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Stripping Efficiencies for 277 MeV/amu Gold Beam on Copper Foils*

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Abstract

Stripping efficiencies were measured for 277 MeV/amu Au^{33+} ions with Copper foils ranging in thickness from 25 μm to 100 μm. The charge state distribution was analyzed using the beam line magnets of the transfer line between the AGS Booster and the AGS at Brookhaven. The relative charge state abundances were analyzed to find the optimum foil thicknesses for fully stripped Au^{79+} and Helium-like Au^{77+}. It was also possible to extract electron stripping and pick-up cross sections.

1 Introduction

For the first acceleration of Gold ions in the AGS complex to 11 GeV/amu Au^{33+} was accelerated in the AGS Booster to 277 MeV/amu and then transferred to the AGS where the final acceleration to the top energy took place[1]. Typically a 50 μm thick Copper foil was used in the transfer line between the Booster and the AGS to strip Au^{33+} to Au^{78+}. The higher charge state allows acceleration to much higher energy in the AGS but is also required because the relatively bad vacuum in the AGS would lead to excessive beam loss due to stripping by the residual gas. However, it is expected that Helium-like Au^{77+} can be accelerated in the AGS without significant losses and, as shown below, can be produced with higher efficiency than fully stripped Au^{79+}.

2 Measurement of Stripping Efficiencies

By varying two dipole magnets following the stripping foil in transfer line between the Booster and the AGS the relative abundance of the charge states Au^{77+}, Au^{78+} and Au^{79+} could be studied with a multi-wire profile monitor. Measurements were made for 25, 37.5, 50, and 100 μm thick foils. One profile alone did not cover the full charge state distribution. Therefore, several profiles had to be taken with different settings for the analyzing magnet. The profiles for different magnet settings were then combined by fitting all profiles with a single distribution made up from three gaussians corresponding to the three charge states 77+, 78+, and 79+. The gaussian distributions all had the same width and were separated by equal distances. A typical result is shown in Figure 1 and Table 1 gives the fitting parameters for the four foil measurements.

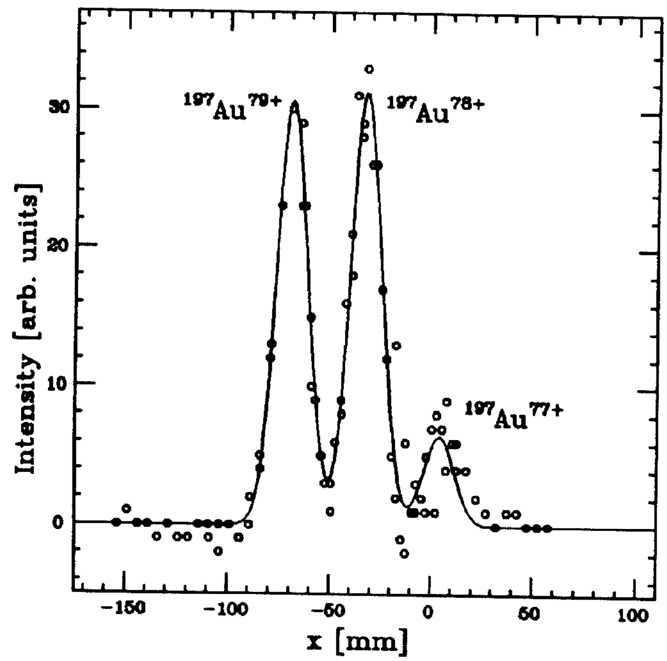

Figure 1: Fit to the charge state distribution of the measurements with the 50 μm thick Copper foil.

