Charge Exchange Studies with Gold Ions at the Brookhaven Booster and AGS*

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Abstract

Efficient acceleration of Gold ions to $11\,GeV/nucleon$ places strong constraints on the vacuum and also on the choice of thickness and material of the necessary stripping foils. Results of a number of detailed experimental studies performed with the Gold beam at the Brookhaven Booster and AGS to determine the relevant electron stripping and pick-up probabilities are presented. Of particular interest is the lifetime of the relatively low energy, partially stripped Gold beam in the Booster and the stripping efficiency to Helium-like Au^{+77} for injection into the AGS.

1 INTRODUCTION

A Gold beam with a kinetic energy of $11\,GeV/nucleon$ is being used at the Brookhaven AGS for fixed target experiments to study relativistic heavy ion collisions[1]. In the future Gold beams will be accelerated in the Relativistic Heavy Ion Collider (RHIC) to $100\,GeV/nucleon$ to study Gold on Gold collisions at a center-of-mass energy of $200\,GeV/nucleon$. For both programs it is important to achieve high Gold beam intensities. The acceleration efficiencies at the lower energies are strongly affected by the charge exchange processes with residual gas. At the lowest energies, the losses are dominated by electron stripping for Gold ions with a significant number of electrons left and by electron pick-up otherwise. The requirements, imposed by these charge exchange processes, have to be balanced with the stripping efficiencies that can be achieved in stripping foils located between the acceleration stages.

The acceleration scheme used in 1993 consisted of stripping the Au^{14+} from the Tandem accelerator to Au^{33+} before injection into the AGS Booster at a kinetic energy of $1\,MeV/nucleon$. The beam was extracted from the Booster with a momentum of $630\,MeV/c/nucleon$ and then stripped to Au^{77+} and injected into the AGS. In the AGS, the Gold beam was accelerated to a kinetic energy of $10.2\,GeV/nucleon$ and slow-extracted for the fixed target experiments. The beam intensity could be increased six fold at Booster injection by eliminating the low energy stripping foil between the Tandem and the Booster, injecting Au^{14+} directly into the Booster. Subsequent to the measurements to be reported here the transfer line between Tandem and Booster has been modified to make this possible. The lower charge state at Booster injection increases the cross section for electron stripping. Detailed studies using the Au^{33+} beam have been performed to study whether the Booster vacuum is adequate to make Au^{14+} injection into the Booster feasible. The higher rigidity of the Au^{14+} beam reduces the Booster extraction momentum to $330\,MeV/c/nucleon$. At this lower momentum the stripping efficiencies to Au^{77+} become marginal and the stripping foil material and thickness has to chosen carefully. A detailed set of measurements have been performed with the Au^{33+} beam at lower extraction momentum and various materials and thicknesses of stripping foils to study and simulate the situation with the Au^{14+} beam. The stripping efficiencies to the high charge states are dominated by the probabilities for stripping off the last few electrons and should only weakly depend on the initial charge state of the beam. Finally, life time measurements in the AGS have been performed with the Au^{78+} beam to determine the relevant charge exchange cross sections and obtain requirements for the AGS ring vacuum.

2 MEASUREMENTS OF VACUUM INDUCED BEAM LOSSES

The Au^{33+} beam losses during the Booster's 500 msec acceleration cycle have been measured at two vacuum levels, the normal operating pressure of 3×10^{-11} Torr with over 70% hydrogen and a pressure of 1×10^{-9} Torr comprising 50% Ar and 35% CH_4. The higher pressure was reached by turning off all the ring ion pumps. The beam intensity was measured with the beam current transformer. They are normalized to the intensity 16 ms after injection and plotted against the acceleration time in Fig. 1. The calculate beam intensities using cross sections derived from empirical formula outlined in ref.[2] are also plotted in Fig. 1. Good agreement between the measured and the calculated intensity is obtained for pressure of 1×10^{-9} Torr. At the normal operating pressure of 3×10^{-11} Torr, however, the beam loss is higher than predicted. Using the same empirical formula the stripping cross sections are significantly higher for Au^{14+}. The vacuum related beam loss at 3×10^{-11} Torr is estimated to be about 40% during the Booster acceleration cycle.

