NEED FOR HEIDELBERG LINAC

Glenn Young
March 2, 1984

(BNL, January 16, 1984)
Need for Heidelberg LINAC

3/1/84

The point of this note is to look once more at the net current out of the booster as a function of injection energy.

Now that stripping efficiency numbers are available for gold from Wigner’s recent Bevalac run, a check can be made of expected currents out using known efficiencies for all three required stripers.

The argument is as follows. The booster has a given maximum Bp. The charge state of the gold injected is a strong function of injection energy. The injection energy is a strong function of charge state and the stripping efficiency of gold to Au^{74+} is a strong function of booster output energy in the range we have been discussing. However, for a fixed number of turns injected and constant input current, the total number of particles in the booster is also a strong (decreasing) function of injection energy.

This note attempts to assemble all of this.

The “bottom line”, is that for 2 stage tandem operation and 200 μA source output, 1.05 MeV/A is optimum injection energy and no LINAC is needed. For 400 μA source output, 1.7 MeV/A is optimum injection energy and the LINAC is needed.
Particles bunch out of booster as a function of injection energy into booster.

197 Au, Energy In vs Energy Out, for booster

\[ 2\pi R = 201.84 \text{m}, \quad B_p = 16.501 \text{ T-m} \]

\[ (1.2 \text{ T @ } \rho = 13.751 \text{ m}) \]

<table>
<thead>
<tr>
<th>MeV/A_in</th>
<th>β_in</th>
<th>( Q_{MP} )</th>
<th>( \text{foil} )</th>
<th>( \beta_{out}/\beta_{in} )</th>
<th>MeV/A_out</th>
<th>( \beta_{out} )</th>
<th>( E_{strip} )</th>
<th>( N_8 )</th>
<th>( N_{24} )</th>
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<td>1.84</td>
<td>5.52</td>
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\[ \beta_{in} \text{ gives the range of RF frequency swing} \]

\[ N_8 = \frac{8 \cdot 201.84 \text{ m}}{\beta_{in}} \cdot \frac{4.85 \text{ pm A (Au)}}{1.602 \cdot 10^{-19} \text{ part/cell} \cdot E_{strip}} \cdot \text{particles} \]

\[ N_{24} = 3 \cdot N_8 \]

OK, but this is not a fair comparison yet, as there is a space charge limit for the lower injection energies which cuts down their final number of particles.
Now include the space charge limit.

<table>
<thead>
<tr>
<th>MeV/A in</th>
<th>$Q_{imp}^{max}$</th>
<th>$N_{sc}$</th>
<th>$N_{sc} \times \epsilon_{ship}$</th>
<th>$N_{out}^{max}$</th>
<th>$N_{out}$</th>
<th># Turns</th>
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<td>2.24</td>
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<td>6.58</td>
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</table>

# Turns = $N_{sc} \times \epsilon_{ship} \times 8$ i.e. the number of turns to inject to reach the space charge limit at injection.

So, if we are sure at least 8 turns can be injected, then the injection energy is the limit (via space charge) up to $\approx 1.8$ MeV/A. At that point, cleverness in exceeding 8 turns into the booster is required.
However, one last factor must be included. The tandem can only produce $^{197}$Au at 1 MeV/A. To exceed this, we must include a 50% capture efficiency if we propose to use a MPI-type LINAC to boost the energy. The number for $N_{sc}$ does not change, as it depends only on the entrance charge state, booster parameters, and the injection energy. The only problem is your proposed $N_{out}$ must be decreased by 50% above 1 MeV/A if the linac is used, as proposed.

<table>
<thead>
<tr>
<th>MeV/A in</th>
<th>$Q_{ion}$</th>
<th>$N_{sc} \cdot E_{stop}$</th>
<th>$N_{out}$</th>
<th>$N_{out}^{*}$</th>
<th>$N_{out}^{24}$</th>
<th># Turns</th>
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<tbody>
<tr>
<td>0.563</td>
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<td>0.58</td>
<td>1.50</td>
<td>4.50</td>
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<td>0.75</td>
<td>2.24</td>
<td></td>
<td>46.3</td>
</tr>
</tbody>
</table>

To reach $N_{sc} \cdot E_{stop}$
Thus, the line to follow on the "TANDEM+LINAC" graph, to get the maximum particles/bunch out of the booster and into the AGS, is the "Nsc estrip" line up to 1.1 MeV/A and then the "8 TURN INJECTION" line after that. Thus, for 2 stage tandem operation, injecting 5 turns to reach the space charge limit at 1.1 MeV/A gives the greatest booster output.

