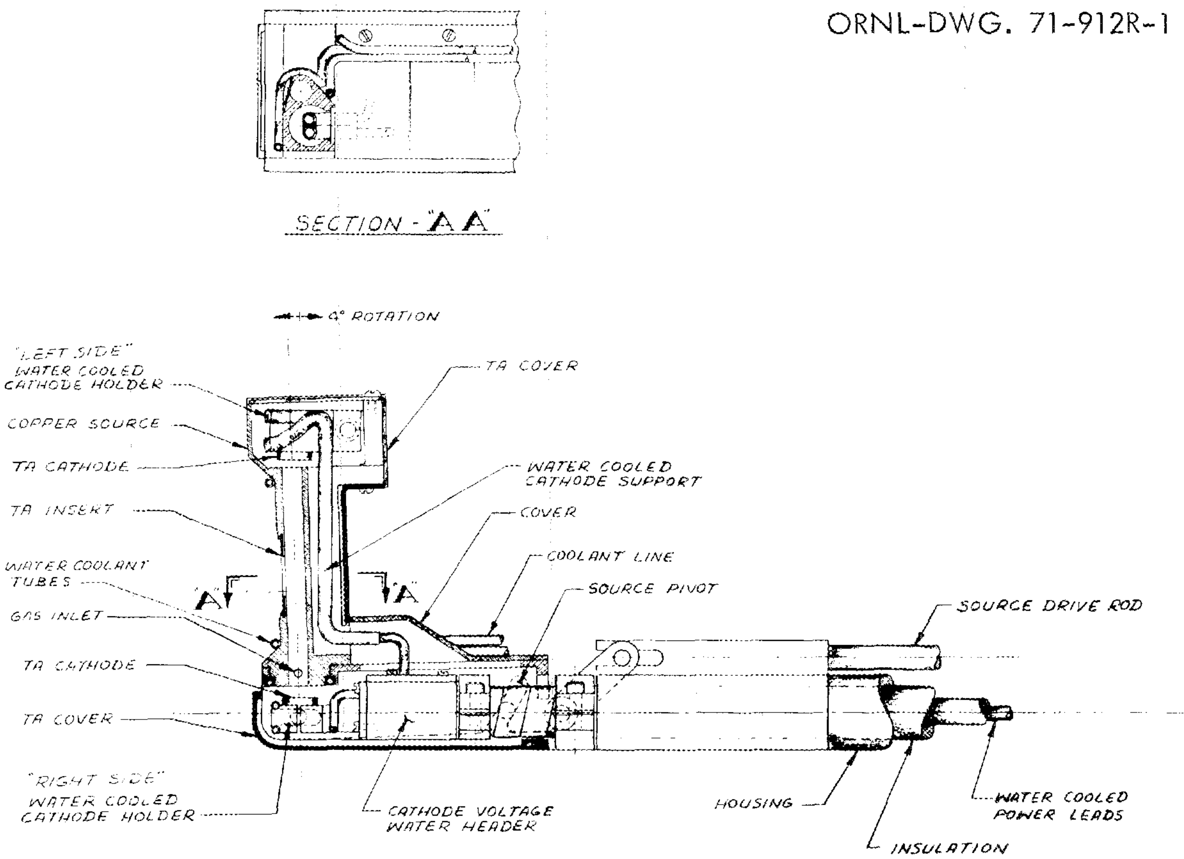

Fig. 1. Sectioned views of the ORIC Penning-type cold-cathode source for heavy ions. To provide for alignment with the magnetic field the 5-1/4 in. source can be ''tilted'' ±2° with respect to the 10-ft. support stem and the stem itself can be rotated ±5°.

