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Low-lying dielectronic resonances of Fe XXII for accurate energy determination of autoionising Rydberg levels on boronlike cores

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Abstract. We present high resolution measurements of dielectronic recombination (DR) of Fe XXII forming doubly excited Fe XXI. These measurements were performed at the Test Storage Ring (TSR) of the Max-Planck-Institute of Nuclear Physics (MPIK). Low-lying DR resonances allow precise energy determination of the doubly excited autoionising levels in Fe XXI and, with suitable future calculations of Rydberg binding energies ($n \geq 7$), of 2$s^22p$ to 2$s2p^2$ excitation energies of the boronlike Fe XXII core.

1. Introduction
Experiments at the TSR have shown that highly precise DR measurements can compete with optical spectroscopy at determining the core excitation energy of a highly charged lithiumlike ion if the autoionising state is sufficiently low-energetic [1, 2]. Such determination of the core excitation energy from DR resonances relies on accurate calculation of the highly-excited Rydberg electron eigenstates. As higher order effects like QED corrections are negligible for the Rydberg electron due to its large distance to the atomic nucleus, its binding energy can be computed within the framework of many-body perturbation theories (MBPT) [1].

While highly precise MBPTs exist for helium- and lithiumlike ionic cores, work on more complex systems with several valence electrons is still underway. We measured low-lying DR resonances of boronlike Fe XXII at an energy resolution much better compared to a previous measurement performed on this system. Our data can thus serve as a testbench for future atomic structure calculations aiming at accurately determining the total energy of the corresponding doubly excited autoionising states.

2. Overview of the experiment
The MPIK's tandem-booster accelerator facility was used to produce a beam of $^{56}$Fe$^{21+}$ at a total kinetic energy of 250 MeV. This beam was injected and stored in the TSR at a magnetic rigidity of about 1.1 Tm. The TSR's electron cooler was used to cool the ion beam down to a cross-section diameter of about 1 mm. Beam cooling with the electron cooler was practically instantaneous, thus a continuous injection scheme could be used during the measurements, in contrast to a more common mode of operation, where, following an ion injection, data taking has to be interrupted for several seconds in order to give the beam time to cool down. While
DR is the resonant capture of a free electron by an atomic ion through an intermediate, doubly-excited state. The incident electron is bound in a high Rydberg state while its energy is absorbed into an ionic core excitation. Subsequently the autoionising state stabilises radiatively, completing the recombination process.

Figure 2. Schematic view of the heavy ion storage ring TSR and close-up view of the electron target. In a straight section of the TSR, the stored ions are collided with a cold electron beam. Recombination products are separated from the stored beam at the TSR’s bending magnet following the electron target and are counted by a scintillation detector.

Circulating ion currents as high as 65 $\mu$A could be achieved through multiturn-injection and electron cooler stacking, low currents of about 5...10 $\mu$A were used in the experiment in order to avoid heating of the ion beam by intra-beam scattering.

In another straight section of the storage ring, the TSR’s second merged electron beam – referred to as the “electron target” – was used to collide the stored ions with a cold electron beam of well defined energy [3]. The collision energy arises from velocity detuning of the electron beam with respect to the ions. At the TSR bending magnet following downstream of the electron target, the charge-changed recombination products are separated from the stored beam, and the electron-ion recombination rate is measured using a scintillation counting detector.

3. Achieving high energy resolution
In order to achieve the highest possible energy resolution in a merged-beams DR measurement several aspects are of importance.

3.1. Low-lying DR resonances
It is a fundamental property of the merged-beams technique that its resolution is highest close to the condition of vanishing electron-ion collision energy. The collision energy arises from the velocity difference $\Delta v$ between electrons and ions. In a non-relativistic approximation on can write

$$E_{\text{coll}} \approx \frac{m_e}{2} \Delta v^2 = \left( \sqrt{E_e} - \sqrt{\frac{m_e}{m_i} E_i} \right)^2 \approx \frac{m_i}{m_e} \left( \frac{\Delta E_e}{4E_i} \right)^2 ,$$

where $E_e$ and $E_i$ are the kinetic energies, and $m_e$ and $m_i$ the masses of electrons and ions respectively. $\Delta E_e$ is the lab-frame energy detuning of the electron target beam. One sees that the collision energy $E_{\text{coll}}$ in the centre-of-mass frame of electron and ion is approximately proportional to the lab-frame energy detuning squared. Thus for small detunings, the resolution in the collision energy $E_{\text{coll}}$ improves linearly with $\Delta E_e$ as one approaches the point of velocity matching between the two beams.
3.2. Independent cooler and target beams

The TSR is the world’s only heavy-ion storage ring featuring two independent electron beam merging sections. For DR measurements the electron beam has to be detuned from velocity matching with the ion-beam. In the case of a single electron beam, the ions velocity will change as they feel a friction force in the velocity-detuned electron bath. While this can to some extent be prevented by fast switching of the electron beam between cooling and collision modes, electron-induced changes of the ion velocity remain the dominant resolution limiting factor for collision energies below 1 eV for DR measurements performed with a single electron merging section [1].

