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An Experimental Proposal to Study Heavy-Ion Cooling in the AGS Due to Beam Gas or the Intrabeam Scattering

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DISCLAIMER

AN EXPERIMENTAL PROPOSAL TO STUDY HEAVY-ION COOLING IN THE AGS DUE TO BEAM GAS OR THE INTRABEAM SCATTERING *

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Abstract

Low emittance of not-fully-stripped gold (Z=79) Au^{+77} Helium-like ion beams from the AGS (Alternating Gradient Synchrotron) injector to the Relativistic Heavy Ion Collider (RHIC) could be attributed to the cooling phenomenon due to inelastic intrabeam scattering [1,2] or due to electron de-excitations from collisions with the residual gas [3]. The low emittance gold beams have always been observed at injection in the Relativistic Heavy Ion Collider (RHIC). There have been previous attempts to attribute the low emittance to a cooling due to the exchange of energy between ions during the inelastic intrabeam scattering. The Fano-Lichten theory [4] of electron promotion might be applied during inelastic collisions between helium like gold ions in the AGS. The two K-shell electrons in gold Au^{+77} could get promoted if the ions reach the critical distance of the closest approach during intra-beam scattering or collisions with the residual gas. During collisions if the ion energy is large enough, a quasi-molecule could be formed, and electron excitation could occur. During de-excitations of electrons, photons are emitted and a loss of total bunch energy could occur. This would lead to smaller beam size. We propose to inject gold ions with two missing electrons into RHIC, at injection energy, and study the beam behavior with bunched and de-bunched beam, varying the RF voltage and the beam intensity. If the "cooling" is observed additional X-ray detectors could be installed to observe emitted photons.

INTRODUCTION: HEAVY ION COOLING

A program of electron and stochastic cooling of the bunched beams in RHIC is in full development stage [5].

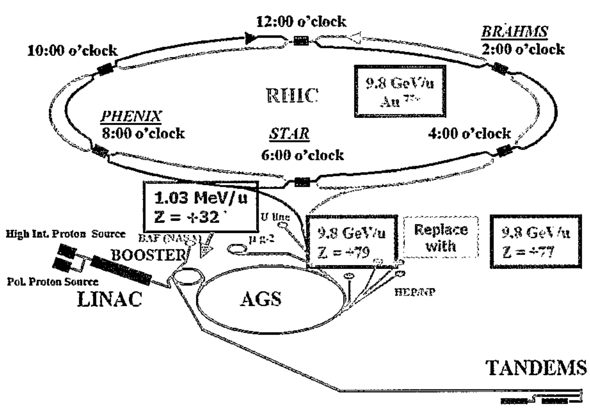

Fig. 1: RHIC layout and proposed changes.

There are already very encouraging stochastic cooling results. Heavy ion cooling has been extensively studied in small storage rings like TSR (Test Storage Ring) at Max-Planck-Institute, TARN II (Test Accumulation Ring for the Numatron Accelerator facility in Tokyo, ESR (Experimental Storage Ring) in GSI, etc [6]. Usual beam cooling techniques are stochastic cooling, electron and laser cooling. Additional cooling mechanism with a broadband lasers was suggested by E. G. Bessonov [7].

The heavy ions, extracted from the AGS, have shown always small emittance of the order of $\varepsilon \sim 10\ \pi$ mm mrad (normalized- 95%). Previous studies of a possible cooling mechanism in the AGS did not show conclusive results due to an observed beam loss. This report examines a possibility of a heavy ion cooling within RHIC with stored gold ions Au^{+77} at injection.

ELECTRON PROMOTION

Electron *"promotion"* occurs during heavy ion collisions through a formation of a quasi molecule and can be analyzed using the Born-Oppenheimer approximation. During collisions nuclei move much slower than electrons in the classical orbits. A quasi molecule made of two collision participants is formed as nuclei approach each other.

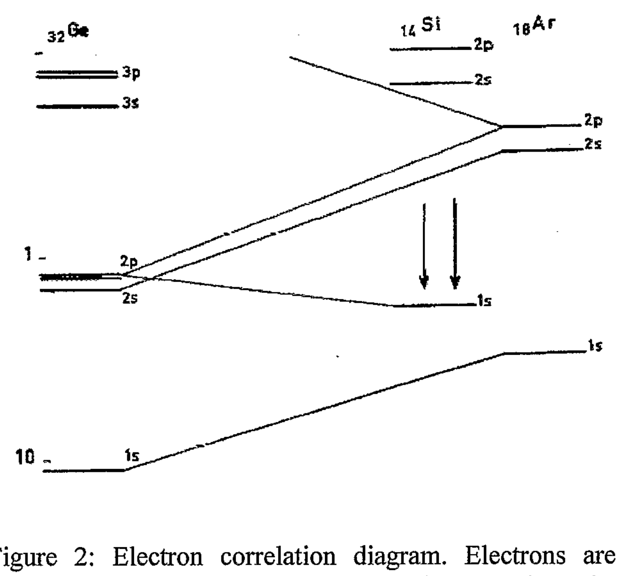

Figure 2: Electron correlation diagram. Electrons are "promoted" if the lines cross, as nuclei approach to the critical distance [8].