For three-stage tandem operation, the optimum energy (see the "TANDEM ONLY" graph) is 1.7 MeV/A and requires 8 turn injection into the booster. However, three stage operation produces \( \text{noble} \text{Pb at } -9 \text{MeV} \text{, } \text{noble} \text{Pb at } +15 \text{MeV} \text{, } ^{197} \text{Au^{7+} at 1.42 MeV/A} \). The space charge limit then corresponds to 7 turn injection.

So, it does not appear the MPI lines will help increase the net output of gold from the booster into the AGS.

**NOTE ADDED 3/1/84**

Harvey Wagner feels the source could be pushed to 400 \( \mu \text{A} \) instantaneous current. The result of this, for 8 turn booster injection, is shown on the "Dependence on source current" graph. Then, the turn over is at 1.7 MeV/A, which needs the Heidelberg LINAC. The result is \( 2.1 \times 10^9 \) gold ions/bunch. It needs to be checked if TBS causes problems with such a number of particles/bunch.
82% 197Au\(^{79+}\) at 500 MeV/amu

\(1\) = Uranium points

\(197\text{Au}\)  MeV/amu
Incident $^{197}$Au $^{61+}$ Ions

- $800 \text{ A} \cdot \text{MeV}$
- $600 \text{ A} \cdot \text{MeV}$
- $500 \text{ A} \cdot \text{MeV}$ (82% $^{79+}$)
- $400 \text{ A} \cdot \text{MeV}$
- $200 \text{ A} \cdot \text{MeV}$

$m^9/\text{cm}^2 \text{ Cu stripping Foil}$

[Graph showing the distribution of ion species at different energies]
Equilibrium
Cu Foil for $^{197}$Au$^{61+}$
(area normalized)

Relative Percent

Energy →

79+

800 MeV/amu

600 MeV/amu

400 MeV/amu

78+

77+

200 MeV/amu

76+
800 MeV/amu
$^{197}$Au $^{61+}$

- $\sim 38 \text{ mg/cm}^2 \text{ Au}$
- $\sim 72 \text{ mg/cm}^2 \text{ Ag}$
- $\sim 145 \text{ mg/cm}^2 \text{ Cu}$
- $\sim 227 \text{ mg/cm}^2 \text{ Al}$
- $\sim 322 \text{ mg/cm}^2 \text{ C}$

Relative percent

Energy
600 MeV/amu
197 Au 61+

% of Total Beam

Cu mg/cm²

139 72 36 21 10 6

Energy →

79+ 78+ 77+ 76+ 75+ 74+
Gold Kinetic Energy "In" vs Current "Out" of Booster

DEPENDENCE ON SOURCE CURRENT

"TANDEM + LINAC"
(21 MeV/n)

8 TURN INJECTION INTO BOOSTER

PARTICLES/BUNCH (x10^9)

OUT OF BOOSTER

10^{-10} TO 1 INCH T. X. 1 INCH INCREDIBLE

400 \mu A SOURCE

200 \mu A SOURCE

E/A MeV/A OUT \theta = \frac{1}{1000}
Electron Capture by $^{91+}$ and $^{92+}$ and Ionization of $^{90+}$ and $^{91+}$

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Experimental cross sections at energies of 962 and 437 MeV/nucleon are reported for $^{92+}$ and $^{91+}$ and for the ionization of $^{91+}$ and $^{90+}$ in Mylar, Cu, and Ta, as well as equilibrium charge-state distributions in these materials. At 962 MeV/nucleon a beam containing over 85% bare $^{92+}$ nuclei is obtained.

PACS numbers: 34.70.+e, 29.25.C~. 34.50.H~

A knowledge of the electron-capture and ionization cross sections for relativistic very heavy ions has application to the determination of nuclear charge from energy-loss measurements—where the rate of energy loss is charge-state dependent—and to the design of an ultrarelativistic heavy-ion accelerator—where the use of higher charge states allows for a smaller and more energy-efficient accelerator.

