RADIATIVE RECOMBINATION OF BARE NUCLEI AND IONS IN ELECTRON COOLING SYSTEM

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OUTLINE

Introduction

1 Analysis of experimental data of radiative recombination (RR) rates for bare nuclei

2 Analysis of experimental data of RR rates for intermediate charge state of ions

3 RR beam lifetime and cooling time

Conclusion

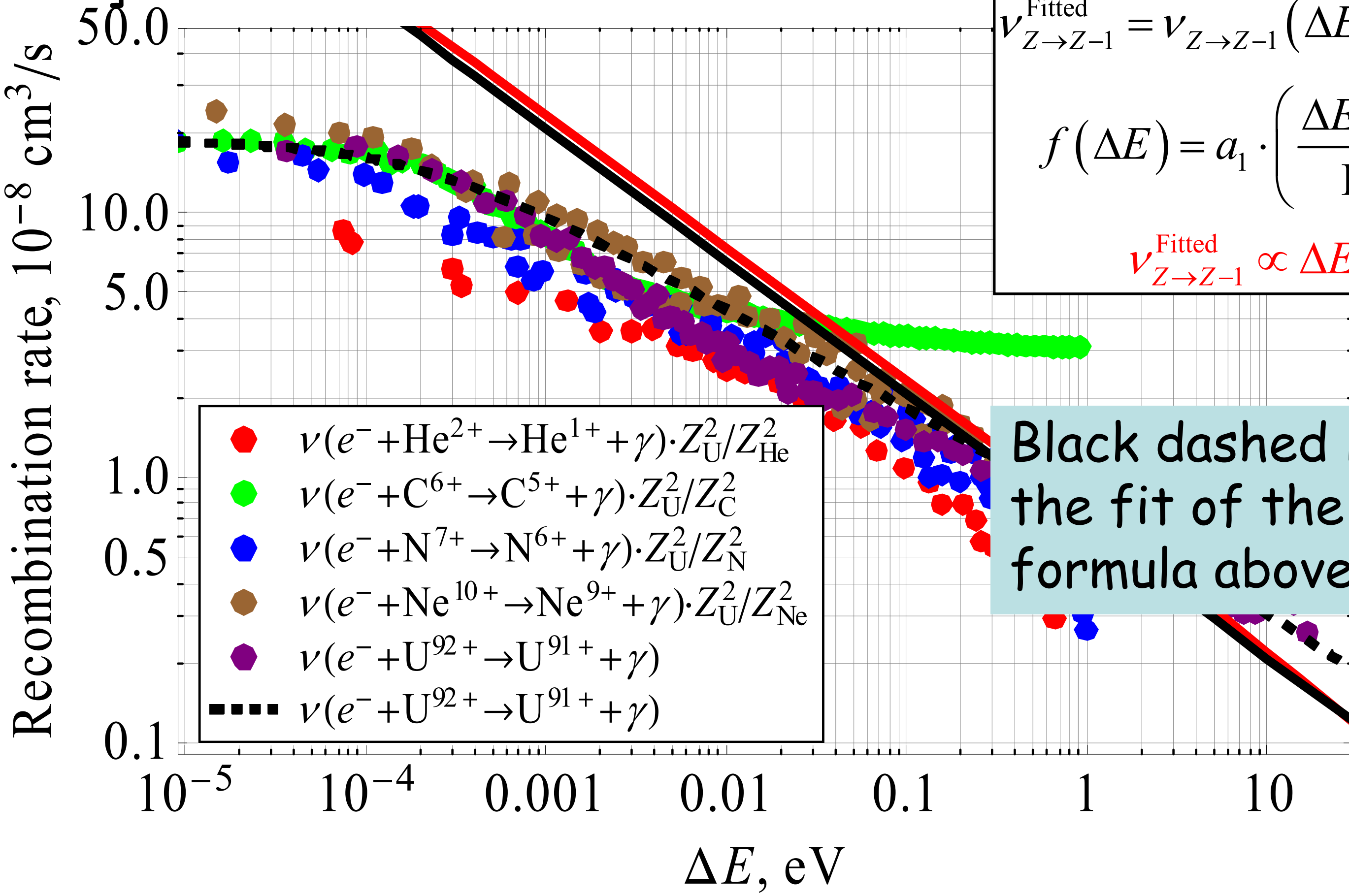
INTRODUCTION

Review of experimental results and their comparison with theoretical approaches is presented in this talk. We consider two essential cases for NICA:

- Recombination of bare gold nuclei in the NICA cooling system,
- Recombination of intermediate charge state of gold ions in the Booster cooling system.

