U+U COLLISIONS NEAR THE COULOMB BARRIER BY CROSSING TWO CO-CIRCULATING BEAMS

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Summary

Experiments with colliding heavy ion beams seem to come into the range of feasibility by means of beam cooling techniques. This note considers, in particular, an alternative to the use of two intersecting storage rings: crossing of two high energy beams co-circulating in one single ring, e.g. in the Experimental Storage Ring ESR [1], on separate closed orbits due to their different magnetic rigidity. Low energy collisions near the Coulomb barrier between two heavy nuclei both highly or even fully ionized or, more generally, systems not accessible to fixed target experiments could be investigated. The study of positron production in the extreme electric field of two colliding, fully stripped uranium ions would be one of the most attractive aims. Estimates for the attainable collision energy, energy resolution and luminosity are given together with a tentative outlook to the experimental arrangement.

Introduction

The results of experiments with the electron cooling of proton beams [2] promise attractive applications of this technique to heavy ion beams. This is demonstrated by a series of heavy ion storage and cooler ring projects worked out in the last years [1]. In many cases, the high phase space density of cooled heavy ion beams will be applied to increase essentially the resolution in atomic and nuclear spectroscopy. On the other side, it could enable to perform colliding beam experiments. Rough estimates of the attainable luminosity promise sufficient counting rates if the interesting reaction cross sections are not too low. Many atomic processes, e.g. electron transfer in a simple symmetric collision between U(+91) and U(+92), could certainly be studied. An example of special attraction is the investigation of the positron production mechanisms in U(+92) on U(+92) collisions at c.m. energies between 1 and 2 MeV/u corresponding to equivalent fixed target energies between 4 and 7.5 MeV/u.

There are ideas to cross a heavy ion beam circulating in a low energy storage ring with an external beam or to merge two counter-circulating beams of heavy ions with reverse charge state polarity [3]. In this case, high ionization states are available only for light ions up to Z=10 due to the low specific ion energy of beams.

Beam Crossing in the ESR

Beams of highly or totally ionized ions up to uranium will be available for the ESR from the heavy ion synchrotron SIS, which is capable to accelerate the heaviest ions up to 1 GeV/u [4]. The uranium beam will be stripped to U(+92) at 556 MeV/u, which corresponds to the maximum bending power $B\rho$= 10 Tm of the ESR, with a yield of ≈ 60%. It can be stored in the ESR and cooled by means of electrons and, if necessary, accumulated to high beam intensities. A beam of 6×10^{10} stored U(+92) with transverse emittances of 10^{-6} π m and a momentum width $\delta p/p$ of 5×10^{-4} (space charge and longitudinal instability limits) could probably be prepared without severe problems by means of electron cooling. Using the SIS 18 for intermediate storage, the cold beam could be splitted into two bunches and either of them re-injected into the ESR in two separate steps. There, the beams could be deposited and adiabatically debunched on different closed orbits.

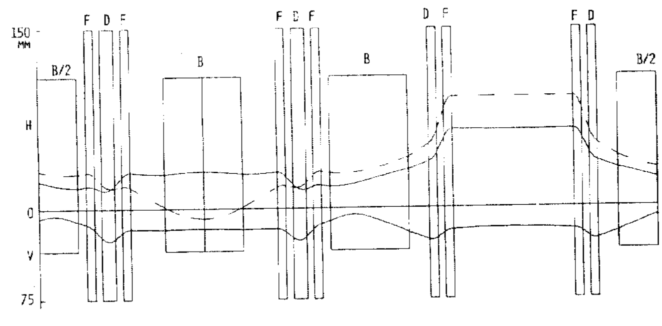

Fig. 1: Envelope functions (solid lines) for $\varepsilon(h)$= 10^{-4} π m (horizontal plane), $\varepsilon(v)$= 2.5×10^{-5} π m (vertical plane) and closed orbit for (dashed line) $\Delta p/p$=+1% in one of two superperiods of the ESR. The characteristic feature of this ion optical mode is the large amplitude of the dispersion function η over 10 m drift length, which is provided for the installation of experimental equipment [4]. By means of additional quadrupole magnets η can easily be adjusted to cross twice the central closed orbit ($\Delta p/p$=0).