In this Letter we report measurements, at energies of 962 and 437 MeV/nucleon, of the cross sections for the capture of an electron by $^{92+}$ and $^{91+}$ and for the ionization of $^{91+}$ and $^{90+}$ in Mylar, Cu, and Ta. These are the first experimental cross sections for capture and loss of an electron by a relativistic heavy ion of nuclear charge $>18$. We find that beams containing nearly 50% bare $^{92+}$ are produced by stripping 437-MeV/nucleon uranium in a 90-mg/cm$^2$ Cu target and that beams containing over 85% bare $^{92+}$ are produced by stripping 962-MeV/nucleon uranium in 150-mg/cm$^2$ Cu or 85-mg/cm$^2$ Ta targets.

Relativistic $^{98+}$ ions are obtained from the Lawrence Berkeley Laboratory Bevalac—a heavy-ion linear accelerator (Super-HILAC) and a synchrotron (Bevatron) operating in tandem. After extraction from the Bevalac, the $^{98+}$ ions pass through a Mylar ($C_2H_4O_2$), Cu, or Ta target located upstream of a magnetic spectrometer. The resulting uranium charge states are spatially separated in the magnetic spectrometer and detected by a position-sensitive proportional counter. At the proportional counter, the separation between adjacent uranium charge states is about 1 cm. The convolution of the beamwidth and the position resolution of the proportional counter is about 0.2 cm full width at half maximum. An energy loss of a few percent or less is observed for uranium ions in targets of sufficient thickness to produce a near-equilibrium charge-state distribution. No increase in the beam width is observed.

We determine the cross sections for capture and ionization by a least-squares fit of single-electron capture and loss cross sections to curves of the relative charge-state populations of $^{98+}$ and $^{92+}$ versus target thickness (Fig. 1). This is a model-independent fit which is blind...
FIG. 2. Charge-state distributions of uranium at energies of 962 and 437 MeV/nucleon for equilibrium-thickness targets of Mylar ($Z_T = 6.6$), Cu ($Z_T = 29$), and Ta ($Z_T = 73$). At 437 MeV/nucleon, Cu produces higher charge states than does Ta.

FIG. 3. Cross sections for capture of an electron by $^{192}_{99}$U and $^{234}_{92}$U at energies of 962 and 437 MeV/nucleon as a function of $Z_T$. Experimental points are for Mylar ($Z_T = 6.6$), Cu ($Z_T = 29$), and Ta ($Z_T = 73$). $\sigma_{REC}$ for $^{234}_{92}$U, calculated from Eq. (1), is shown as the continuous curve.

FIG. 4. Cross sections for ionization of $^{234}_{92}$U and $^{238}_{96}$U at energies of 962 and 437 MeV/nucleon as a function of $Z_T$. Experimental points are for Mylar ($Z_T = 6.6$), Cu ($Z_T = 29$), and Ta ($Z_T = 73$). The continuous curves are the loss cross sections calculated from Eq. (2) for $^{234}_{92}$U (upper curve) and $^{238}_{96}$U (lower curve).
The error is relatively large because only a few targets were used to cover a large range of target thicknesses and the useful data for determining the cross sections are limited to from three to six (average 4.2) charge-state distributions.

Figure 3 shows the experimental cross sections for capture of an electron by $^{229+}$ and $^{92+}$ at energies of 962 and 437 MeV/nucleon in Mylar (effective $Z_T \approx 6.9$), Cu ($Z_T = 29$), and Ta ($Z_T = 75$). Relativistic uranium captures electrons by radiative electron capture (the inverse of photoionization) and by charge exchange. We first consider radiative electron capture. With neglect of binding energy of the target-atom electrons, the cross section $\sigma$ per target electron for radiative electron capture, $\sigma_{REC}/\text{electron}$, may be written in terms of $\alpha$, the photoionization cross section, and $X$, the fraction of the shell of the uranium atom which is unoccupied:

$$\sigma_{REC} = \frac{[(\gamma - 1) + 2B_n/mc^2]^2 X \alpha}{[\gamma + 2B_n/mc^2]^2 - 1}. \quad (1)$$