Based on these comparisons we evaluated the contribution of the RR losses of intermediate charge state of gold ions: Au^{32+}, Au^{33+}, Au^{43+}, Au^{51+}, Au^{61+}, Au^{68+} and Au^{69+} during their acceleration in the Booster and the beam lifetime of the gold bare nuclei Au^{79+} in NICA.

RR rates vs. the electron relative energy ΔE, experiments: TSR, CRYRING, ESR. Red solid line — theoretical models of H.A. Kramers [Phil. Mag. V. 46. 1923. P. 836.], black solid line — R. Schuch [Phys. Rev. A. V. 45. N. 11. 1992. P. 7894-7905.].



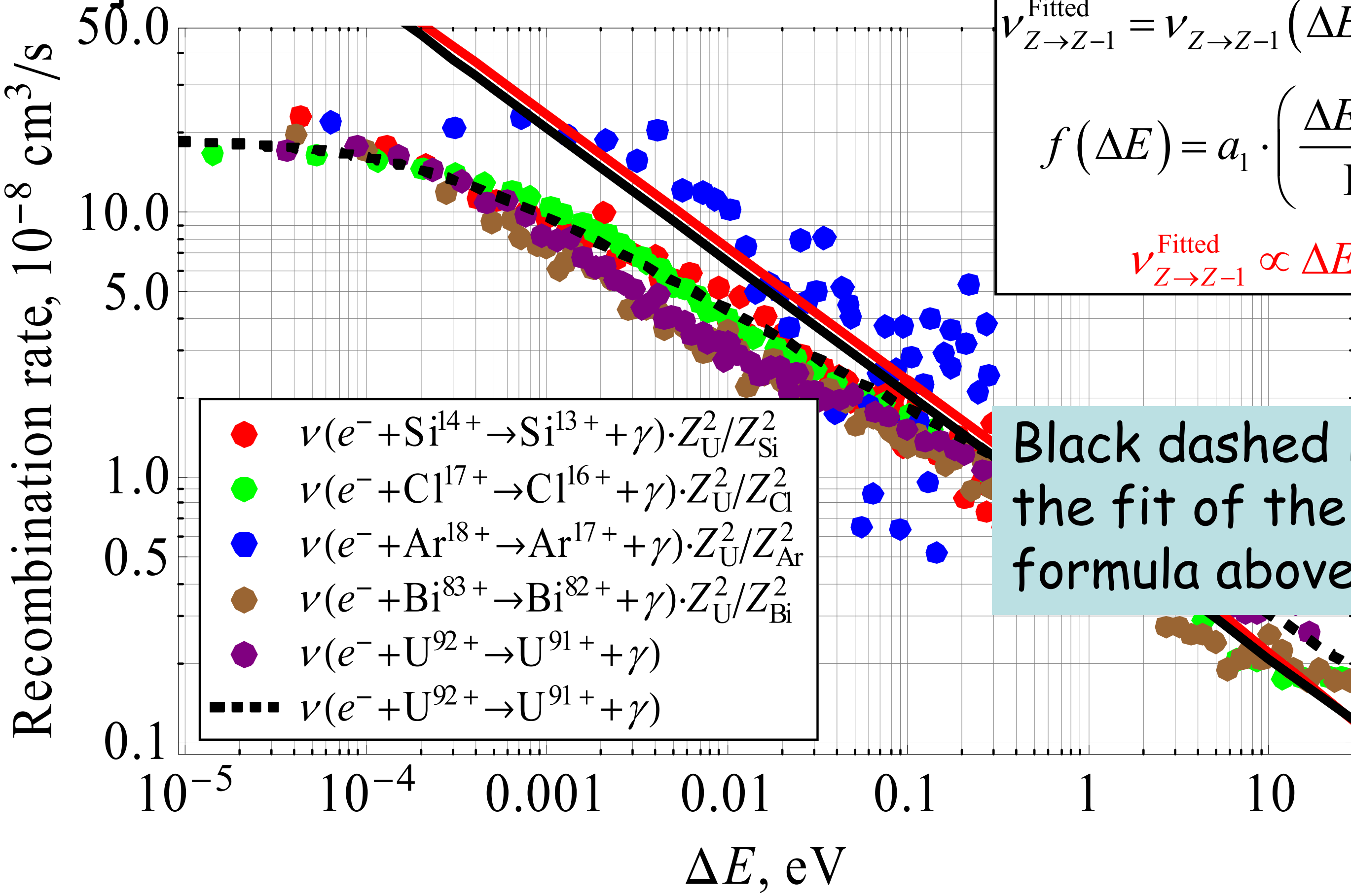
$$\nu_{Z\to Z-1}^{\mathrm{Fitted}} = \nu_{Z\to Z-1}(\Delta E)\cdot f(\Delta E),$$