However, usage of the TSR’s independent electron target section completely eliminates this limitation, as the ion velocity continues to be defined by the dedicated electron cooler, even for very small detunings of the electron target beam corresponding to collision energies of only a few meV [3].

3.3. Ultra-cold electron target beam

The target beam is produced by a cryogenic photoelectron gun based on GaAs-photocathodes [4, 5]. This electron source provides a free electron gas of an initial thermal energy spread $k_BT = 10...15$ meV [4]. Magnetic expansion of the electron beam by guiding field ratios of typically 20 to 40 reduce the kinetic energy spread transverse to the beam propagation direction down to $k_BT_\perp = 1...2$ meV. Subsequent acceleration to ion velocity kinematically reduces the longitudinal velocity spread down to values $k_BT_\parallel \approx \text{few } 10^{-5}$ eV in the centre-of-mass frame.

4. Experimental results

The experimentally determined recombination rate coefficient of Fe XXII is shown in figure 3. The improvement in energy resolution compared to an earlier measurement also performed at the TSR, but employing the electron cooler alone [6], is significant. Our measurement with the

![Figure 3](image1.png)

**Figure 3.** Our experimental recombination rate coefficient for Fe XXII forming Fe XXI (solid red) and indicative DR resonance positions, calculated assuming a hydrogenic potential for the Rydberg electron and using core excitation energies taken from [7]. The dotted black curve is an earlier TSR measurement performed using only the electron cooler [6].

![Figure 4](image2.png)

**Figure 4.** Blow-up of the highlighted part of the experimental DR spectrum shown in figure 3 (red dots). A fit to the data (solid black) suggests that the four lowermost lines in the observed spectrum are individually resolved. The fit assumes delta-shaped DR resonances convoluted with the electron velocity distribution in the target beam. The resonance positions are indicated in blue.
electron target unveils complex resonance structures at electron-ion collision energies of 100 meV to 600 meV which were previously washed-out by the limited energy resolution of the electron cooler.

The origin of the magnitude difference between both measurements is unclear. It could arise from the fact that we used – in an effort to achieve the lowest possible beam temperature – low ion currents of 5...10 µA. At such low currents the TSR’s build-in beam diagnostics is estimated to be accurate to around 40%. Thus we might underestimate the ion-current which would lead to a systematically too high recombination rate coefficient. It should be noted however, that the energy scale calibration of the measurement is ion-current-independent, i.e. an uncertainty in the ion-current measurement does not affect the spectroscopic reliability of the data.

A simple calculation of the Rydberg binding energies in the Dirac approximation indicates that 3 excitations of the Fe XXII core from its $2s^22p(2P_{1/2})$ ground state [7] can lead to doubly excited Rydberg states of energies below 0.6 eV:

$$\text{Fe}^{21+} \left[ 2s^22p(2P_{1/2}) \right] + e \rightarrow \left\{ \begin{array}{l}
\text{Fe}^{20+} [2s2p^2(2P_{3/2}) 7j], \Delta E_{\text{core}} = 123.032 \text{ eV} \\
\text{Fe}^{20+} [2s2p^2(2P_{5/2}) 8j], \Delta E_{\text{core}} = 94.130 \text{ eV} \\
\text{Fe}^{20+} [2s2p^2(4P_{1/2}) 11j], \Delta E_{\text{core}} = 50.158 \text{ eV}
\end{array} \right. \ (2)$$

The respective core excitation energies $\Delta E_{\text{core}}$ are taken from [7] which reports an absolute uncertainty of ±37 meV for the three transitions. Each principal number $n$ of the Rydberg electron leads to a $j$ series of DR resonances (c.f. figure 3). Due to angular momentum coupling between Rydberg and core shell electrons, each $(n, j)$-state itself splits into fine structure components of total angular momentum $J$. In a more accurate calculation the states of low $j$ are expected to be shifted to lower energies as the quantum defect rises for orbitals of small angular momentums. Some states might even be shifted down to negative energies and thus not contribute to dielectronic recombination.

Figure 4 shows a blow-up of the lowest-lying lines observed in the recombination rate coefficient in the energy range 100 meV ... 160 meV. A fit to the data assuming 4 delta-shaped DR resonances convoluted with the electron velocity distribution in the target beam is also shown. The quality of the fit suggests that these four lines are individually resolved. They appear thus suitable to accurately derive the energies of the corresponding autoionising Rydberg levels $(2s2p^2 n_j j)$ for $n = 7, 8, 11$ once they can be identified on the basis of theoretical calculations.

5. Conclusions

Employing the Heidelberg TSR’s twin merged beam setup and ultracold electron target, low-energy dielectronic resonances on boron-like iron ions have been measured at highest spectroscopic resolution. In the energy range below 0.6 eV, the number of observed resonances is at least doubled compared to earlier measurements [6]. A fit to the data suggests that the four lowermost autoionising Rydberg states with a boron-like excited core are individually resolved and thus promise sensitive probing of awaited theoretical predictions for these energy levels.

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