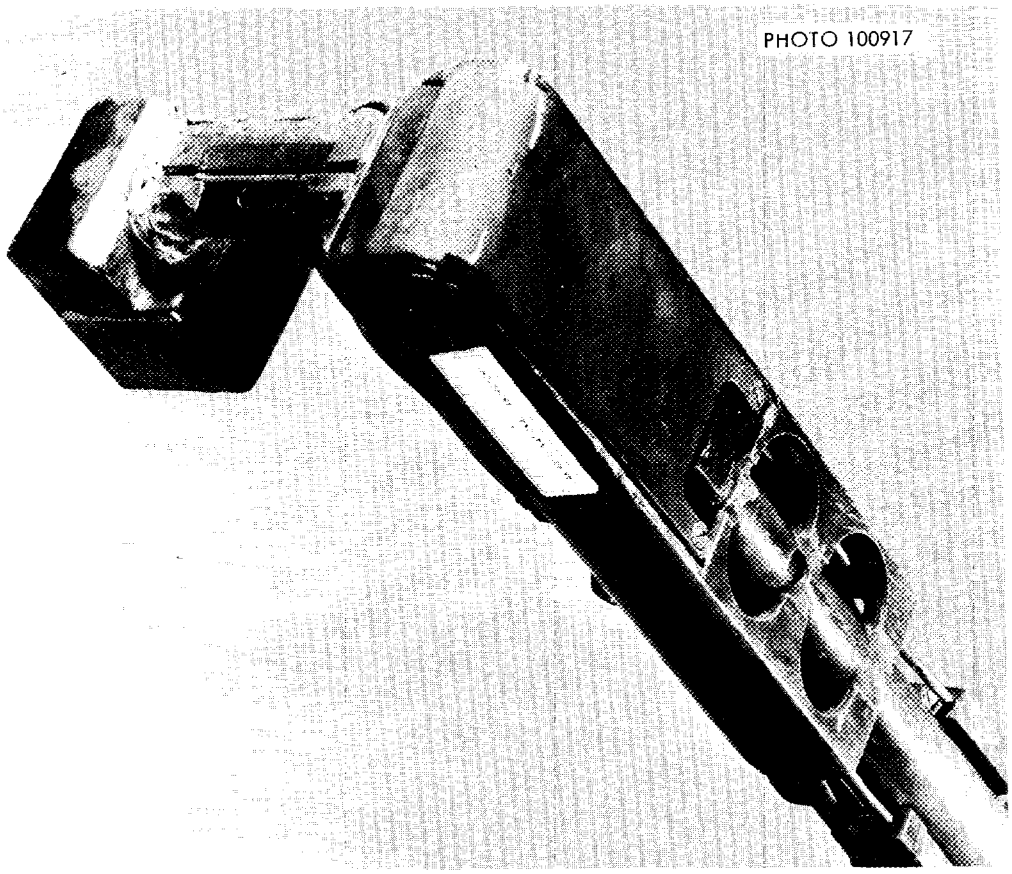

Fig. 2. The ORIC Heavy-Ion Source. Positive ions emerge from the 3/16 by 5/8 in. oval defining slit and orbit clockwise about the source.

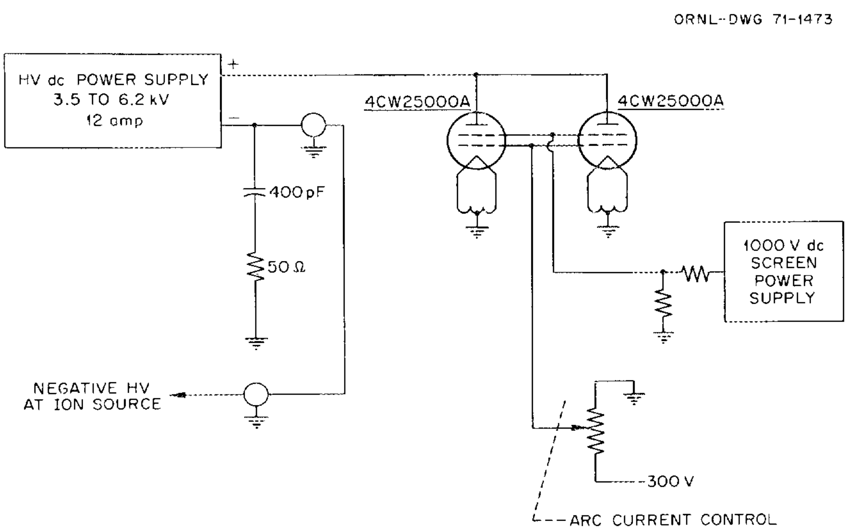

Fig. 3. Schematic of the arc power regulator for the heavy-ion source. The arc power can be varied from 3.5 to 6 kV and up to 10 amperes.