Here $B_n$ is the binding energy of an electron in the $n$th shell, $m$ is the electron mass, and $c$ is the speed of light. Also, $\gamma = (1 - \beta^2)^{-1/2}$ and $\beta = v/c$, where $v$ is the uranium velocity. At 962 MeV/nucleon ($\gamma \approx 2.0$) and at 437 MeV/nucleon ($\gamma \approx 1.5$) photon energies from radiative electron capture into the K shell are 0.66 and 0.37 MeV, respectively. (Capture into higher shells lowers the photon energies by $\approx 0.1$ MeV.) The total cross sections for photoionization $\alpha$ of all shells by 0.66- and 0.37-MeV photons are 25 and 90 b, respectively. Multiplying by the number of electrons in the target atom, we obtain values of $\sigma_{REC}$ for $^{229+}$ shown in Fig. 3. $\sigma_{REC}$ for $^{91+}$ is about half as large.

The second process for electron capture is nonradiative charge exchange. Precise calculations of the relativistic cross sections for nonradiative charge exchange with a complex target atom are not yet available. Present calculations$^8$ of the charge-exchange cross sections from hydrogenlike targets by 962- and 437-MeV/nucleon $^{229+}$ find a strong dependence on the nuclear charge of the target. In low-$Z_T$ targets these cross sections are much smaller than $\sigma_{REC}$ and in high-$Z_T$ targets they are somewhat larger.

With the assumption of a negligible contribution to the capture cross section from nonradiative charge exchange in Mylar, our experimental data for Mylar are in satisfactory agreement with $\sigma_{REC}$ calculated from Eq. (1). The difference between the experimental capture cross section and $\sigma_{REC}$ for heavier targets in Fig. 3 is consistent with the increasing importance of nonradiative charge exchange for increasing $Z_T$ and decreasing projectile energy.

To calculate the cross sections for ionization of $^{90+}$ and $^{91+}$, we note that the relativistic Bethe theory$^7$ for energy loss by a heavy charged particle in matter predicts the cross sections for ionization and excitation of the target by the projectile. Reversing the role of the target and the projectile, we calculate the cross section $\sigma_i$ for ionization of $^{90+}$, $^{91+}$:

$$\sigma_i = 4\pi a_o^2 \left\{ \frac{\alpha}{\beta} \right\}^2 \frac{1}{B_K} (Z_T^2 + Z_T) f_K \left\{ \ln \left( \frac{2\beta y/\alpha^2}{0.048 B_K} \right) \right\}.$$  

(2)

Here $a_o$ is the Bohr radius of hydrogen, $\alpha$ is the fine-structure constant, $B_K$ is the binding energy of a K-shell electron in units of rydbergs (1 Ry $\approx 13.6$ eV). The quantities $\beta$ and $\gamma$ have the same meaning as in Eq. (1), $Z_T$ is again the nuclear charge of the target, and $f_K$ is a constant times the oscillator strength for transitions from the K shell to the continuum: $f_K = 0.29$ and 0.58 for $^{91+}$ and $^{90+}$, respectively. Within the experimental error, the agreement in Fig. 4 between measured cross sections and cross sections calculated from the Bethe theory is satisfactory.

In conclusion, we find that beams containing more than 85% bare $^{229+}$ nuclei can be obtained by stripping $^{238+}$ Cu and Ta targets of 150 mg/cm$^2$ and 85 mg/cm$^2$, respectively, and that beams containing about 50% bare $^{229+}$ nuclei can be obtained by stripping 437-MeV/nucleon uranium in 90 mg/cm$^2$ Cu. Our data are consistent with radiative electron capture being the dominant process at these energies for electron capture from light targets. It is clearly possible at these energies to produce beams of bare uranium nuclei for acceleration to ultrarelativistic energies and beams of few-electron uranium for atomic-physics tests of quantum electrodynamics.

We thank Mr. Douglas MacDonald, Mr. Ismael Flores, and Dr. Jose Alonso for their assistance in setting up the experiment and analyzing the data; and Professor Richard Marrus and Dr. Howel Pugh for their encouragement and support. We especially thank the operators and staff of the Bevalac whose skill and dedication made this experiment possible. This work was supported by the Director, Office of Energy Research; Office of Basic Energy Sciences, Chemical Sciences Division; and Office of High Energy and
1See, for example, J. R. Alonso et al., Science 217, 1135 (1982).