NEW SOURCE OF HIGHLY STRIPPED HEAVY IONS*

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The acceleration of heavy ions is presently limited by the lack of a source capable of producing substantial currents of very highly stripped heavy ions.[1] The basic difficulty is the production of heavy ions having a sufficiently large value of the charge-to-mass ratio to permit their acceleration in machines of reasonable size. In existing sources both the ion containment time and the electron temperature limit the degree of stripping attained to the removal of roughly ten electrons; above this stripping level, the extracted currents decrease precipitously. We suggest that a device operating on the principles of the heavy ion plasma accelerator (HIPAC)[2,3] could be used as a source of very highly stripped ions. Realization of this idea would permit the acceleration of ions of any atomic number to energies of nuclear interest in many existing or proposed accelerators.

The HIPAC is shown schematically in Fig. 1. This device creates a topologically closed potential well by virtue of the space charge of a cloud of electrons contained in a toroidal vacuum vessel. The electrons themselves are contained by an azimuthal magnetic field. Since the kinetic energy of the electrons in the HIPAC is ~10 keV, ions trapped by the potential well will become highly stripped. The deep potential well due to the space charge (~20 MV) then accelerates the stripped heavy ions to energies of nuclear interest. Our suggestion is that the stripped ions created in a HIPAC-like device be extracted for subsequent acceleration in any type of accelerator, conventional or unconventional. Such an ion source differs from a HIPAC principally in that there is no requirement for a deep potential well for accelerating the ions. The mode of operation would be as follows: First, the electrons and the magnetic field are introduced simultaneously, using the technique of inductive charge injection.[3-5] Second, a number N of atoms of the species of interest are introduced into the torus where, after the first ionization, they are trapped. Third, stripping of these ions to the desired degree takes place in a time governed by the electron density and energy. Fourth, after stripping is accomplished, the magnetic field is reduced, allowing the electrons to move towards the wall. The last step "slowly" reduces the depth of the potential well and therefore allows the trapped ions to reach the wall. If a small portion of the wall containing an aperture is biased negatively, then for a sufficiently slow field reduction (~5 to 10 msec), the bulk of the ions will leave the device through this aperture. The whole process would then be repeated.

Consider, for example, a device having a maximum major radius of 40 cm and a minor radius of 10 cm. At an electron density of 2×10^{10} cm^{-3} injection experiments show[5] that the associated magnetic field would be ~5 kG, well above the magnetic field required for electron stability (magnetic energy per electron $\gtrsim$5 MeV).[4,6] The electron space charge would create a potential well of $\approx$2 MV and a peak electric field E of $\approx$0.4 MV/cm. The electron kinetic energy [approximately $\frac{1}{2}m(E/B)^2$] would be >10 keV.

The time required for the stripping of any element to any desired degree in this environment is shown in Fig. 2(a). It is seen that if the containment time exceeds roughly 0.1 to 1 sec, a very interesting degree of ionization can be produced. We believe that the ion charge density should not exceed about 10% of the electron charge density, so that $n_i < 0.1 n_e/Z_{\text{eff}}$ (Z_{eff} = number of electrons removed). Since the duration of an operating cycle is principally de-

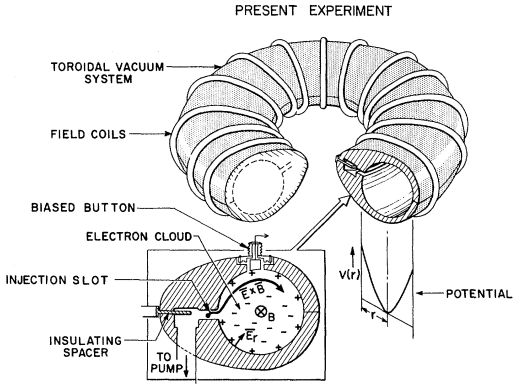

FIG. 1. Schematic diagram showing the basic features of a suggested source of highly stripped heavy ions.

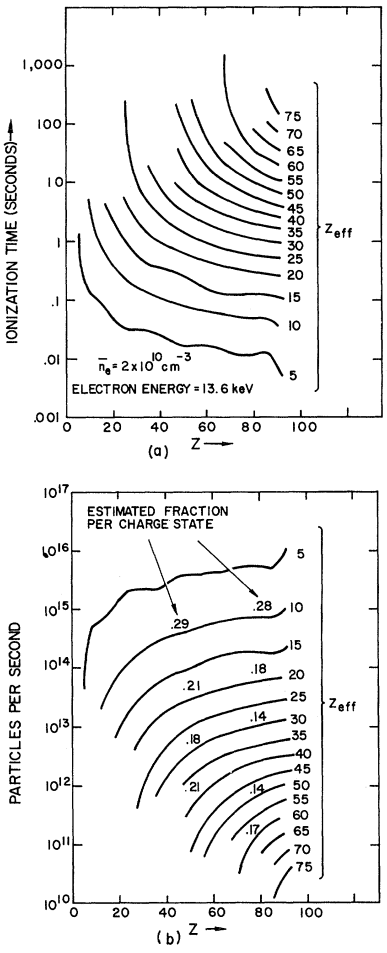

FIG. 2. (a) Time required to remove Z_{eff} electrons from element Z under the stated conditions. (b) Estimated production rate of the ion source having the general dimensions quoted in the text. The total number of ions is at any time concentrated in a few charge states. The estimated fraction of the total ions in the desired charge state is indicated.

termined by the ionization time, the average rate of production of stripped heavy ions is roughly the quotient of the total number of ions in the device and the ionization time. This quantity is shown in Fig. 2(b). A typical figure for U^{+60} (60 times ionized uranium) would be 10^{11} ions/sec. This figure allows for the fact that not all of the ions would be in exactly the desired charge state.