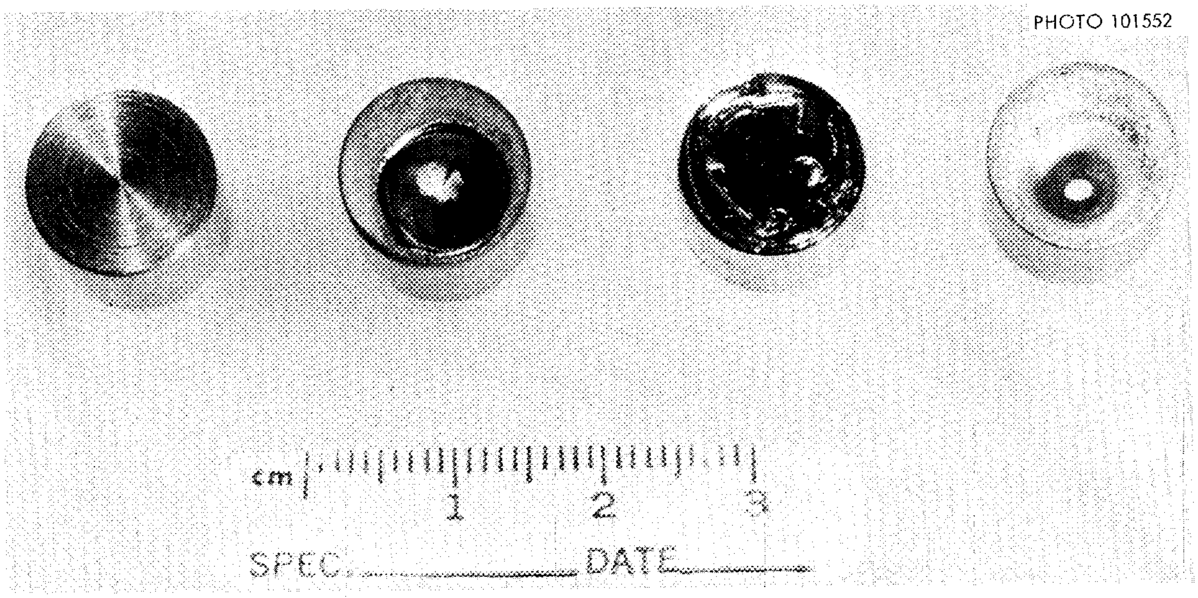

Fig. 4. Cathodes: at left Ta, unused; central pair Ta with and without water cooling; right Cu, eroded through.

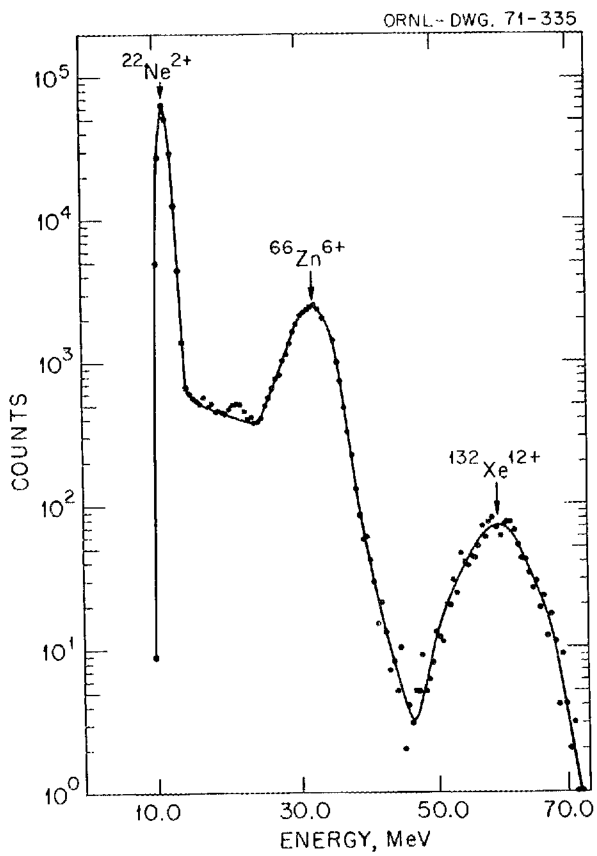

Fig. 5. Components of the q/m=1/11 extracted beam. The three beam components can be selectively enhanced by small adjustments in the magnetic field. The peak of the initial analogue beam subsides with time.

