RADIATIVE RECOMBINATION OF HEAVY BARE NUCLEI AND IONS IN ELECTRON COOLING SYSTEM

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Abstract

An overview of experimental data of radiative recombination (RR) rate of nuclei (from helium to uranium) and various intermediate charge states of ions in electron coolers is presented at the report.

The fit of RR rates energy dependence the electron energy shift is found (formula (1) below). This dependence is significantly different from that one presented in theoretical works of H. Kramers and R. Schuch. It was found also the dependence of bare nuclei RR rates on transverse temperature as $T_\perp^{-0.95}$ that differs with theoretical result obtained by M. Bell and J. Bell.

Analysis of the experimental data for cooled heavy ions in intermediate charge state shows a RR critical dependence on the ion charge state (electron configuration of ion shells). Particularly, for some charge states RR rate increases essentially having a resonant character.

The estimations of RR rate losses of the Au^{32+}, Au^{33+}, Au^{50+}, Au^{51+} ion beams in the electron cooler of the Booster is presented. The limitation of Au^{79+} ions lifetime by RR process in the electron cooler of the Collider NICA is analyzed and measures of its increasing are considered.

INTRODUCTION

Application of the electron cooling of heavy ions to the Booster and the Collider of the NICA accelerator facility is necessary to obtain the project luminosity [1]. However, according to the theoretical models [2]-[4] RR can significantly affect the beam losses in the Booster and the Collider NICA. Therefore an experimental verification of theoretical formulae validity is of a great importance. Such a verification has been performed on the basis of the experimental works results [5]-[16].

THE BARE NUCLEI EXPERIMENTAL DATA ANALYSIS

The experimental data of RR rate dependence on the electron energy shift ΔE (relatively to optimal electron energy value) in different electron coolers for different nuclei U^{92+} [5], Bi^{83+} [6], Ar^{18+} [7], Cl^{17+} [8], Si^{14+} [9], Ne^{10+} [10], N^{7+} [9], C^{6+} [11] and He^{2+} [9] can be fitted (Fig. 1 a, b) with the following formula:

$$\nu_{Z\to Z-1}^{\text{Fitted}}\left(\Delta E\right) = a_1 \cdot Z^2 \cdot \left(\frac{\Delta E + b_1}{\text{Ry}}\right)^{-3/8}. \qquad (1)$$

Here $\nu_{Z\to Z-1}^{\text{Fitted}}(\Delta E)$ is RR rate fit in cm^3/s; ΔE is electron energy shift from its optimal value in the particle rest frame (PRF); a_1=2.8·10^{-13} cm^3/s and b_2=2·10^{-4} eV are the fit parameters; Ry=13.6 eV is the Rydberg constant. In all figures below the fit is shown with black dot line.

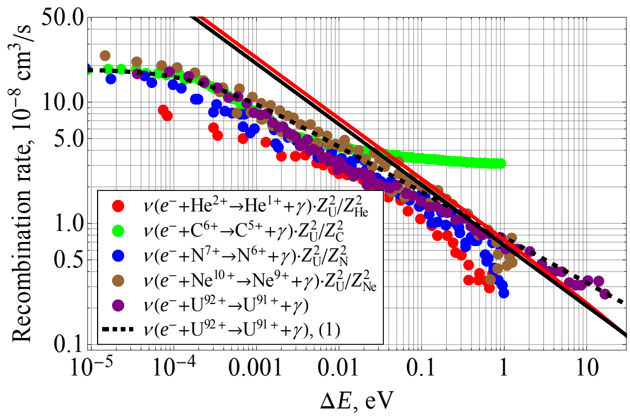

Figure 1 a. Experimental values of RR rates in 10^{-8} cm^3/s for bare nuclei: U^{92+} [5], Ne^{10+} [10], N^{7+} [9], C^{6+} [11] and He^{2+} [9] (in dots) and theoretical dependences by Kramers [2] (red line) and Schuch [3] (black line); the black dot line is the fit with formula (1).

