Plasma Centrifuge

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Mass separation in magnetized, highly ionized, rotating metal plasmas is described. Plasma rotation velocities up to 7.4×10^3 m/sec with centrifugal enrichment of up to a factor of 2 for ^{65}Cu were measured. Such enrichments are significantly in excess of values reported earlier.

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Element and isotope separation in rotating multicomponent plasmas have been the subject of considerable research effort during the past decade. Bonnevier[1] reported up to 5% enrichment[2] of ^{22}Ne in a partially ionized rotating neon discharge plasma. James and Simpson[3] later achieved up to 20% enrichment of ^{22}Ne. Walsh, Brand, and James[4] introduced copper and nickel into a rotating argon plasma and measured radial separation between the two metals. Recently, Wijnakker and Granneman[5] have pointed out that mass separation in weakly ionized plasma centrifuges is severely limited by neutral-atom viscosity. Since all prior reported experiments were performed in weakly ionized gases, the deleterious effects of neutral-atom viscosity have resulted in plasma rotation rates well below the Alfvén critical velocity,[6] with corresponding low mass separation. In a partially ionized plasma, the Alfvén velocity limit is reached when the rotational energy of the ions equals the ionization energy of the neutral atoms. Further energy input to the rotating plasma then goes primarily into the ionization of residual neutrals. A fully ionized plasma is not subject to this limit.

This Letter reports centrifugal separation measurements on rotating metal plasmas. The plasmas used were highly ionized (e.g., Cu^{3+} and Cu^{4+} were the dominant ions in the case of copper), and had ion densities on axis of the order of 10^{19} m^{-3}. Copper plasmas were rotated at up to 7.4 $\times10^3$ m/sec, in excess of the Alfvén critical velocity of 4.84×10^3 m/sec, indicating that neutral species were not an impediment. The concomitant separations achieved thus significantly exceed earlier reported values.

Figure 1 is a schematic of the experimental apparatus. A 1-J, 100-ns CO_2-laser pulse, when focused on the 2.5-cm-diam metal-target surface, triggers a several-kiloampere peak current, millisecond-duration pulse from the negative target (cathode) to the grounded vacuum-vessel wall. Current flow across the dc axial magnetic field (up to 0.5 T) causes bulk rotation of the 15-cm-diam metal plasma column. Rotation was measured by radially movable Langmuir probes, disposed azimuthally and axially about the plasma column. From phase correlations in small amplitude, periodic fluctuations (~ 10%) of ion saturation current to these probes, solid-body rota-

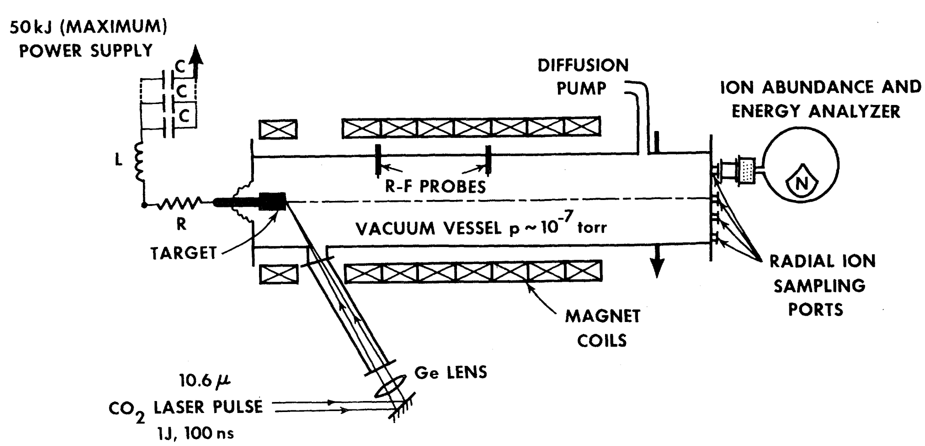

FIG. 1. Schematic of the experimental arrangement.

tion with an angular rotation rate of 10^5 rad/sec was inferred for pure-copper and copper-nickel plasmas. Periodic fluctuations were observed only when arc current and magnetic field were carefully adjusted. Two series of experiments are described in this Letter.

In the first, an alloy target (Advance) was used, consisting of 55% copper and 45% nickel. With an axial magnetic field of 0.2 T and current pulses of 2 kA peak with 2 msec RC decay time, a rotating column of copper and nickel ions was produced. After 50 shots under identical conditions, the plasma was deposited as a thin layer of metal on a Mylar sheet attached to the end flange (Fig. 1). The Mylar sheet was removed and the radial relative abundance of copper and nickel was measured using an electron spectroscopy for chemical analysis (ESCA)[7] technique. In Fig. 2, the full circles show the measured ratio of Cu/Ni versus radius, normalized to unity on axis. Radial separation between the two metals is observed. The relative Cu abundance is 60% higher at a radius of 6 cm than it is on axis.

To verify that the observed separation was indeed due to centrifuging in the rotating plasma, 5600 laser shots were fired with the same axial field but with the cathode grounded, so that no current was discharged. Metal deposited on the Mylar-covered end flange by this laser-blowoff plasma was similarly ESCA analyzed. The measured ratios of Cu/Ni versus radius in this nonrotating plasma are plotted as the full triangles

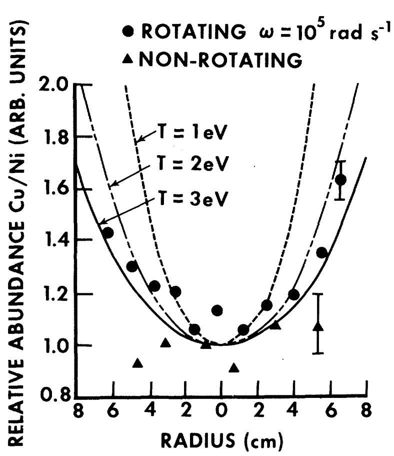

FIG. 2. Measured ratio $R(r)/R(0)$ of Cu/Ni vs radius. Full circles are data from a rotating ($\omega = 10^5$ rad sec^{-1}) discharge plasma. Full triangles are data from a nonrotating, laser-blowoff plasma. Axial magnetic field $=0.2$ T in both cases. The three curves are plots of $R(r)/R(0)$ vs r from Eq. (1) of the text.

in Fig. 2, again normalized to unity on the axis. In this case, no radial separation between the metals is observed.