From the variation of the peak position of charge state 77+ with the foil thickness one can extract the energy loss in the Copper foil of 99 $\frac{MeV/amu}{g/cm^2}$. The expected value obtained from the Bethe-Bloch equation[2], which leads to the scaling law

$$\left.\frac{dE}{dx}\right|_{AXZ} = \frac{Z^2}{A} \times \left.\frac{dE}{dx}\right|_{proton} \left(p = \frac{px}{A}\right), \qquad (1)$$

is 80 $\frac{MeV/amu}{g/cm^2}$, in good agreement with the measured value. The total energy loss for the 100 μm foil was therefore about 9 MeV/amu.

The increase of the width of individual charge state peaks is due to multiple scattering in the foil which leads to an increase of the divergence and of the energy spread

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Foil Thickness [μm]	25	37.5	50	100
Center of 77+ Peak [mm]	22.6 ± 0.2	7.2 ± 0.2	3.9 ± 0.2	-18.7 ± 0.3
Width of Peaks [mm]	8.2 ± 0.3	9.1 ± 0.2	10.7 ± 0.3	13.6 ± 0.4
Abundance of 77+ [%]	51 ± 5	13 ± 1	9 ± 1	4 ± 9
Abundance of 78+ [%]	40 ± 5	44 ± 1	46 ± 1	42 ± 4
Abundance of 79+ [%]	10 ± 1	44 ± 1	45 ± 1	54 ± 5

Table 1: Fitting parameters for the four foil measurements

of the beam. In gaussian approximation the multiple scattering adds in quadrature to the initial beam width which results in the following dependency of the beam width σ on the foil thickness d:

$$\sigma = \sqrt{\sigma_0^2 + \alpha d} \qquad (2)$$

The result of a fit is $\sigma_0 = 4.8\,mm$ and $\alpha = 1.7\,\frac{mm^2}{\mu m}$. The contribution to α from increased divergence based on the gaussian approximation to Moliere's theory[3] is only $0.92\,\frac{mm^2}{\mu m}$, where we used the calculated projection factor of $9.8\,\frac{mm}{mrad}$ for the beam transport between foil and monitor. This suggests that half of the increase in the beam width is due to increased energy spread.

Clearly the foil leads to a significant beam emittance blow-up of up to a factor of 8. A more optimized situation should include a thinner foil, as discussed below, and a smaller beam spot at the foil.

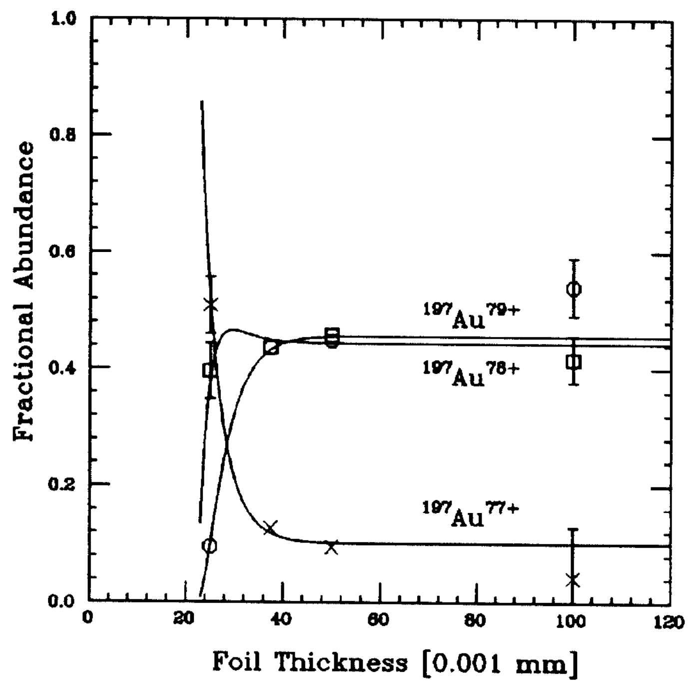

Figure 2: Relative charge state abundance vs. foil thickness. The Au^{79+}, Au^{78+}, and Au^{77+} abundances are shown as circles, squares and crosses, respectively, together with the model calculations. The model is based on rate equations between these three charge states only.

