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Future experiments using forward electron spectroscopy to study the quantum dynamics of high-Z ions at the ESR/CRYRING storage rings

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Abstract

At the FAIR facility for antiproton and ion research, the new ESR + CRYRING combination of storage rings CRYRING@ESR opens up a wealth of opportunities for in-ring atomic physics experiments on few-body quantum dynamics. The low-energy storage ring CRYRING will serve in its new location at FAIR/ESR for experiments with decelerated antiprotons and highly charged ions. We will discuss selected new experiments in the field of quantum dynamics of high-Z ions, for example for adiabatic superheavy quasi-molecules transiently formed with bare and H-like projectiles. Such experiments will be for the first time possible at the future CRYRING at ESR.

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(Some figures may appear in colour only in the online journal)

1. Introduction

Ion storage rings such as the Experimentierspeicherring (ESR) and the Testspeicherring (TSR) have for many years offered powerful tools by providing highly luminous beams and extremely clean conditions for fundamental experiments in atomic spectroscopy and collision dynamics. In the following, we illustrate splendid opportunities opened by

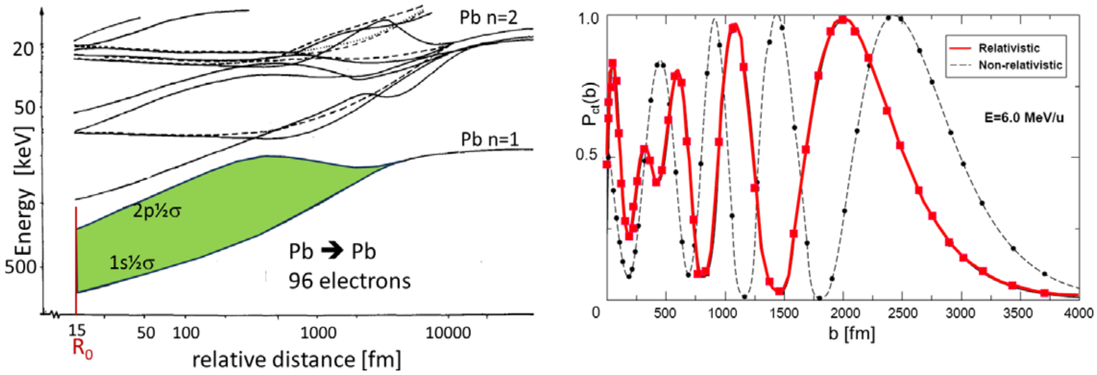

Figure 1. Left: dependence of innermost MOs and $\Delta E(R)$ on internuclear separation R; right: oscillation of 1s–1s vacancy transfer probability P for $U^{91+} + U^{92+}$ collisions [3, 4] as a function of impact parameter b.

integrating the storage ring CRYRING into the FAIR project at GSI [1, 2]. The CRYRING storage ring (magnetic rigidity $B\rho \leqslant 1.44\,\mathrm{T\,m}$) to be transferred from the Manne Siegbahn Institute in Stockholm will receive beams from the ESR and thus may store heavy ions up to $Z = 92$ in charge states up to H-like and bare ions for energies from about 0.1 to 10 A MeV. This configuration will thus decisively extend the current range of energies of the ESR to very low collision energies significant for highest resolution spectroscopy and adiabatic collisions in the realm of strong perturbations. Whereas the differential ionization cross section for fast U^{28+} projectiles is considered to be urgent as a benchmark for theoretical predictions with predictive power concerning beam lifetimes and collisional losses, the spectroscopy of superheavy quasi-atoms and the kinematically complete bremsstrahlung experiment can also commence immediately after completion of transfer of the CRYRING to the ESR.

2. New avenues toward a spectroscopy of inner orbitals in transient superheavy quasi-atoms $Z > 100$

The future combination of the CRYRING storage ring with the existing ESR storage ring will open unprecedented, previously not available possibilities for investigation of the 1sσ molecular orbital (MO) in transient superheavy quasi-molecules. Storage ring technology has now enabled us to produce and store intense beams of bare U^{92+} and H-like U^{91+} at energies ranging from 1 to 10 A MeV in the CRYRING and from 10 to 400 A MeV in the ESR. This option of H-like and bare projectiles at very low collision velocities, where the ion velocity v_{proj} is very much smaller than the velocity v_{K} of an electron in its K-shell, i.e. $v_{\mathrm{proj}} \ll v_{\mathrm{K}}$, is the all-decisive step beyond the experimental situation existing previously. Whereas the corresponding early experiments at GSI were dependent on producing a vacancy in the K-shell of one of the collision partners on the incoming part of the trajectory in order to create positrons or an MO x-ray emitted around the turning point and distance of closest approach R_0 of the trajectory, the new storage rings permit controlled experiments where every projectile brings one or even two K-vacancies into the collision—this amounts to an enhancement of several orders of magnitude.