$$f(\Delta E) = a_1 \cdot \left(\frac{\Delta E + b_1}{\mathrm{Ry}}\right)^{1/8},$$

$$\nu_{Z\to Z-1}^{\mathrm{Fitted}} \propto \Delta E^{-3/8}.$$

Black dashed line is the fit of the formula above.

RR rates vs. the electron relative energy ΔE, experiments: TSR, CRYRING, ESR. Red solid line — theoretical models of H.A. Kramers [Phil. Mag. V. 46. 1923. P. 836.], black solid line — R. Schuch [Phys. Rev. A. V. 45. N. 11. 1992. P. 7894-7905.].



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1 ANALYSIS OF EXPERIMENTAL DATA OF RR RATES FOR BARE NUCLEI (Contnd)

RR rates vs. magnetic field strength B, experiment: ESR.
[M. Steck, et al. EPJ D. 15. 2001. P. 145-154.]

$$\nu_{Z\to Z-1}^{\text{Fitted}} = \nu_{Z\to Z-1}(\Delta E)\cdot f(\Delta E),$$

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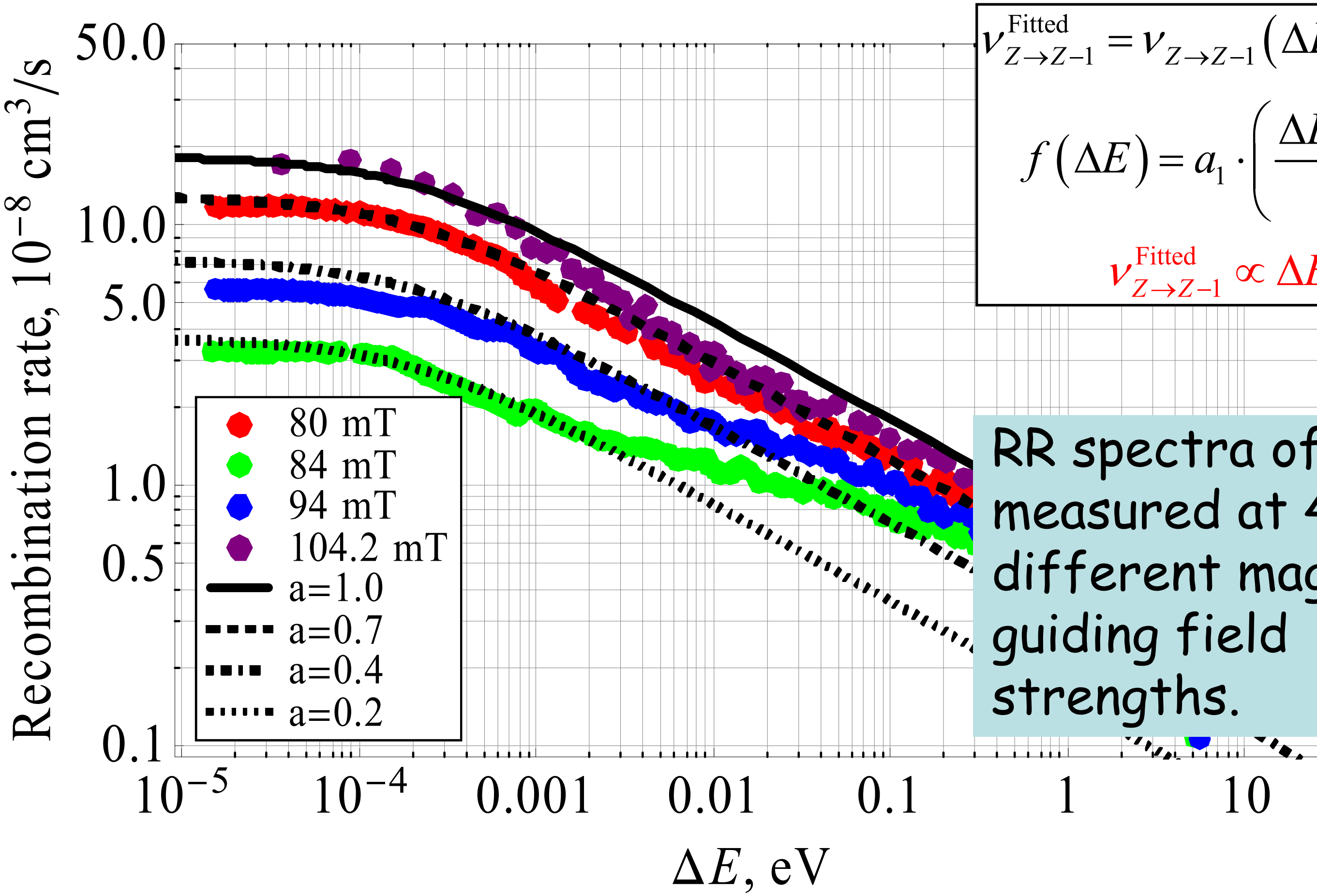