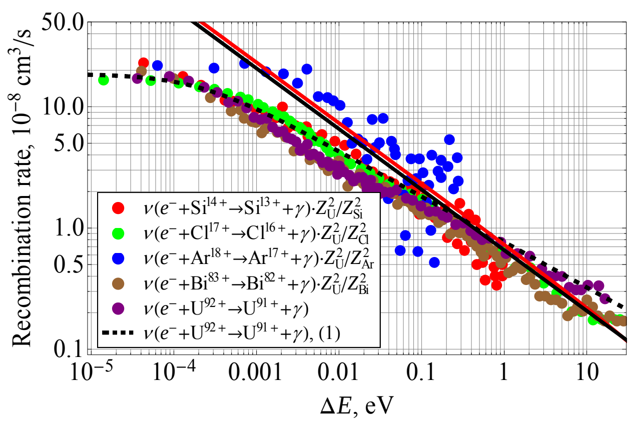

Figure 1 b. Experimental RR rates in 10^{-8} cm^3/s of bare nuclei U^{92+} [5], Bi^{83+} [6], Ar^{18+} [7], Cl^{17+} [8] and Si^{14+} [9] (in dots) and theoretical dependences by Kramers [2] (red line) and Schuch [3] (black line); the black dot line is the fit with formula (1).

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Note that in Ref. [5]-[11], the RR rates are given for energy shift in the Laboratory RF: $\Delta E_{\text{lab}}=\gamma_Z\cdot\Delta E$, where γ_Z is the Lorentz factor.

The experimental results shown in Fig. 1 were recalculated to common scales: ordinate values by multiplying with ratio of $Z^2_{\text{nucl}}/Z^2_{\text{U}}$, abscissa as $\Delta E=\Delta E_{\text{lab}}/\gamma_Z$. As the data in Fig. 1 a, b show, the normalized experimental results for most of the nuclei in the whole ΔE range are well described by the approximating formula (1) (taking into account the coefficient $Z^2_{\text{nucl}}/Z^2_{\text{U}}$).

The C^{6+} nucleus RR rate (Fig. 1 a, green dots) is also well described by formula (1) at $\Delta E<0.01$ eV, but differs significantly at $\Delta E>0.01$ eV. Similar deviation takes place for Ar^{18+}. However, both experimental results have been obtained with rather poor accuracy.

In Fig. 1 a, b the calculations based on the Kramers [2] and Schuch [3] formulae for $n_{\max}=Z_{\text{U}}$ are shown also. One can see their significant disagreement experimental data.

Consequently, we can assume that the dependence (1) applicable to other heavy nuclei.

In Ref. [5], [6] the dependence of the RR rate of the U^{92+} and Bi^{83+} nuclei on the longitudinal magnetic field value in the cooling system is presented (Fig. 2). As can be seen from this figure, the magnitude of this dependence is mostly manifested at $\Delta E<0.1$ eV.

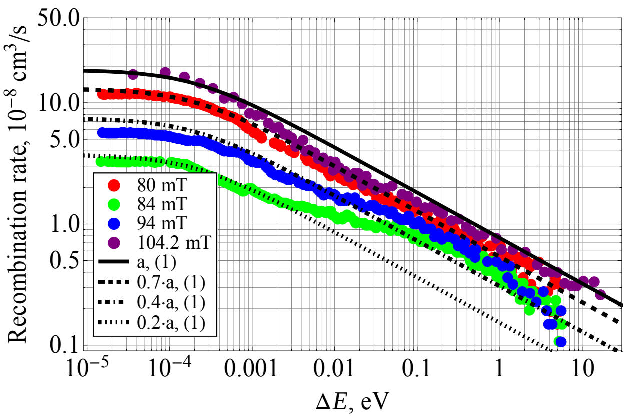

Figure 2: RR rates in 10^{-8} cm^3/s of U^{92+} depending of D*E* measured at four different magnetic guiding field values [5].

Most probably this effect is related to the electron beam quality that varies with fine tuning of the magnetic field ("the resonant optics effect").

ANALYSIS OF THE EXPERIMENTAL DATA FOR IONS IN INTERMEDIATE CHARGE STATE

The RR rate vs. electron energy shift ΔE measured for ion U^{28+}([Xe]6s^{2}4f^{7}5d^1) [12] and the fit with formula (1) are presented see Fig. 3. One can see a perfect agreement the experimental data and the fit. One should note this ion has "solitary" electron in the shell 5*d*.