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At a distance of the closest approach $b=0$ the electron wave functions correspond to the molecule made of unified nuclei (energy levels of for example of the two unified gold atoms Au+Au with $Z=154$ are 1*s* ½, 2*p* ½, 2*p* 3/2 etc). The electron energy level at $r=\infty$ are of the separated ions in the example of the gold ions these will be 1*s* ½, 2*s* ½, 2*p* ½, 2*p* 3/2, etc. An electron correlation diagram can be constructed by connecting the energy levels of the single ions using the molecular orbital (MO) $1\sigma, 2\pi, 3\sigma$, by following the selection rules. *Electron-electron interactions will cause transitions between diabatic molecular orbital of like parity s-s, s-d, p-p, p-f and equal angular momentum* λ [3]. Transitions of molecular orbital of like parity and $\Delta\lambda=\pm 1$ are $\sigma-\pi$, $\pi-\sigma$ etc. As ions approach at a critical distance the energy levels cross. This indicates a high probability of *"electron promotion"* or electron transition to the energy levels of the higher shells. These transitions create electron excitations. Photon emission occurs when the electrons return to their ground state. This "loss" of energy reduces internal energy of particle within a bunch: cools the beam.

HEAVY ION COLLISIONS

The helium like gold ions Au^{+77} accelerated in the AGS could collide with the residual gas. There is a variable leak valve to adjust the local gas pressure for ionization profile monitor in the AGS while in RHIC the Hydrogen atomic JET target could be used. Two electrons in the K-shell are excited during collisions with the residual gas as the distance of the closest approach is extremely small at ~1-0.9 GeV/amu (the laboratory frame) energies. Electron excitations and X-ray emissions from the helium like ions during the beam gas collisions have been previously reported [9]. Electron excitation of the residual gas happens at the same time and are used them to obtain the beam profiles in both AGS and RHIC.

The K-X ray spectrum was obtained from the collisions of Pb+Pb quasi-molecules [10]. The K vacancy production is explained in Figure 3. The K electron is promoted from 2pσ MO to the 2pπ.

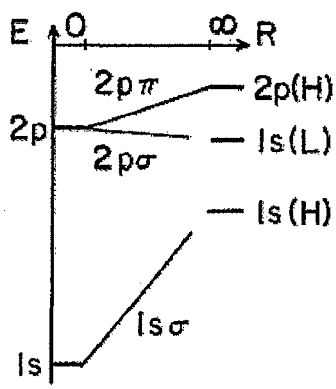

Figure 3: The K-vacancy production in symmetric Heavy-Ion Collisions and X-ray emission.

The kinetic energies of Pb lead ions of 900 MeV and 100 MeV created during collision the electron promotion and X-ray de-excitation at the distance of the closest approach of the order of b~400 fm [11]. Two photons decay measured from the gold ions Au^{+77} with energy of 106.6 MeV/n hitting the Al foil, in Darmstadt [12] is another example of the de-excitation of the excited K-shell electrons.

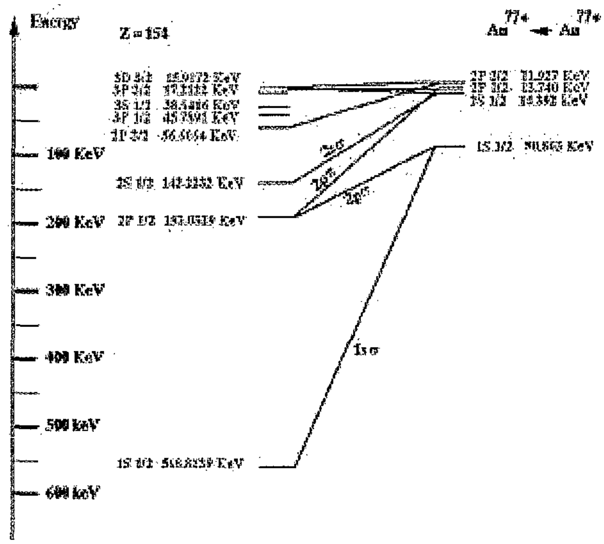

Figure 4: Energy diagram for electron promotion during gold Au^{+77}+ Au^{+77} collisions. Energy levels of the quasi-molecule are reported in [13].