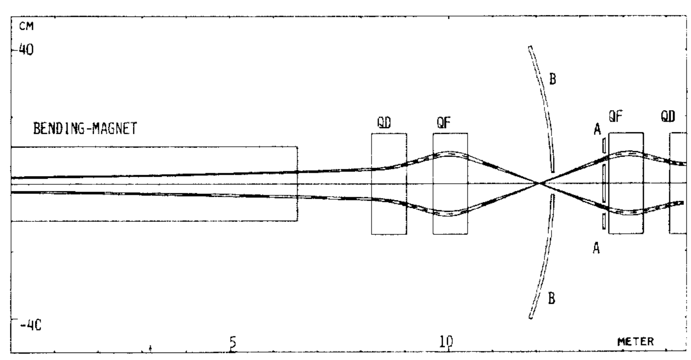

Fig. 2: Preliminary scheme of beam crossing in the ESR. A-A are position and time sensitive counters for the ions scattered out of beams. B-B designates a spherical arrangement of position and energy resolving detectors for electrons, positrons or X-rays emitted during the collision process [5].

Due to the large aperture of 30 cm diameter in the ESR quadrupole magnets, a special operation mode of the ring allows a large amplitude of the dipersion function (η=9.3 m) along the nearly 10 m long straight sec-

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tion provided for the installation of experimental equipment (Fig. 1). By means of additional quadrupole magnets η can be adjusted to cross the central orbit for $\Delta p/p=0$ at two stable positions, where also two beams having different mean momenta, co-circulating on their closed orbits, will cross each other (Fig. 2). With a relative momentum difference $\Delta p/p= 1\%$ between beams a crossing angle α of about 0.1 rad is possible.

Collision Energy

The available collision energy depends on the ion energy T, averaged over the ions in both beams, and on $\Delta p/p$. The crossing angle α is linearily coupled to $\Delta p/p$ by $\eta' = d\eta/ds$, hence, $\alpha = \eta'\ (\Delta p/p)$. If both, α and $\Delta p/p$, are assumed to be << 1, then, for symmetric systems with identical ions in either beam, the equivalent fixed target energy T(ft) is in good approximation

$$T(ft)\ [MeV/u] \simeq 0.5\ Eo\ \beta^2\gamma^2\ [\alpha^2+(\Delta p/p)^2/\gamma^2)] \qquad (1)$$

Eo= 931.5 MeV/u is the rest energy of the atomic mass unit, $\gamma = 1+T/Eo$ and $\beta^2 = 1+1/\gamma^2$.

The mean quadratic spread of T(ft) is mainly influenced by α, the emittance in the crossing plane $\varepsilon(h)$, by the momentum spread $\delta p/p$ in the beams and by the lattice functions $\beta(h)$ and η' at the crossing point. Neglecting the small contribution coming from the uncertainty of the mean momentum, i.e. of the bending fields of magnets, we get the approximate formula

$$<(\delta T(ft)/T(ft))^2> \simeq (4/\alpha^2)[(\eta')^2(\delta p/p)^2+\varepsilon(h)/\beta(h)] \qquad (2)$$

For the ESR, at T= 556 MeV/u ($\beta = 0.78$, $\gamma = 1.6$), the following parameters are assumed:

$\eta \simeq 0.1$
$\eta' \simeq 1$
$\alpha' \simeq 0.1$
$\Delta p/p \simeq 0.01$
$\delta p/p \simeq 5\times10^{-4}$
$\beta(h) \simeq 0.5$ m.
$\varepsilon(h) \simeq 10^{-6}\ \pi m$

The values for $\delta p/p$ and $\varepsilon(h)$ result from the matching of the longitudinal instability limit of a coasting beam to the space charge limit for the incoherent depression of the betatron tune $\Delta Q=-0.05$:

$$\varepsilon(h) \simeq 0.64\ R\ (\delta p/p)^2/\gamma^2 \qquad (3)$$

This approximate expression is valid if γ is far below the transition point of the ring and the mean beam cross sections and betatron tunes in either transverse direction are of comparable magnitude. The mean radius R of the central orbit in the ESR is 16.4 m. We find at T=556 MeV/u the relation $\varepsilon(h)= 4.1\ (\delta p/p)^2$ m.

From formulae (1) and (2) and the assumptions listed above we get

$$T(ft)= 7.3\ MeV/u \pm 3\%$$

for the equivalent fixed target energy attainable in the ESR with the beam crossing scheme described above. Energy variation down to below 1 MeV/u can easily be done by reducing the mean energy T of the beams. It should be mentioned that the main contribution to the error comes from the angular spread in the beams.