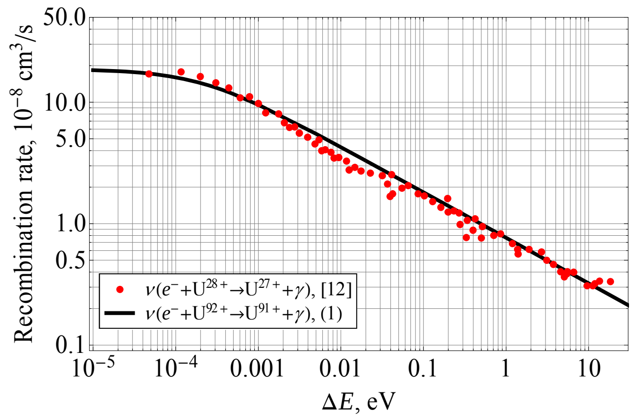

Figure 3: Experimental RR rate in 10^{-8} cm^3/s of U^{28+} ions (dots) [12] and fit with formula (1) (solid line).

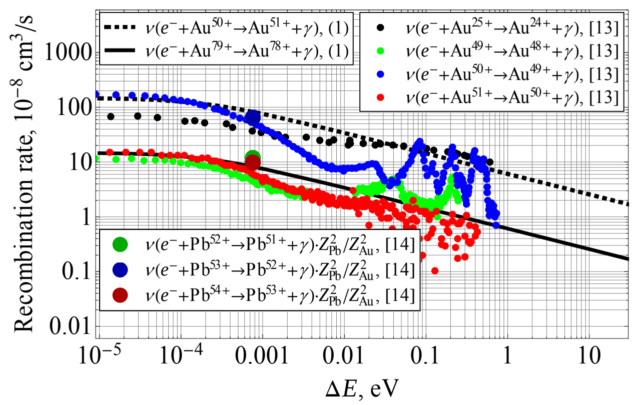

Figure 4: Dependence of experimental RR rates of intermediate charge state of Au^{25+}, Au^{49+}, Au^{50+}, Au^{51+} ions [13], Pb^{51+}, Pb^{52+} and Pb^{53+} ions [14] on electron energy shift (colored points) fitted with formula (1) for Au^{79+} nuclei black dots and solid curves).

Moreover in Fig. 4, one can see there two pronounced levels of RR rates which differ by one order of magnitude practically. The higher level to the ions having one missing electron in outer shell.

Note that the configuration of the electron shells are similar for pairs of ions: Au^{51+} and Pb^{54+} are [Ar]4s^{2}3d^8, Au^{50+} and Pb^{53+} are [Ar]4s^{1}3d^{10}, Au^{49+} and Pb^{52+} are [Ar]4s^{2}3d^{10}, Au^{48+} and Pb^{51+} are [Ar]4s^{2}3d^{10}4p^1. The RR rates for these ion pairs have close values (Fig. 4). As we understand these data in Fig. 5 were taken at optimal cooling conditions when ΔE~1 meV.

The same peculiarity can be seen in the experimental dependence of the RR rates of different ions on the number of electrons in the ion shells (Fig. 5).

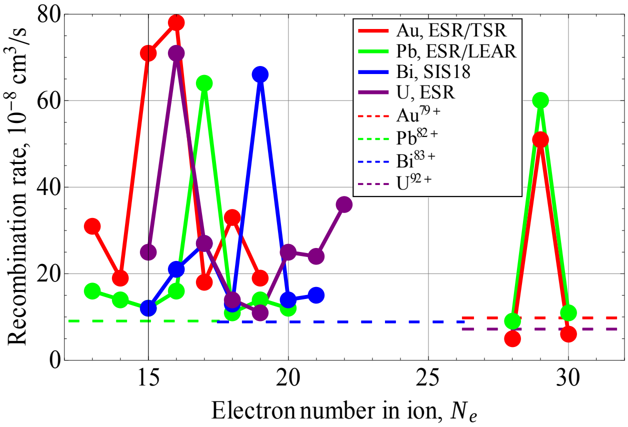

Figure 5: Experimental RR rates in 10^{-8} cm³/s of intermediate charge state of gold [13], [15], lead [14], bismuth [15] and uranium ions [15]. The horizontal dashed lines correspond to the bare nuclei RR rates of the same ions (not scaled by $Z^2_{\rm nucl}/Z^2_{\rm U}$).