The collision velocity and impact parameter dependence of the transfer probability P for a K-vacancy from the projectile into the target produces characteristic oscillations (figure 1(b)) as P contains the impact parameter (b)-dependent integral over $\Delta E(R) = E_{1s\sigma}(R) - E_{2p\sigma}(R)$, where R signifies the internuclear distance [3–5]. The transfer probability P can be shown in a two-state approximation to be given by an instructive and illustrative formula (1):

$$P \sim \sin^2\left[\frac{1}{v_{\mathrm{proj}}}\int_{R_0}^{\infty} \Delta E(R)\frac{R}{\sqrt{R^2 - R_0^2}}\mathrm{d}R\right]. \tag{1}$$

With these new conditions now high-resolution experiments on electron-, positron- and MO x-ray emission during those phases of the collisions come into reach, where for bare and H-like projectiles in the course of a sufficiently close collision around the turning point R_0 an empty or singly occupied 1sσ MO may be diving into the Dirac sea (see also figure 1(a)) [3, 6]. It is to be emphasized that the CRYRING is an almost indispensable facility for these experiments as its lowest energy for usefully stored bare highly charged ions is well below that practical for the ESR. For a sensible investigation of quasi-molecules, one has to take into account that their 'lifetime' during a collision quickly decreases with increasing collision velocity—this makes the CRYRING such a supremely attractive facility for all studies of transient superheavy quasi-molecules. Experiments will study the collision dynamics and MO structure of transient superheavy quasi-molecules—beginning with $Xe^{53+} + Xe$—via the emission of electrons, positrons or x-rays in coincidence with outgoing recoil ions and the projectile's scattering angle in order to determine the impact parameter, i.e. the internuclear distance during the collision event [3–5]. Suitable forward imaging electron spectrometers, reaction microscopes and large-area two-dimensional (2D) position-sensitive x-ray detectors will be designed and employed. We anticipate that for commencing experiments with superheavy systems with $Z_{\mathrm{UA}} > 137$, the system Hg^{80+}–Hg is an attractive first candidate: the promising 2D and three-dimensional (3D) MOTs for Hg described in the literature [7] shall be adapted to operate within a reaction microscope in the storage ring in order to offer the possibility for a symmetric truly superheavy collision system. A homologous 2D–3D MOT for Li has been successfully implemented into the TSR at the MPI-K, Heidelberg by Fischer *et al* [8].

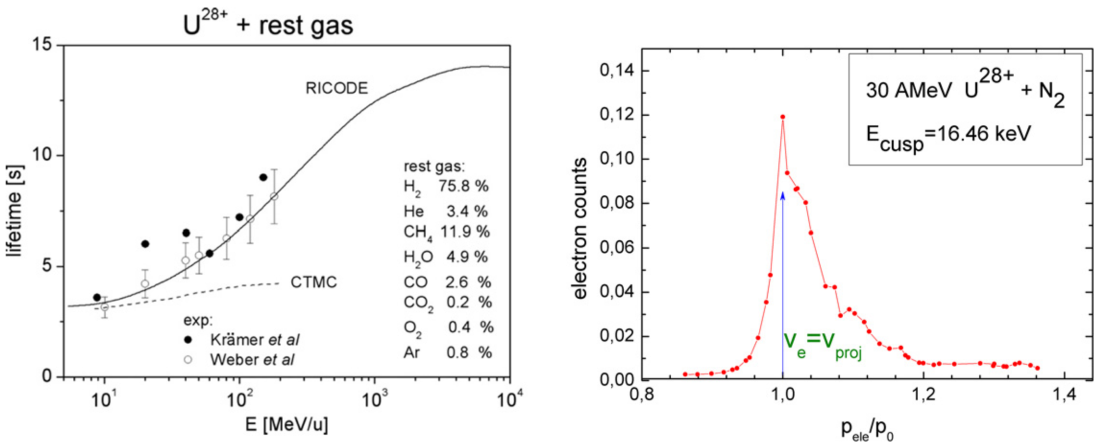

Figure 2. Left: comparison of measured beam lifetimes of U^{28+} in SIS with calculations [9, 10]; right: 0° electron loss to the continuum cusp for 30 A MeV U^{28+} in ESR; note the strong asymmetry of the cusp [15].

