FULLY STRIPPED HEAVY ION YIELD VS ENERGY FOR XE AND AU IONS*

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Introduction

Synchrotrons designed originally for proton acceleration are now being modified for heavy ion acceleration. Their vacuum which is suitable for good proton operation is usually too poor for the acceleration of fractionally charged heavy ions and, consequently, they can only be used to accelerate fully stripped or bare ions. Some kind of injector accelerator must provide the necessary fully stripped ions with adequate intensity for the planned research program which means that the yields of fully stripped ions from various kinds of stripping foils must be known as a function of energy.

The Bevalac is now capable of accelerating ^{238}U ions to approximately 1 GeV/amu and measurements have shown that fully stripped ^{238}U ions are produced with good yield at these energies.[1] However, knowing the stripping yields at different energies for ^{238}U does not allow an accurate prediction for other, lower Z projectiles. Consequently, extensive stripping yield measurements were made for $^{197}_{79}Au$ and $^{129}_{54}Xe$ ions.

In addition to the stripping measurements from the direct Bevalac beam, pickup measurements were also made with specially prepared bare, one electron, and two electron ions. Since many research groups are considering heavy ion storage rings and/or synchrotrons, the pickup cross section for bare ions is important to estimate beam lifetime in terms of the average machine vacuum. Since the Mylar target provides a pickup probability similar to air, a preliminary analysis of the Xe^{54+} and U^{92+} data will be presented along with predictions for other ions ranging down to Fe^{26+}.

Experimental Procedure

Heavy ion beams of $^{197}Au^{61+}$ at 200,400,600, and 800 MeV/amu; and $^{129}Xe^{45+}$ at 85,140,200, and 300 MeV/amu were provided by the Bevalac and directed into the B40 experimental area shown in Fig. 1. Various thickness foils or targets made of Be, Mylar, Al, Cu, Ag, and Au can be inserted by remote control into the focussed beam passing down the beam line. The resulting stripped ion groups are then refocussed by a quadrupole (B40,Q2A,Q2B) onto a position sensitive ionization chamber after passing through two large bending magnets (B40,M2,M3) which disperse the charge states. The focussed charge groups are approximately 5 millimeters wide and separated from each other by approximately 3 centimeters. These charge state distributions are accumulated in a computer based multichannel analyzer for display, storage and ultimate area analysis. A complete study was made for all charge states from the incident beam charge state up to the fully stripped or bare ion state; however, this paper will only discuss the bare ion yields.

Atomic Theory Calculations

With the three sets of measurements for U, Au, and Xe ions the data can be parameterized with atomic theoretical calculations so that other projectile stripping characteristics can be fairly reliably predicted. Predictions of bare ion yields for $_{71}Lu$, $_{63}Eu$, $_{41}Nb$, and $_{26}Fe$ were calculated so that accelerator designers may interpolate from the figures for any projectile Z desired.

The yield of charge fractions of relativistic ions penetrating through foils is determined by a competition between electron stripping ("ionization") and pickup ("capture").[2] Ionization occurs if the electric field of the target atom transfers sufficient momentum to a projectile electron to eject it from its shell. Ionization cross sections vary approximately proportional to Z_t^2, where Z_t is the target atomic number.[3] For direct capture to occur, the target electron must "run along" with the relativistic projectile. In light target ions, this is unlikely, and capture is accompanied by emission of a photon ("radiative electron capture", or "inverse photoelectric effect")

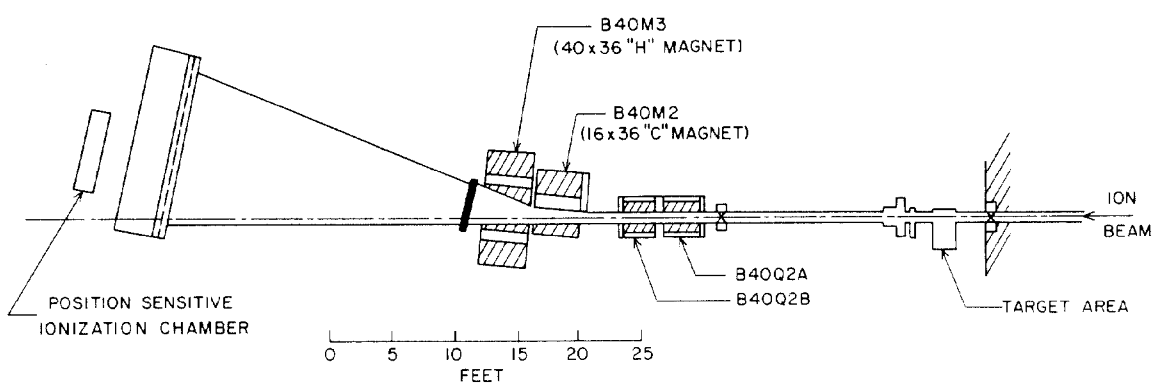

Fig. 1 Schematic diagram of the experimental apparatus (see text).