Two observations suggest that this conclusion may be optimistic. First, the decrease in Gold intensity during the acceleration cycle at normal operating pressure is similar to that which would be predicted if the pressure seen by the beam were actually two or three times higher than measured. Of course another mechanism may be responsible for this loss but that mechanism has not been identified. Secondly, in an effort to increase the beam intensity, the

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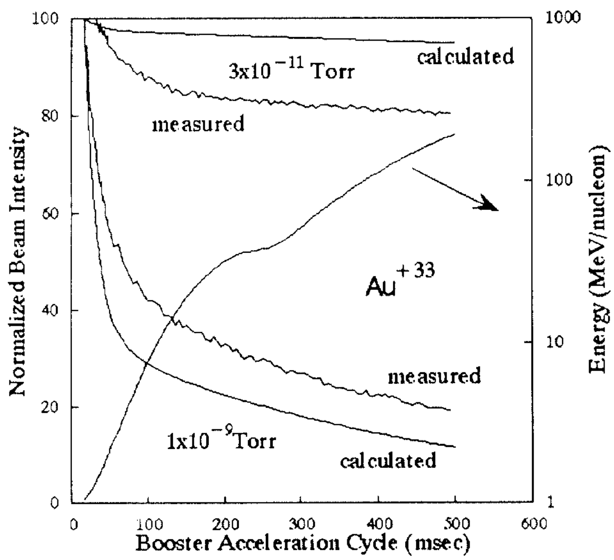

Figure 1: The fraction of survival of Au^{33+} beam during the Booster acceleration cycle at vacuum levels of 1×10^{-9} Torr and 3×10^{-11} Torr.

duration of the injected beam pulse from the Tandem was increased from $700\,\mu s$ to $1000\,\mu s$. Although the Booster intensity at injection increased as expected, the late intensity was actually lower for the longer pulse. Indications of some degradation of the vacuum at the injection point was observed though the ring average did not degrade significantly. Again if the pressure seen by the beam degraded by about 50% the results would be expected, and again an alternative explanation has not been found. Measurements of the beam profiles in both the transfer line and in Booster showed no change between the two conditions.

The survival of the Au^{78+} beam at a kinetic energy of $267\,MeV/nucleon$ has also been measured at several vacuum levels in the AGS ring. In this study, the injection flat porches were stretched from $\sim$ 50 msec to over 1 sec. The average ring pressure was raised from 2×10^{-8} Torr to 2×10^{-7} Torr by bleeding CO_2 gas through a variable leak valve into the beam chamber, which created a pressure bump up to 1×10^{-5} Torr over a 50 m zone. The beam intensity was measured by a beam current transformer during the entire flat porches. To improve statistics, the transformer signals from consecutive pulses were accumulated and averaged. The beam profile was also measured periodically with an ionization profile monitor to ensure that the beam loss due to beam blowup was negligible during the period. The results are summarized in Fig 2 where the fractions of beam survival per second are plotted against the average CO_2 pressure. The solid line represents the least square fit to the data. The total charge exchange cross section at this kinetic energy, derived from the slope of the line, is estimated to be less than $3.5 \times 10^{-21}\,cm^2$. For Au^{78+} at $267\,MeV/nucleon$, the capture process is dominated by the radiative electron capture and is estimated[3]