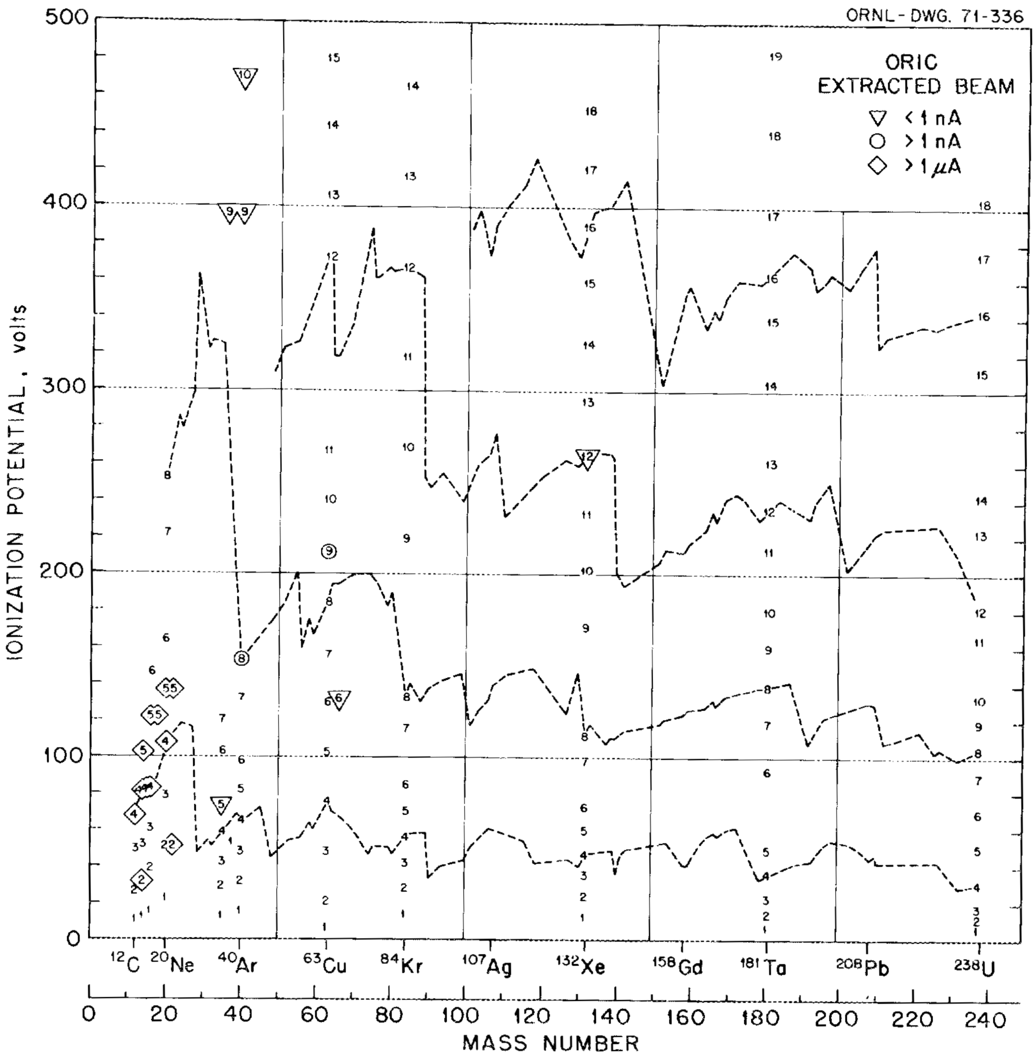

Fig. 6. Calculated ionization potentials of the outer electrons of various heavy elements. Dotted profiles identify selected electron levels. Geometric symbols indicate external beam currents that have been obtained with the Heavy-Ion Source in ORIC.