3. 20–50 A MeV U^{28+} + He: dynamics of single- and multi-electron projectile ionization (ELC) via 0° electron spectroscopy

For the future accelerator project FAIR, very high intensity beams of relativistic high-*Z* projectiles such as uranium are envisaged; the needed luminosity of the beam can only be achieved for such ions of high *Z* when a low charge state q of the ion to be accelerated keeps the space charge limit ($\sim A/q^2$) at a high level [9, 10]. A technically optimal solution for the existing UNILAC accelerator facilities serving FAIR is uranium beams with a mean charge state 28+ (i.e. $\ldots 4f^{14}5s^25p^2$) accelerated to 7.1 A MeV in the UNILAC and then further in the Schwerionensynchrotron (SIS) 12/18 to 50 A MeV. The SIS12/18 needs to inject 1.3×10^{11} ions at 2.6 Hz into the SIS100 synchrotron, which then provides beams from 400 A MeV to 2.7 A GeV for experiments. For the charge state 28+ of the U beam, the dominant beam loss is projectile ionization $U^{28+} + \{A\} \rightarrow U^{(28+n)+} + \{A^{+*}\}$ with $n \geqslant 1$; a fraction exceeding 40% has been calculated [9–12] for multiple loss $n \geqslant 2$ arising from the large number of weakly bound electrons on the projectile ($E_B = 930$ eV for the ionization potential of U^{28+}). Attempts at first-order theoretical description of the ionization of U^{28+} in fast collisions ($v_e \ll v_{\text{projectile}}$ for outermost electrons) have surprisingly produced mixed results. The complication arises from dense unoccupied states above the least bound electron in U^{28+}([Kr]$4f^{14}5s^25p^2$). So at all times multiple excitation of electrons from f-states to close-lying bound states will compete with single and multiple direct ionization of s- and p-states [13, 14], whose binding energies differ very little; thus autoionization out of excited manifolds arising from 4f will then merge with direct ionization continua (see figure 2). It is thus straightforward to see that first-order theories of direct single ionization will most likely miss describing the actual ionization process [13, 14]; at this time the total cross sections reported by first-order theories are not able [13, 14] to predict single differential cross sections for electrons in the continuum. It is in our view thus imperative to measure differential cross sections for the electron projectile ionization cusp in U^{28+} in coincidence with the outgoing charge state of the projectile to unambiguously distinguish between direct single and multiple ionization contributions for a first critical benchmark for theory.

4. Radiative e^- capture into the projectile continuum (RECC) and the high-energy endpoint of e^- nucleus bremsstrahlung

It is intended to substantiate the theoretically claimed deep relations between electron–nucleus bremsstrahlung in the immediate vicinity of its high-energy endpoint, the photoionization of the high-*Z* ion and the radiative recombination into bound states in kinematically complete experiments for most stringent tests of the currently most advanced theories [16, 17]. In inverse kinematics the inelastically scattered electron corresponding to electron–nucleus bremsstrahlung at the high-energy endpoint, i.e. near complete kinetic energy loss of the incident electron, is to be found in a very low-lying near-threshold continuum state of the projectile. Its emission characteristics and angular distribution (see figure 3) can thus be conveniently investigated using 0° electron cusp spectroscopy and imaging forward electron spectroscopy. For every bremsstrahlung photon emission direction, one can thus obtain the in-plane and out-of-plane angular distribution of the corresponding electron for complete reconstruction of the fundamental electron–nucleus bremsstrahlung process at the high-energy tip. This has, for reasons given above, so far never been accomplished in standard kinematics and can only be done at CRYRING@ESR.

5. 20–50 A MeV U^{92+} + Xe: topologically stable multi-electron transfer to the projectile continuum (ECC) for Sommerfeld parameter $q/v \gg 1$

Experiments under adiabatic conditions with perturbation $q/v > 1$ have shown that in multiple ionization there does not appear the usual 'cusp' of low-energy electrons close to $v_e \approx 0$; in the adiabatic case, surprisingly, instead a topologically stable multi-electron transfer into the projectile continuum dominates. This is entirely at variance with expectations derived from electron emission observed in fast ionizing collisions of very heavy ions that single