During the stripping phase, the ions oscillate in the potential well, their kinetic energy being least when they are nearest to the wall. Thus, although the ion U^{+60} might have as much energy as 120 MeV at the bottom of the well, extraction at the wall can be at low kinetic energies. Estimation of the energy spread of the extracted ions is difficult and depends on details of the ion trajectories which have not been investigated in general. However, for a cylinder with a parabolic potential well (an idealized case corresponding to a torus having a small ratio of minor to major radius) the energy spread depends only on the extraction time. For extraction times roughly equal to the ionization times (i.e., for a 50% duty cycle) the spread can be shown to vary from about 50 keV in Kr^{+10} to less than 1 keV in U^{+60}. It would therefore appear that an intense stream of highly stripped positive ions could be extracted from a device of this type with an energy spread sufficiently small to allow its introduction into many existing or proposed accelerators. In particular, the performance of a HIPAC accelerator would be much improved by injecting into it from an adjacent source of the type described ions already stripped to high values of the charge-to-mass ratio.

Experiments[5] have been conducted in an apparatus similar in dimensions to the example quoted. The aim of these experiments has been to study and develop the inductive charging method of injectioning the electron cloud, and to study so far as possible the containment of this cloud. With a $\dot{\Phi}$ (rate of rise of the magnetic flux threading the torus) of 800 V and an injector bias of 2.4 kV an average electron density of 4×10^9 cm^{-3} has been achieved. The experimental evidence indicates that this density can be proportionately increased by increasing these voltages. Significant increases are, of course, entirely feasible with existing high-voltage technology. A further experiment on our present apparatus lends support to the suggestion that the stripped ions can be extracted from an ion source. As shown in Fig. 1, a small biasable section of the wall was isolated, principally for use as a diagnostic technique. When biased suitably negative, this button collected ions formed during a typical experiment.

Electron containment in the experiments performed so far has been limited by a relatively poor vacuum (pressure $> 10^{-7}$ Torr) to times too short for any appreciable multiple ionizations to take place. The evidence[5] shows the electron cloud is contained for a time inversely proportional to the density. At significantly lower pressures, the electron density will greatly exceed any induced ion density, a condition which the evidence shows should be stable.

For an operating ion source, a base vacuum of 10^{-10} mm is required. At this pressure, the number density of background gas atoms is much less than even the density of the species to be stripped. A new experiment with a design vacuum of 10^{-10} mm and dimensions close to those quoted is presently under construction.

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DIRECT SPIN-PHONON INTERACTION IN SOLID He^3 †

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The spin-lattice relaxation time T_1 in solid He^3 has a complicated temperature behavior, presumably because of the existence of three energy reservoirs whose interactions are strongly temperature dependent. We have studied these relaxation mechanisms at low temperatures by modifying the spectrum of lattice phonons and observing the effect of this modification on T_1.

Previous measurements of the spin-lattice relaxation time in solid He^3 can be successfully explained in terms of the three-energy-reservoir model first applied to solid He^3 by Garwin and Landesman,[1] and since elaborated on by others.[2-5] The three reservoirs are the Zeeman, the exchange, and the lattice reservoirs. Each of the reservoirs can be characterized by a separate energy and temperature. At various temperatures different interactions between the reservoirs become important, and contribute in various degrees to the Zeeman-lattice relaxation, since the temperature of the exchange reservoir can be measured only in the limit where it is in equilibrium with either the Zeeman or the lattice reservoir.

Above about 1.3°K, the Zeeman reservoir relaxes directly to the lattice by means of diffusion.[6] As one goes below this temperature, diffusion becomes less important, and the Zeeman system relaxes to the lattice through the exchange reservoir. The interaction between the Zeeman and exchange reservoirs becomes much stronger at these temperatures than the direct Zeeman-lattice interaction and the limiting relaxation time becomes the Zeeman-exchange time since now the exchange reservoir is closely coupled to the lattice. Because the Zeeman-exchange relaxation is dependent on T_2, which is constant with temperature in this region, T_1 exhibits a plateau.

Below approximately 0.6°K, T_1 exhibits another rise which is attributable to the decoupling of the exchange and lattice reservoirs. This decoupling is due to the decreasing number of phonons by means of which the two reservoirs interact, with the two-phonon Raman interaction being more important than the one-phonon process.[7] Below about 0.2°K, T_1 develops another plateau attributed by Hunt et al.[8] to diffusion and relaxation of the spins at crystal boundaries. Below 0.1°K, Hunt et al.[8] report a further rise in T_1. This is attributed to the fact that energy transport from the spins to the heat reservoir takes place by means of a narrow band of lattice phonons, thus producing a bottleneck. An extrapolation of the expressions given by Hunt et al.[8] shows that in the geometry of the experimental arrangement described below the onset of this bottleneck comes at a rather high temperature, and thus exists throughout the temperature range of the measurements reported here.

In our experiment, the phonon spectrum of the lattice was modified by inducing a sound wave in solid He^3 by means of a piezoelectric crystal, thus enhancing the number of phonons