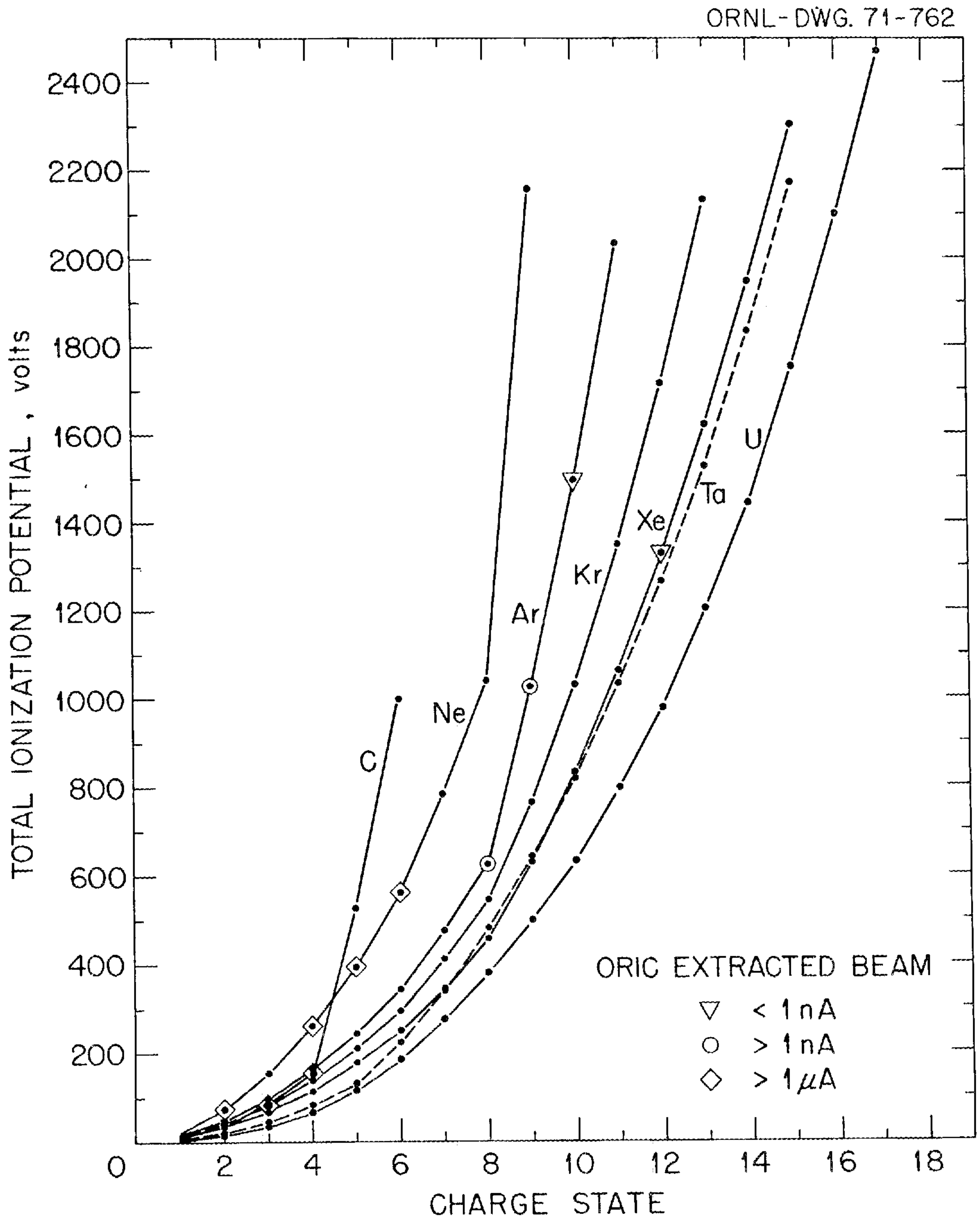

Fig. 7. Calculated total ionization potentials required for multiply-charged heavy ions of interest. Geometric symbols indicate external beam currents that have been obtained with the Heavy-Ion Source in ORIC.

Table I. Heavy-ion beams that had been extracted in ORIC by Feb. 1, 1971; note particularly Ar^{10+} and Xe^{12+}.

PARTICLE	Rf FREQUENCY (MHz)	HARMONIC	MAXIMUM ORIC ENERGY[a] (MeV)	MEASURED ENERGY (MeV)	EXTERNAL BEAM CURRENT eμ A[b]
$^{12}C^{3+}$	21.9	3	67		> 10
$^{12}C^{4+}$	9.2	1	120	119	> 12
$^{14}N^{2+}$	12.4	3	26		> 20
$^{14}N^{4+}$	7.9	1	103		> 20
$^{14}N^{5+}$	9.9	1	161	165	2
$^{15}N^{4+}$	22.2	3	96		3
$^{16}O^{4+}$	20.7	3	90	80[c]	> 4
$^{16}O^{5+}$	8.6	1	140		20
$^{18}O^{5+}$	7.7	1	125	122	20
$^{20}Ne^{4+}$	16.7	3	72		> 1
$^{20}Ne^{5+}$	20.7	3	112		> 1
$^{20}Ne^{6+}$	8.3	1	162	167	3
$^{22}Ne^{2+}$	7.9	1	16		> 100 enA[d]
$^{22}Ne^{5+}$	18.9	3	102		80 enA[d]
$^{35}Cl^{5+}$	12.4	3	64		> 1 enA
$^{36}Ar^{9+}$	20.7	3	202		$\sim 5 \times 10^5$ part/sec
$^{40}Ar^{8+}$	16.7	3	144	146	300 enA
$^{40}Ar^{9+}$	18.8	3	182	180	$\sim 1 \times 10^8$ part/sec
$^{40}Ar^{10+}$	20.7	3	225	205[c]	$\sim 5 \times 10^4$ part/sec
$^{63}Cu^{9+}$	12.4	3	116		1 enA[e]
$^{66}Zn^{6+}$	7.9	1	49		0.1 enA[e]
$^{132}Xe^{12+}$	7.9	1	98	98	$\sim 1 \times 10^7$ part/sec

a. BASED ON 90 q^2/A
b. ELECTRICAL MICROAMPERES EXCEPT AS NOTED
c. CYCLOTRON ADJUSTED FOR AN ENERGY BELOW MAXIMUM
d. NATURAL ISOTOPIC ABUNDANCE GAS AS SOURCE FEED
e. FROM ION SOURCE MATERIAL OF CONSTRUCTION

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