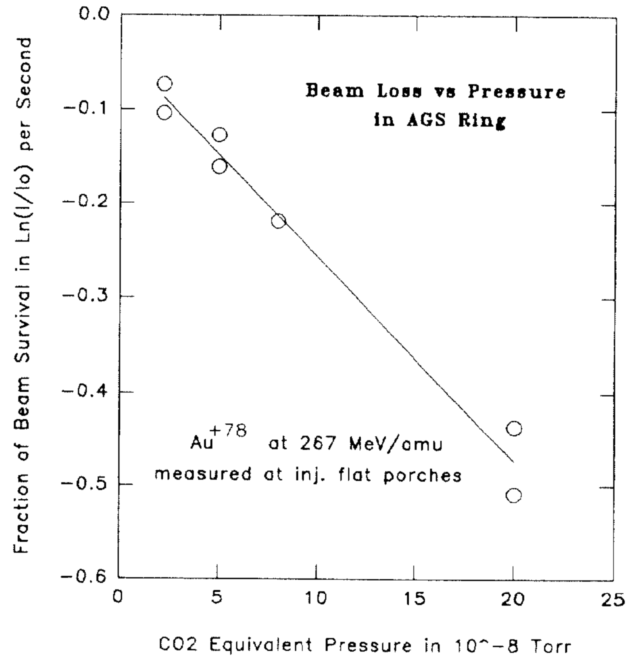

Figure 2: The fraction of survival of Au^{78+} beam at 267 MeV/nucleon versus the CO_2 equivalent ring pressure in AGS ring.

to be $5 \times 10^{-22}\,cm^2$; and the cross section for electron stripping predicted by the theory of Bethe[2] is estimated to be $1.5 \times 10^{-21}\,cm^2$. They are in reasonable agreement with the measured total cross section.

3 FOIL STRIPPING EFFICIENCY MEASUREMENTS

By varying two dipole magnets following the stripping foil in the transfer line between the Booster and the AGS the relative abundance of the charge states of the Gold beam after the stripping foil could be studied with a multi-wire profile monitor. 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 multiple gaussians corresponding to the various charge states. The gaussian distributions all had the same width and were separated by equal distances. The same technique has previously been used to measure stripping efficiencies at a higher momentum of $760\,MeV/c/nucleon$ with thicker Copper foils[4].

Measurements were performed for 7 different foils made of Copper, Aluminum and Carbon and 5 different beam momenta ranging from $330\,MeV/c/nucleon$ to $630\,MeV/c/nucleon$. Figures 3 and 4 show the results for the 27 $\frac{mg}{cm^2}$ thick Carbon foil and the 16 $\frac{mg}{cm^2}$ thick Copper foil, respectively. Clearly the measurements show the very different momentum dependence of the stripping efficien-

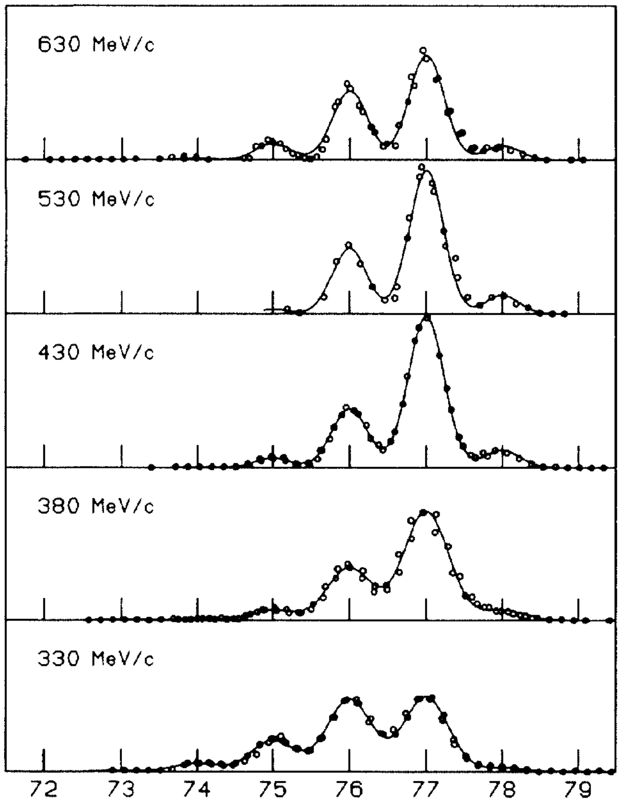

Figure 3: Charge state distribution for a 27 $\frac{mg}{cm^2}$ thick Carbon foil for various beam momenta