The quasi-molecule formation in collisions of the gold Au^{+77} ions is presented in Fig. 4. A possible electron promotion from the 1s ½ K-shell is by the quasi-molecular orbital 2pσ-2pπ, similar as in the Fig. 3.

Intrabeam scattering

The intrabeam scattering is multiple small-angle Coulomb scattering within the charged particle beam circulating in a storage ring. During the intrabeam scattering of gold ions there are possibilities of ionization, charge transfer, elastic and inelastic collisions [1]. Of interest is a possible electron excitation during inelastic collisions and a subsequent photon emission $Au^{+77}+Au^{+77} = Au^{+77} + Au^{+77*}$. The center of mass momentum during intrabeam scattering excitation p^* is [1]:

$$p^* \Rightarrow \left\{ \frac{\Delta p_L \dfrac{1}{\gamma}}{\Delta p_T = p_o\ \theta_{x,y} = p_o\left(\dfrac{\varepsilon_x}{\beta_x^*} + \dfrac{\varepsilon_y}{\beta_y^*}\right)} \begin{array}{l} long. \\ transv. \end{array} \right.$$

The intrabeam collision energy, relevant to all cross sections, is:

$$E_c = \frac{(p^*)^2}{M} \approx \frac{1}{M}\left[\frac{(\Delta p_z)^2}{\gamma^2} + \frac{p_o^2}{\pi}\left(\frac{\varepsilon_x}{\beta_x} + \frac{\varepsilon_y}{\beta_y}\right)\right]$$

The average velocity of the gold Au^{+77} ions during the intrabeam scattering was calculated to be v_{ions}~3 x 10^5 m/s, with the relativistic factor of $\beta=10^{-3}$ or with an average kinetic energy of E_k=91.843 KeV [14]. The distance of the closest approach is $b \sim Z_1^2 e^2/E_{klab}$ = 4.89 10^{-11} m = 48900 fm. During the intrabeam scattering of gold Au^{+77} ions the distance of the closest approach is dramatically larger than for the residual gas scattering and the probability for the K-shell electron promotion is negligible. The other estimates are also small [16].

Upper Hyperfine structure excitations

Additional possibility for electron excitation during the intrabeam scattering was previously reported: *"Hydrogen like thallium ions traveling together in the same bunch would undergo low energy collisions in the intrabeam scattering which would repopulate the upper hyperfine structure. This would produce a continuous glow of the M1 decay"*[2, 15]. If the M1 decay occurs it would produce the ion cooling as the overall energy of ions is reduced.

EXPERIMENTAL PROPOSAL

Presently the gold Au^{+77} ions extracted from the AGS lose two electrons through the foil stripping and the fully stripped gold Au^{+79} ions are transported through the beam line (ATR-AGS to RHIC) and injected into RHIC:

$$p = zeB\rho_{RHIC} = 79\, e\, B\rho_{RHIC},$$

The beam momentum of the AGS:

$$p = zeB\rho_{AGS} = 77\, e\, B\rho_{AGS}.$$

The experimental proposal is to change the energy of the AGS (by adjusting the $B\rho$) from:

$$B\rho_{RHIC\_before} = \frac{79}{77} B\rho_{AGS\_before}$$

A new requirement for the AGS magnetic field:

$$B\rho_{AGS\_new} = \frac{79}{77} B\rho_{AGS\_before}$$

This would be only 2.6% larger field in the AGS magnets than during the regular gold ion operation. Injected gold Au^{+77} ions in RHIC will circulate at the injection energy. First goal is to measure and observe emittance of the stored beam in time by using the ionization profile monitors (IPM). If there is a reduction of emittance without a beam loss this will be the first confirmation of a possible cooling effect. Adjustment of the longitudinal space by the RF cavity voltage is an additional parameter to vary and observe emittance. As mentioned above, there is a possibility of using the hydrogen JET made for the proton beam polarization measurements. This might be useful if the cooling is due to the collisions of the beam with the residual gas.

CONCLUSIONS

The low emittance of the gold ions from the AGS had not being expected, and is an intriguing not yet understood. If a cooling mechanism exists either from the continuous M1 glow due to low energy collisions during intrabeam scattering and repopulation of the upper hyperfine structure [2,15] or due to beam gas scattering an emittance reduction will be possible to observe. Control of beam gas conditions is also possible by using the existing jet target. If the experiment in RHIC shows no indications of cooling, the AGS experiments should be repeated.

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