Luminosity

The luminosity is approximately independent of α and $\Delta p/p$. This, at first sight surprising, fact comes from the coupling between both quantities mentioned above. The increase of the crossing volume by means of smaller α is counter-balanced by the decrease of the longitudinal velocity difference between the beams. Therefore, we find

$$L[cm^{-2}s^{-1}] \simeq (N^2\beta c)/(\gamma\ h\ U^2) \qquad (4)$$

The circumference U of the ring should be as small as possible. In the ESR $U \simeq 10^4$ cm and, an effective vertical beam height h=0.2 cm seems to be feasible. We assume $N \simeq 3\times10^{10}$ ions per beam. This is a factor 2 below ΔQ-limit, because - during the first period of beam preparation (accumulation, cooling, and intermediate storage in SIS) - all ions are concentrated in one beam.

Using these numbers and the parameters listed above the luminosity estimate for the ESR at T= 556 MeV/u is:

$$L \simeq 7\times10^{23}\ cm^{-2}s^{-1}.$$

This is very low compared to the values in high energy colliders. To attain sufficiently high counting rates, the cross sections for the investigated reactions should be ≥1 barn, i.e. in the order of atomic cross sections. On the other side, L could be increased very efficiently if larger momentum spread and emittances in the beams, i.e. reduced energy resolution, would be tolerated.

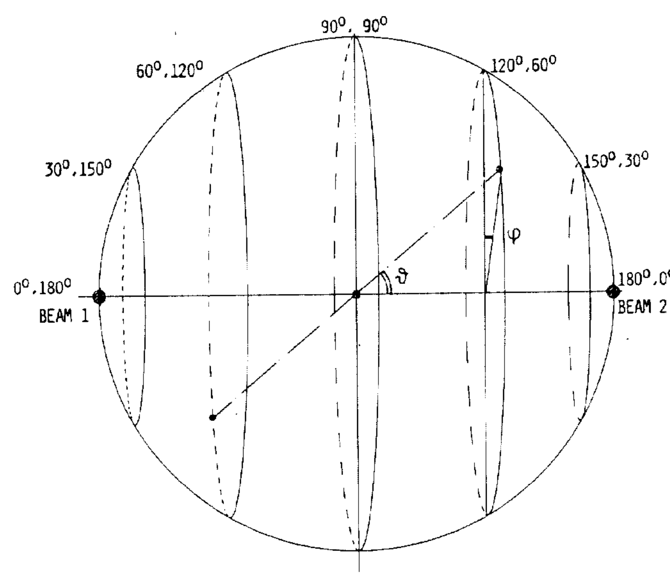

Fig. 3: Projection of c.m. eleastic scattering angles ϑ(c.m.) of a symmetric system on plane AA in Fig. 1. Due to the symmetry of the collision, one will observe in each scattering event a pair of recoils on opposite positions of the globe.

Observation of Recoils

The projection of elastic scattering angles in the c.m. system of a symmetric collision $\vartheta=\vartheta(\text{c.m.})$ on a plane perpendicular to the c.m.-motion of the crossed beams is plotted in Fig. 3. The 'equator' of the projected scattering globe belongs to $\vartheta=\pi/2$, the poles to the centres of the two beams ($\vartheta=0$ or $\vartheta=\pi$). Compounds of the collision partners would be found in the centre of the envelopping circle. Due to the longitudinal momentum difference between the colliding ions the lines of constant ϑ are overlapping ellipses. Best resolution is found in peripherical zones where, fortunately, the solid angle fraction is large.

By means of fast position sensitive detectors - a time resolution of $\delta t \approx 10$ ps would be needed - forward and backward scattered recoils could be discriminated and the three- dimensional scattering globe be reconstructed. However, in symmetric collisions, c.m. scattering angles ϑ cannot be discriminated from $\pi-\vartheta$. The resolution of ϑ is, moreover, determined by the projection of the beam crossing volume on the detector and the lattice functions at the crossing point.

Observation of Electrons or Positrons

The investigation of positron production in the supercritical Coulomb field of two colliding, totally stripped uranium ions is one of the most exciting possibilities of using the described crossed beam technique. Due to the low dynamic cross section for this process $\sigma \simeq 0.12$ barn [5] one could expect counting rates of 0.084/s or one count every 12 s. This rate is reduced by the duty factor (< 1) and the fraction of c.m. solid angle accessible to the counters (≈ 0.6). Altogether, the estimate shows that this special experiment would consume much operation time of the ESR.