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to conserve momentum and energy. In heavy target atoms, direct ("non-radiative") capture dominates.[4] The cross section for radiative capture varies proportional to Z_t,[4] that for non-radiative capture approximately proportional to Z_t.[5,6]

The target thickness (t) dependence of the yield of a particular ion species with n electrons is fairly complicated, but after a sufficient thickness (t_{eq}) is traversed, the yield becomes independent of t.[7] At that point, there is an equilibrium between stripping and pickup of electrons. If the equilibrium yields of ions with n>2 are negligible, one can show that the equilibrium yields of ions with n=0, 1 and 2 are, respectively:[8]

$$F_0=[1+(p_0/s_1)\ (1+p_1/s_2)]^{-1}, \qquad (1)$$

$F_1=(p_0/s_1)F_0$, $F_2=(p_1/s_2)F_1$, where p_n is the pickup and s_n is the stripping cross section for an n-electron ion. One can also show, that to a good approximation the equilibrium thickness is given by[8]

$$t_{eq}= 4.6/[n_t(s_1+p_0/2)] \qquad (2)$$

where n_t is the number of target atoms per unit volume.

In Fig. 2 the equilibrium yield F_0 in mylar, Al and Cu, computed for various projectiles as a function of projectile energy is shown. Comparisons are made with these measurements and others.[1] For the stripping cross sections, relativistic plane wave Born approximation calculations of Anholt were used.[3] Expressions based on relativistic eikonal calculations by Eichler were used for the pickup cross sections.[10] Arrows on the figures indicate the calculated minimum energy that must be reached in order to obtain an 80% yield of bare ions. Table I lists the corresponding equilibrium thicknesses. For a particular projectile-target combination, t_{eq} is not very energy dependent above 300 MeV/N. Hence, Table I can be used as a guide for different projectile energies.

As previously discussed, it is important to compute the electron pickup probability for a bare ion ($=n_tp_0t$) traversing large distances in an accelerator vacuum. The pickup cross section p_0 in mylar, which has a Z_t composition similar to air is shown in Fig. 3. Here, at higher energies, capture is nearly all radiative, and there should be no disagreement with measured cross sections, since the theory (inverse photo-electric effect) is well understood.[11] The disagreements found may point to some difficulties in the measurements.