As one can see, the majority of ions RR rates are close to those ones of the corresponding bare nuclei. However, for some ions the RR rates are larger by almost one order of magnitude higher than the RR rate of the corresponding nuclei. That looks like a resonance capture for ions which have one missing electron in outer shell see Au^{50+} (N_e=29), Pb^{53+} (N_e=29). The same situation we have for Bi^{64+} (N_e=19) and Pb^{65+} (N_e=17). However there are exceptions of such a simple model: N_e=19 for Au^{60+}, Pb^{63+}, U^{73+} and N_e=17 for Au^{62+}, U^{75+}, Bi^{66+}.

RADIATIVE RECOMBINATION RATE DEPENDENCES ON TRANSVERSE TEMPERATURE (ESR EXPERIMENT)

The RR rate dependence on electron transverse temperature has been studied in the ESR experiment [16] for U^{92+} nuclei at energy of 400 MeV/u. The electron transverse velocity was varied with application of transverse electric field. The experimental data analysis show that initial electron gun cathode temperature was less than 0.1 eV. Approximation dependence of experimental data (Fig. 6) on electron transverse temperature $T_\perp$ (average kinetic energy of electrons in crossed fields) can be fitted with the following formula:

$$\tau^{\rm Fitted}_{\rm ESR} = a_2\left(\frac{T_\perp}{\rm Ry}\right)^{b_2},$$
$$\tau^{\rm RR}_{\rm NICA} = \left(\frac{\gamma_{\rm NICA}Z_{\rm Au}}{\gamma_{\rm ESR}Z_{\rm U}}\right)^2 \frac{\eta_{\rm ESR}}{\eta_{\rm NICA}}\frac{n_{e,\rm ESR}}{n_{e,\rm NICA}}\tau^{\rm Fitted}_{\rm ESR}. \qquad (2)$$

Here fit parameters are $a_2=3\cdot10^4$ s, b_2=0.95; $\gamma_{\rm ESR}$=1.43 is Lorentz factor of uranium nuclei at 400 MeV/u; $\tau^{\rm RR}_{\rm NICA}$ and $\tau^{\rm Fitted}_{\rm ESR}$ are RR time in seconds. The second formula in (2) has to be applied for lifetime estimation in a cooler ring (e.g. Au^{79+} in Collider NICA).

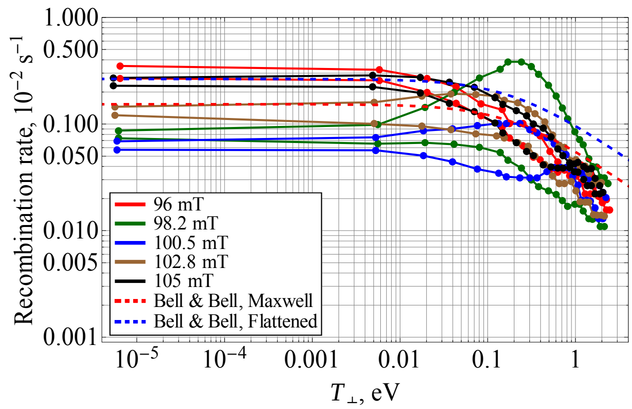

Figure 6: RR rates of U^{92+} nucleus vs. transverse electron temperature $T_\perp$ ESR experiment [16].

ESTIMATION OF IONS LOSSES IN BOOSTER AND NUCLEI LIFETIME IN COLLIDER NICA

The definition of the RR time $\tau^{\rm RR}_{q\to q-1}$ is as follows:

$$\tau^{\rm RR}_{q\to q-1} = \frac{\gamma^2}{\nu^{\rm RR}_{q\to q-1} n_e \eta_c}. \qquad (3)$$

Here η_c is ratio of the cooling section length to the ring circumference; n_e is electron beam density in LRF; γ is Lorentz factor; the $\nu^{\rm RR}_{q\to q-1}$ values are defined by formula (1).

Table 1: Parameters of electron cooling systems of the Booster and the Collider NICA.

