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FULLY STRIPPED HEAVY ION YIELD VS ENERGY FORXE 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. 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 $^{197}$Au and $^{129}$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 $^{197}$Au and $^{129}$Xe data will be presented along with predictions for other ions ranging down to Fe$^{56}$.

Experimental Procedure

Heavy ion beams of $^{197}$Au$^{61+}$ at 200, 800, 8000, and 900 MeV/amu; and $^{129}$Xe$^{54+}$ at 85, 850, 8500, 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, O, Ag, and Au can be inserted by remote control into the focused beam passing down the beam line. The resulting stripped ion groups are then refocused 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 $^{71}$La, $^{63}$Zn, $^{3}$He, 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"). 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 $Z^2$, where $Z$ is the target atomic number. 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).

to conserve momentum and energy. In heavy target atoms, direct ("non-radiative") capture dominates. The cross section for radiative capture varies proportional to $Z_t$, that for non-radiative capture approximately proportional to $Z_t^5$. 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 $t$. 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:

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

$$F_1 = (p_0/s_1) F_0, \quad F_2 = (p_1/s_2) F_1,$$

where $p_0$ 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

$$t_{eq} = 4.6/[n_0 (s_1 + p_0/2)],$$

where $n_0$ is the number of target atoms per unit volume.

In Fig. 2 the equilibrium yields $F_0$ 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. For the stripping cross sections, relativistic plane wave Born approximation calculations of Anholt were used. Expressions based on relativistic eikonal calculations by Eichler were used for the pickup cross sections. 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 ($=n_{pick}$) 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. The disagreements found may point to some difficulties in the measurements.
TABLE I

<table>
<thead>
<tr>
<th>Stripping Foil</th>
<th>Mylar</th>
<th>Aluminum</th>
<th>Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (MeV/N)</td>
<td>t_e (mg/cm²)</td>
<td>E (MeV/N)</td>
<td>t_e (mg/cm²)</td>
</tr>
<tr>
<td>26Fe</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>60</td>
</tr>
<tr>
<td>93Nb</td>
<td>70</td>
<td>110</td>
<td>140</td>
</tr>
<tr>
<td>54Xe</td>
<td>160</td>
<td>150</td>
<td>210</td>
</tr>
<tr>
<td>63Cu</td>
<td>310</td>
<td>240</td>
<td>300</td>
</tr>
<tr>
<td>71Cu</td>
<td>530</td>
<td>370</td>
<td>380</td>
</tr>
<tr>
<td>79Au</td>
<td>760</td>
<td>570</td>
<td>500</td>
</tr>
<tr>
<td>232U</td>
<td>&gt;1000</td>
<td>&gt;1100</td>
<td>&gt;360</td>
</tr>
</tbody>
</table>

*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 H₂ 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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