Equilibrium centrifugal separation in a two-ion cylindrical plasma column rotating as a solid body may be described by a simple analytical expression, when axial and azimuthal gradients and viscous effects are ignored:

$$R(r)/R(0) = \exp[(\Delta M)\omega^2 r^2/2kT], \qquad (1)$$

where $R(r)$ and $R(0)$ are the ratios of the heavier to lighter ion specie at radius r and at the rotation axis, respectively. Here ΔM is the mass difference between ion species, ω the angular rotation rate, T is the temperature (assumed uniform), and where both ions have the same charge. Equation (1) is very similar to that obtained for mechanical centrifuges. For equally charged copper and nickel ions rotating at $\omega = 10^5$ rad/sec, $R(r)/R(0)$ is plotted versus r in Fig. 2 for three chosen values of $T = 1$, 2, and 3 eV. The measured values of $R(r)/R(0)$ are observed to roughly fit the simple analytical curve for $T \sim 2$ eV. Such an ion temperature is not unreasonable for these arcs.

In the second series of experiments, the alloy target was replaced by an oxygen-free high-conductivity copper target. Rotation at $\omega = 10^5$ rad/sec was achieved with an axial field of 0.2 T and discharges of 3 kA peak current and 1 msec RC decay time. Relative-ion-abundance measurements were made with use of an energy/momentum spectrometer[8] which, unlike the ESCA spectrometer, is capable of resolving the two stable isotopes of copper and provides a measure of their relative abundance with microsecond time resolution.

Figure 3 shows mass scans over the singly ionized copper isotopes at two radii on the end flange: on axis [Fig. 3(a)], and at $r = 4$ cm [Fig. 3(b)]. In each figure the peak relative abundance of $^{63}Cu^+$ is set to unity. Relative abundance (hereafter called abundance) versus mass is plotted for three different times during the discharge: 0.75, 1.0, and 1.25 msec. Figure 3(a) reveals that the $^{65}Cu^+$ abundance on axis varies between 0.42 and 0.45 during the discharge. These values agree, within the measurement error, with the natural ^{65}Cu abundance of 0.45. Off axis, at $r = 4$ cm, there is a marked increase in the $^{65}Cu^+$ abundance, as shown in Fig. 3(b). The $^{65}Cu^+$ peak abundance increases with time, from 0.80 at 0.75 msec to 0.94 at 1.25 msec, which is more than a twofold enrichment. Such an isotopic enrichment

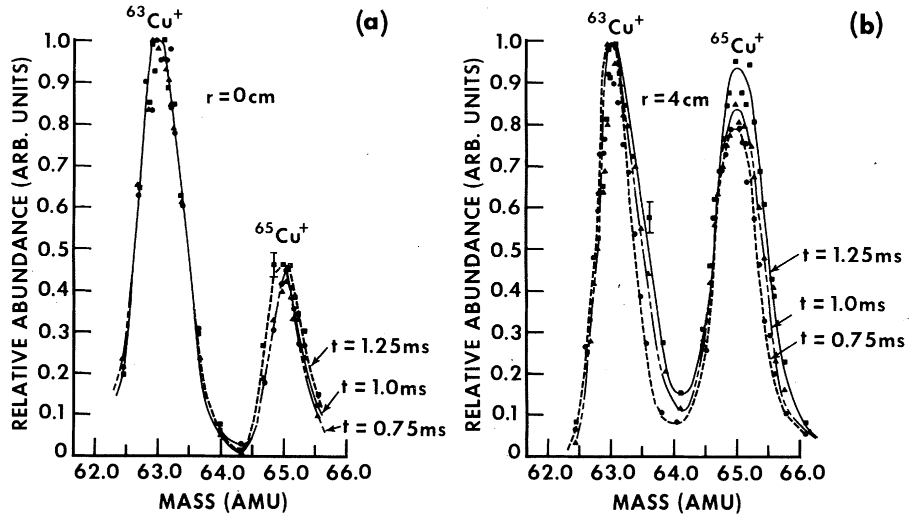

FIG. 3. Relative abundance vs mass in an oxygen-free high-conductivity copper plasma rotating at 10^5 rad sec^{-1}, measured at two radii: (a) on axis and (b) at $r = 4$ cm. The peak $^{63}Cu^+$ abundance is set to unity in both figures.

is in excess of earlier reported values for rotating plasmas.

In conclusion, rotating metal plasmas were produced by using a laser-initiated vacuum arc. The high degree of ionization characteristic of such arcs, along with measured rotation rates in excess of the Alfvén critical velocity, suggest that neutral-atom viscosity does not play a significant limiting role in such arcs. Time-resolved measurements of centrifugal isotope separation indicate that the factor-of-2 enrichment observed (see Fig. 3) may not be an upper limit; higher enrichments may be possible with a larger apparatus and longer discharge times.

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[2]Enrichment is defined here as $\{[(^{22}Ne/^{20}Ne)_p - (^{22}Ne/^{20}Ne)_n]/(^{22}Ne/^{20}Ne)_n\} \times 100\%$, where subscripts p and n refer to plasma samples and natural abundance, respectively.

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