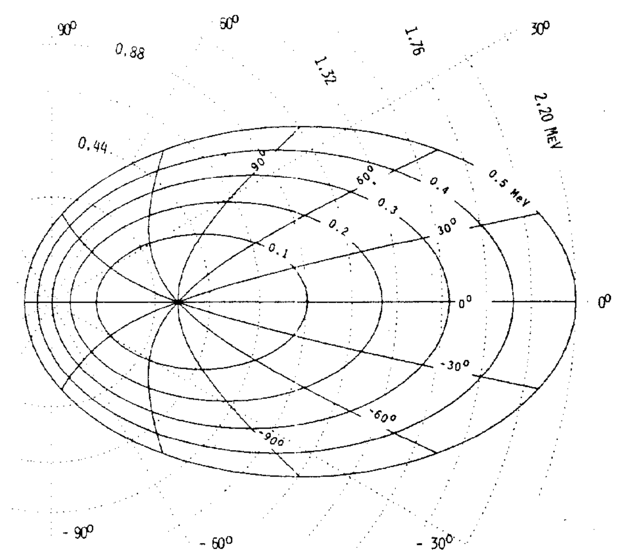

Fig. 4: Direction (radial lines) and energy (circles) in the laboratory system of electrons emitted at different angles (curved lines) and energies (ellipses) in the c.m. system. The c.m. is moving from left to right with $\beta = 0.78$.

Electron and X-ray emission can be expected from all energetic binary collision between heavy ions where at least one of the ions possesses electrons. Of special interest is the study of heavy quasimolecules with only one or few electrons. Measurements of energy and angular distribution of emitted electrons or MO-X-rays in coincidence with the c.m. scattering angle $\vartheta(\text{c.m.})$ could give valuable information about inner shell excitation mechanism and binding energies without any perturbation by outer electrons. The cross sections for these processes are typically 1 barn or larger and electron or X-ray counting rates are expected to be $\geq 1/\text{s}$.

The relativistic transformation of energy and direction of electrons emitted from the collision moving with the c.m. velocity $\beta=0.78$ at T=556 MeV is illustrated in the polar diagram of Fig. 4. In the laboratory system the c.m. solid angle is focused to the foreward direction. The ellipses are lines of constant c.m. energy of the emitted electrons, the dotted circles lines of constant energy in the laboratory frame. The plot describes, how for an observer in the laboratory frame, i.e. for the counters B-B in Fig. 2, the electrons emitted from the moving system are shifted in energy and direction. For instance, the full solid angle of electrons with energies of 0.1 MeV (c.m.) is observed in the laboratory system within $\pm 30°$.

Conclusions

Atomic physics experiments using two crossed heavy ion beams co-circulating in a single ring seem to be feasible. In the ESR the attainable collision energy, expressed in terms of equivalent fixed target energy, is 7.3 MeV/u - i.e. comfortably above the Coulomb barrier for collisions between the heaviest ions - and can easily be varied down to below 1 MeV/u. The spread in the collision energy of a few percent appears to be tolerable for the major part of experiments. The luminosity of nearly 10^{24} $\text{cm}^{-2}\text{s}^{-1}$ will allow the study of atomic processes with cross sections ≥ 1 barn.

This study of the principle has to be extended to a detailed investigation of more technical problems as, for example, beam preparation procedure, beam instabilities in the crossing mode and space charge interaction between beams, especially beam-beam tune shifts. In addition, in-ring detectors suitable for ultra-high vacua near 10^{-11} mbar have to be developed and background problems to be investigated. At least, some experience with the ESR operation will be required until one would decide to install expensive equipment for this experimental technique.

References

[1] B. Franzke, "Heavy Ion Storage Rings for Atomic Physics", this conference

[2] G.I. Budker et al., 5th Nat. Conf. on Particle Accelerators, Dubna/USSR 1976, Proceedings, p. 236 (1976)

[3] CRYRING Report, Research Inst. of Physics, Stockholm, (March 1985)

[4] K. Blasche, D. Böhne, B. Franzke, H. Prange, "The SIS Heavy Ion Synchrotron Project", this conference

[5] H. Backe, D. Schwalm, "Arbeitstreffen über Experimente am geplanten ESR", GSI note, p. 79 (1984)