3 A Simple Model

The relative abundance of the three charge states can be understood within the framework of a simple model if we assume that after a short distance d_0 all electrons except the K shell electrons are stripped off. Beyond this initial stripping foil thickness the relative abundances of the three charge states are then determined solely by single electron pick-up and stripping between the three charge states 77+, 78+, and 79+[4]. This can be described by a set of coupled differential equations:

$$\frac{d}{dx}\begin{pmatrix} r_{79} \\ r_{78} \\ r_{77} \end{pmatrix} = \begin{pmatrix} -p_1 & s_1 & 0 \\ p_1 & -(s_1+p_1) & s_2 \\ 0 & p_2 & -s_2 \end{pmatrix}\begin{pmatrix} r_{79} \\ r_{78} \\ r_{77} \end{pmatrix} \qquad (3)$$

where r_{79}, r_{78}, and r_{77} are the relative abundances as listed in Table 1. s_1 and s_2 are stripping probabilities for $78 \rightarrow 79$ and $77 \rightarrow 78$, respectively, whereas p_1 and p_2 are the pick-up probabilities for $79 \rightarrow 78$ and $78 \rightarrow 77$, respectively. The system of linear differential equations can easily be solved. The eigenvalues are:

$$\begin{aligned} \lambda_1 &= 0 \\ \lambda_2 &= \frac{a-(p_1+p_2+s_1+s_2)}{2} \\ \lambda_3 &= \frac{-a-(p_1+p_2+s_1+s_2)}{2} \end{aligned} \qquad (4)$$

with

$$\begin{aligned} a^2 = p_1^2 + p_2^2 + s_1^2 + s_2^2 - 2p_1p_2 + 2p_1s_1 + 2p_2s_1 \\ -2p_1s_2 + 2p_2s_2 - 2s_1s_2 \end{aligned}$$

A fit to the data is shown in Fig. 2 and gives the following results:

$$\begin{aligned} d_0 &= 22.4 \pm 0.5\,\mu m \\ s_1 &= 0.20 \pm 0.04\,\mu m^{-1} \\ s_2 &= 0.27 \pm 0.07\,\mu m^{-1} \\ p_1 &= 0.19 \pm 0.04\,\mu m^{-1} \\ p_2 &= 0.06 \pm 0.02\,\mu m^{-1} \end{aligned} \qquad (5)$$

This simple model describes the dependency of the abundances on foil thickness very well, which is reflected in a confidence level of 40% of the χ^2 distribution. For a very thick foil these probabilities result in asymptotic abundances of

$$\begin{aligned} r_{77} &= 10\% \\ r_{78} &= 44\% \\ r_{79} &= 46\% \end{aligned} \qquad (6)$$

The probabilities calculated above can be used to determine absolute cross sections:

	This experiment	Predicted
$\sigma(78 \to 79)$	$(24 \pm 5) \times 10^{-21} cm^2$	$9 \times 10^{-21} cm^2$
$\sigma(77 \to 78)$	$(32 \pm 8) \times 10^{-21} cm^2$	$22 \times 10^{-21} cm^2$
$\sigma(79 \to 78)$	$(22 \pm 5) \times 10^{-21} cm^2$	$12 \times 10^{-21} cm^2$
$\sigma(78 \to 77)$	$(7 \pm 2) \times 10^{-21} cm^2$	$6 \times 10^{-21} cm^2$

The predicted cross sections are based on the relativistic Bethe-Bloch theory[2] for the stripping cross sections and on an extrapolation of eikonal calculations of non-radiative-capture for a Xe projectile on a Cu target[5]. Note that the prediction for the contribution of radiative capture is a factor of 10 smaller for a heavy target such as Cu.

4 Conclusion

This analysis shows that, even with this relative high energy beam, it is possible to produce Helium-like Au^{77+} ions with high efficiency. This can be achieved with a thin $22\,\mu m$ thick foil which also introduces only minimal emittance growth.

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