	Booster	**Collider NICA**
Ion energy, GeV/u	0.1	1÷4.5
Electron beam radius, cm	2.5	1
Electron beam current, A	≤1.0	≤0.5
η_c	0.014	0.012

Two options of ions accelerated in the Booster are considered presently: Au^{33+} and Au^{51+}. The electron cooling is designed to be applied at the ion energy of 100 MeV/u during acceleration up to energy of 600 MeV/u on a plateau of 1 s duration. Electron cooling of nuclei Au^{79+} in the Collider NICA will be used in ion energy range of 1÷4.5 GeV/u (Table 1).

According Fig. 4 and formulae (3), (1) the estimation of RR losses in Booster for gold ions Au^{33+} and Au^{51+} less that 2% in all ΔE range. For Au^{32+} and Au^{50+} we have the same losses but for ΔE>0.1 eV.

The estimation of beam lifetime of Au^{79+} nuclei in Collider NICA based on analysis results (formulae (3) and (2)) have been produced (Fig. 7, 8).

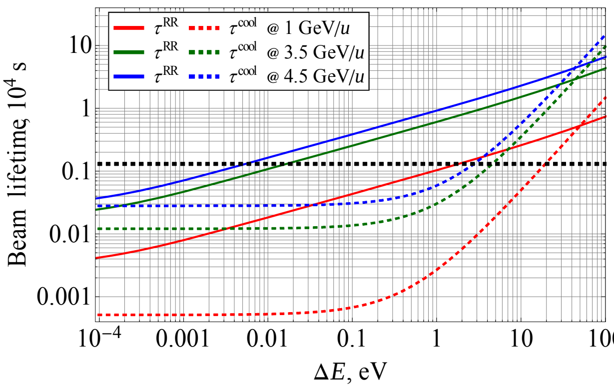

Figure 7: Beam lifetime of Au^{79+} nuclei in Collider NICA vs. electron energy shift ΔE for different cooling energy. Dashed black line represents to the intrabeam scattering (IBS) time τ_{IBS}=1300 s.

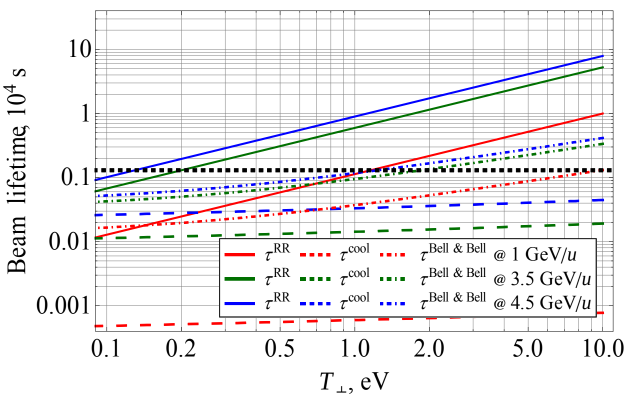

Figure 8: Beam lifetime of Au^{79+} nuclei in Collider NICA vs. transverse temperature $T_\perp$ for different values of ion energy. Dashed black line represents to the intrabeam scattering (IBS) time τ_{IBS}=1300 s.

In Fig. 7, 8 the corresponding cooling time τ^{cool} was calculated using "Parkhomchuk formula" [17]. The gold bare nucleus lifetime values according to the M. Bell and J. Bell [4] formula is also shown in Fig. 8 differ significantly with experimental fit.

CONCLUSION

Energy dependence of the RR rate of bare nuclei is scaled as $\Delta E^{-3/8}$ (1). At ΔE=0 the RR rate dependence on transverse temperature scaled as $T_\perp^{-0.95}$ (see inverse formula (2)) that differs with theoretical result obtained by M. Bell and J. Bell.

The RR rates for some ions in an intermediate charge state have resonance character. In order to avoid a large RR rates of such ions one has to choose ions with completed electron shell configuration either having even number of electron in outer shell.

The beam lifetime of gold bare nuclei in cooling system can be increased by two methods: with introduction of optimal electron energy shift ΔE, and either with artificial increase of the electron transverse temperature $T_\perp$. The second method is more preferable because its influence is more significant.

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