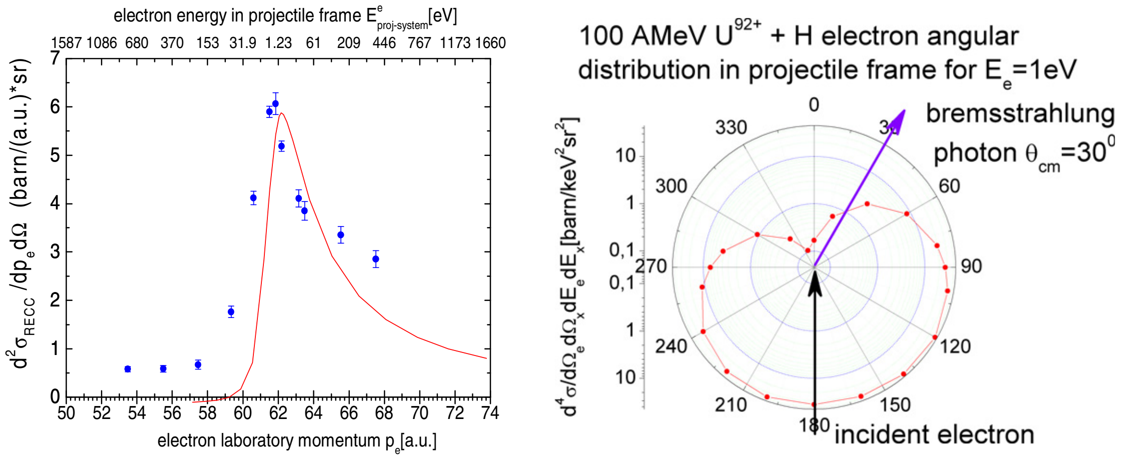

Figure 3. Left: RECC cusp for 90 A MeV $U^{88+} + N_2$ [16, 17]; right: theoretical electron distribution for 1 eV electrons coincident with a bremsstrahlung tip photon emitted at 30° [16, 17].

and multiple electron continua are dominated by electrons being removed with minimum momentum transfer into the continuum and thus electrons are found with low kinetic energies near threshold in the laboratory; instead, for the slow adiabatic collisions with a large Sommerfeld parameter $q/v \gg 1$, the multi-electron continuum is dominated by a sharp ECC electron cusp at $v_e = v_{proj}$ [18]. This indicates that some new propensity rule may be active, which one may speculate leads phenomenologically to near conservation of the nodes in the electron density profile during transfer. This observation can at this time not be described by theory. For the future CRYRING at FAIR, it is intended to investigate for the strongest perturbation for highly charged $U^{91+,92+}$ ions transferred from the ESR in adiabatic collisions the electron continua corresponding to multiple ionization up to complete atomic fragmentation with a reaction microscope and in complete kinematics. These experiments are expected to provide necessary benchmarks for advanced *ab initio* theories for describing the apparently highly structured multi-electron continua generated in strongly perturbing highly adiabatic collisions.

6. Unambiguous 1s ionization via (e, 2e) using H-, He-like projectiles: $U^{91+}(1s) + He \rightarrow U^{92+} + e_1(\theta_1) + e_2(\theta_2)$

The interest in (e, 2e) experiments at storage rings such as CRYRING@ESR with highly charged ions is based on the following reasoning: (a) Highly charged ions in storage rings such as CRYRING or ESR provide in inverse kinematics luminosities for (e, 2e) experiments on ions exceeding by orders of magnitude those feasible for classical electron ion-target collision experiments. (b) (e, 2e) experiments measuring triply differential cross sections (TDCS) for inner-shell ionization (applying inverse kinematics using highly charged ions with bare outer shells, for example U^{91+} instead of U^{1+}) removes essential ambiguities arising from multiple outer-shell ionization in measurements of TDCS for inner-shell ionization [19, 20]. (c) The TDCS for ionization in the Wannier regime close to the ionization threshold is of particular importance theoretically [21, 22]. The narrow impact energy range above the threshold of validity of Wannier theory (typically a few eV) for ions is open to debate for ions/atoms other than H or He, particularly when the Z dependence is considered. The situation is even less clear for highly charged ions with charge states $q \gg 1$. It is in this context decisive to note that the momentum transfer vector, which is very meaningful at collision energies well above threshold because it provides an orientation axis for most of the emitted electrons, loses its relevance entirely close to threshold [14]. This axis corresponds to the direct ionization amplitude but is meaningless for the other ionization amplitudes (exchange and resonance/capture) that close to threshold in the Wannier region, however, have magnitudes comparable to the direct amplitude. (d) The tremendous success of *a priori* theories such as exterior complex scaling and convergent close coupling [21–27] in correctly producing the full TDCS for H and He over the entire collision energy range had given rise to hopes for a final theoretical solution of impact ionization [26, 27]. However, it was found that the validity of these two most advanced theories at this time is indeed restricted to bound s-states and H- and He-targets. Already for the initial p-states of Ne they fail to reproduce the experimental TDCS cross sections. It is thus of utmost importance to provide experimental benchmarks for TDCS for 1s ionization for ions of H- and He-isoelectronic sequences for medium and high Z as well as for Ne- and Ar-isoelectronic sequences for closed p-shells. Experiments will be performed with a reaction microscope and the 2D position-sensitive in-ring forward electron spectrometer, for medium Z in the CRYRING and for high Z in the ESR.

7. Summary

We have presented a selection of experiments on the quantum dynamics of high-Z ions that will exploit the singular opportunities created by the ESR/CRYRING combination of storage rings.

Acknowledgment

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