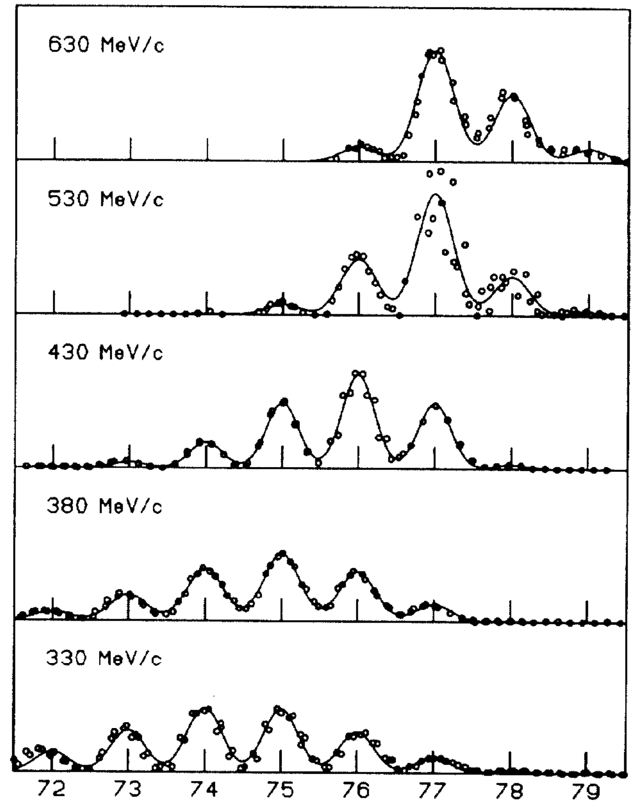

Figure 4: Charge state distribution for a 16 $\frac{mg}{cm^2}$ thick Copper foil for various beam momenta

cies for the two foils. Non-radiative electron capture[5] from the heavier target nucleus seems to significantly reduce the stripping efficiencies at the lower energies.

Table 1 summarizes the stripping efficiencies to Au^{77+} for all momenta and foils. In this energy region the stripping efficiency to Au^{79+} is quite low whereas the Helium-like Au^{77+} is produced with good efficiency and also has only minimal vacuum related losses in the AGS. At the higher momenta the heavier foil material gives better efficiencies and less beam blow-up as can be seen from Fig. 4, whereas at lower energies lighter foil material has to be used to achieve acceptable efficiencies.

Beam momentum	330	380	430	530	630
Co, 16 $\frac{mg}{cm^2}$	6.2	7.5	24.8	53.0	54.3
Al, 70 $\frac{mg}{cm^2}$	6.1	11.6	45.1	54.0	30.7
Al, 34 $\frac{mg}{cm^2}$	11.4	25.6	49.1	57.2	46.3
Al, 14 $\frac{mg}{cm^2}$	6.9	25.8	52.1	65.3	64.0
C, 56 $\frac{mg}{cm^2}$	24.9	59.8	64.7	67.5	65.1
C, 27 $\frac{mg}{cm^2}$	38.9	59.3	63.5	61.9	50.9
C, 18 $\frac{mg}{cm^2}$	36.3	48.0	45.3	53.1	36.1

Table 1: Efficiencies in percent for stripping to Au^{77+} for various beam momenta and various stripping foils

4 CONCLUSIONS

Many factors contribute to the change in accelerated Gold ion intensity as the ion charge state delivered from Tandem to Booster is reduced from 33 to 14. The present analysis predicts this change would increase final intensity, perhaps by a factor of two or three, but with some uncertainty. The satisfactory bottom line here is that the setup for the Gold run of the AGS accelerator complex in September 1994 will be done without stripping foil between Tandem and Booster, and the predictions can confront reality.

5 REFERENCES

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