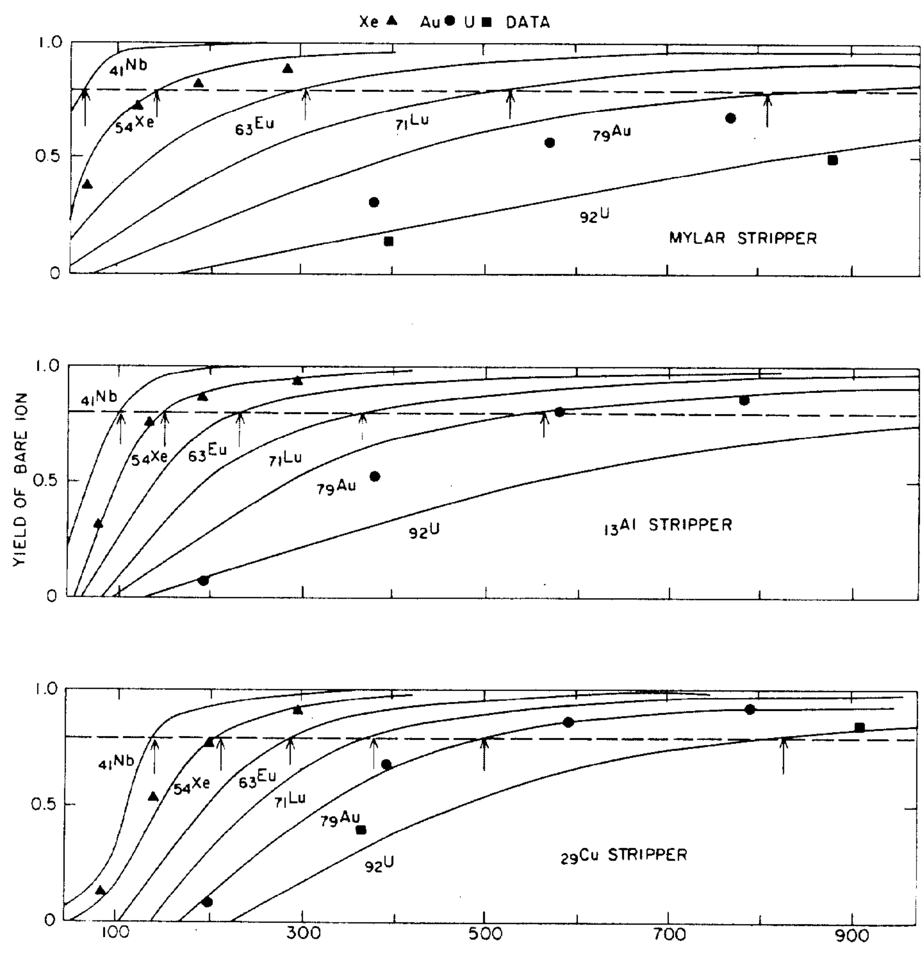

Fig. 2 Fractional equilibrium yields of bare ions stripped in mylar, aluminum, and copper foils as a function of ion energy. Arrows indicate minimum projectile energy for a calculated 80% yield. Measured yields from Ref. 9 (Au,U) and present work.

TABLE I

Projectile Energies for 80% Bare Ion Yield and Equilibrium Thickness*

Projectile	Stripping Foil					
	Mylar		Aluminum		Copper	
	E (MeV/N)	t_{eq} (mg/cm^2)	E (MeV/N)	t_{eq} (mg/cm^2)	E (MeV/N)	t_{eq} (mg/cm^2)
$_{26}$Fe	<50	<5	<50	≈3	60	1.6
$_{41}$Nb	70	25	110	15	140	8
$_{54}$Xe	160	80	150	45	210	25
$_{63}$Eu	310	170	240	85	300	45
$_{71}$Eu	530	270	370	140	380	70
$_{79}$Au	760	400	570	210	500	100
$_{82}$U	>1000	>600	≈1100	≈360	820	180

*These thicknesses are well beyond the "knee" of the bare ion yield vs. thickness curve. In order to minimize multiple Coulomb scattering in good accelerator design, 1/2 of the above thicknesses will still provide a 65-70% bare ion yield.

Future Measurements

Since the technique of preparing 0,1, or 2 electron ions has now been demonstrated for Xe, similar methods may be used in the future for U ions where all of the pickup phenomena will be under the most extreme conditions. In addition, plans are being made to check these cross sections in a few gases as well as the solids used in this work. Direct measurements in H_2 will be important for all of the ultra high vacuum heavy ion storage rings which end up with a residual tiny quantity of hydrogen as a background.

Acknowledgements

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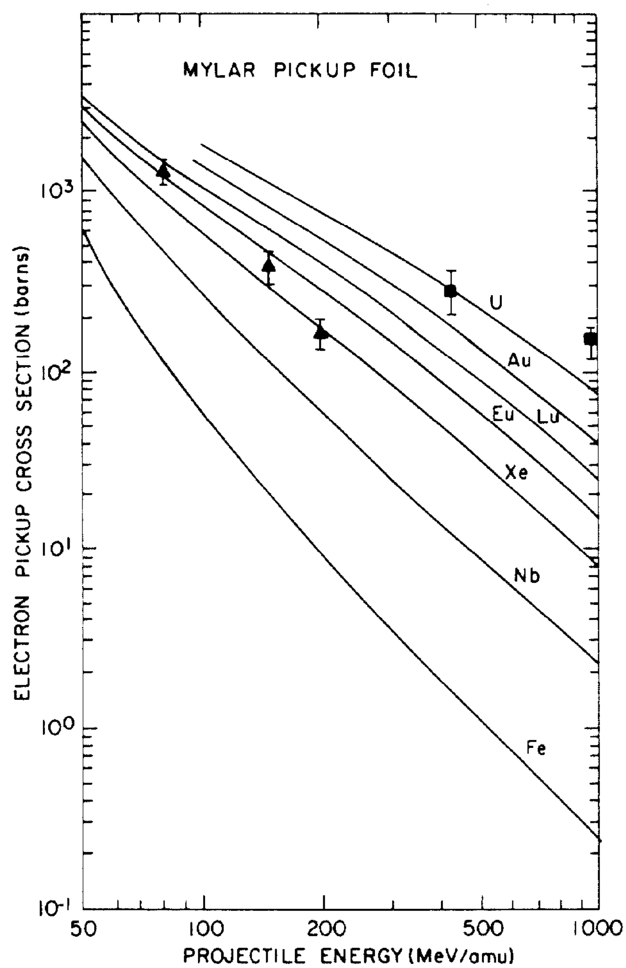

Fig. 3 Electron pickup cross section for various bare ions traversing mylar, as a function of ion energy. Measurements from Ref. 9 (U) and present work (Xe).

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