RR spectra of U^{92+} measured at 4 different magnetic guiding field strengths.

RR rates vs. transverse electron temperature $T_\perp$ experiment: ESR.
[M. Steck. NIM A. 2004. V. 532. P. 427-432.]

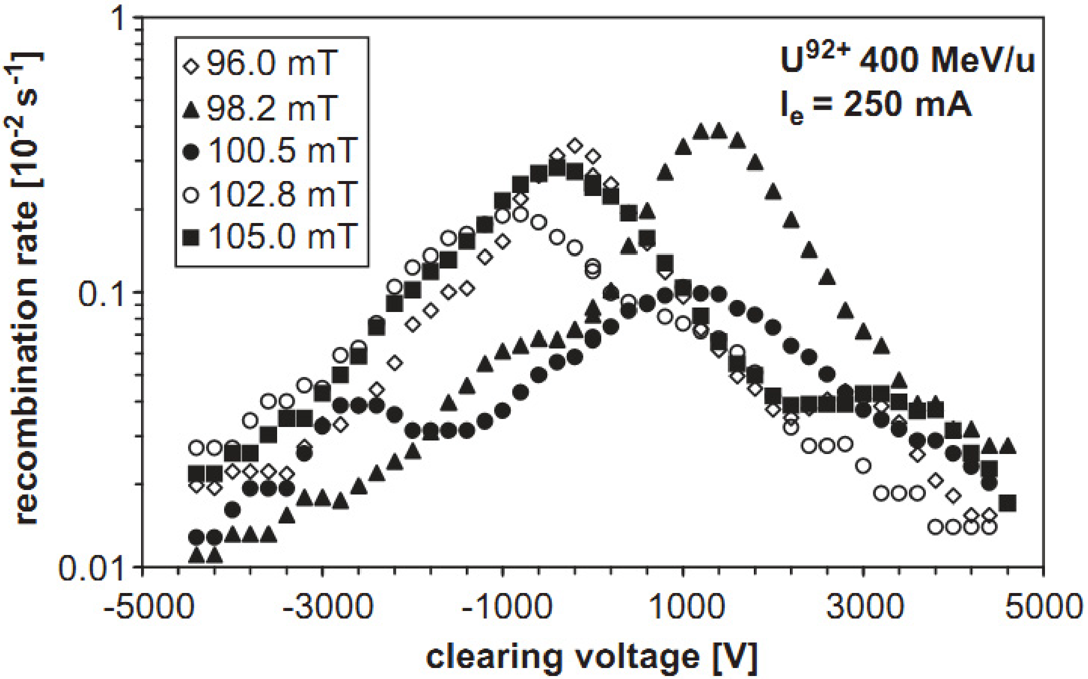


Fig. 3. Recombination rate of U^{92+} at 400 MeV/u as a function of the potential applied to the clearing electrodes. The two opposing plates were on opposite potential.

$$V_d\,[\mathrm{cm/s}] = \frac{E\,[\mathrm{V/cm}]}{B\,[\mathrm{Gs}]},$$

$$E\,[\mathrm{V/cm}] = \frac{U_{\text{clearing voltage}}\,[\mathrm{V}]}{l\,[\mathrm{cm}]},$$

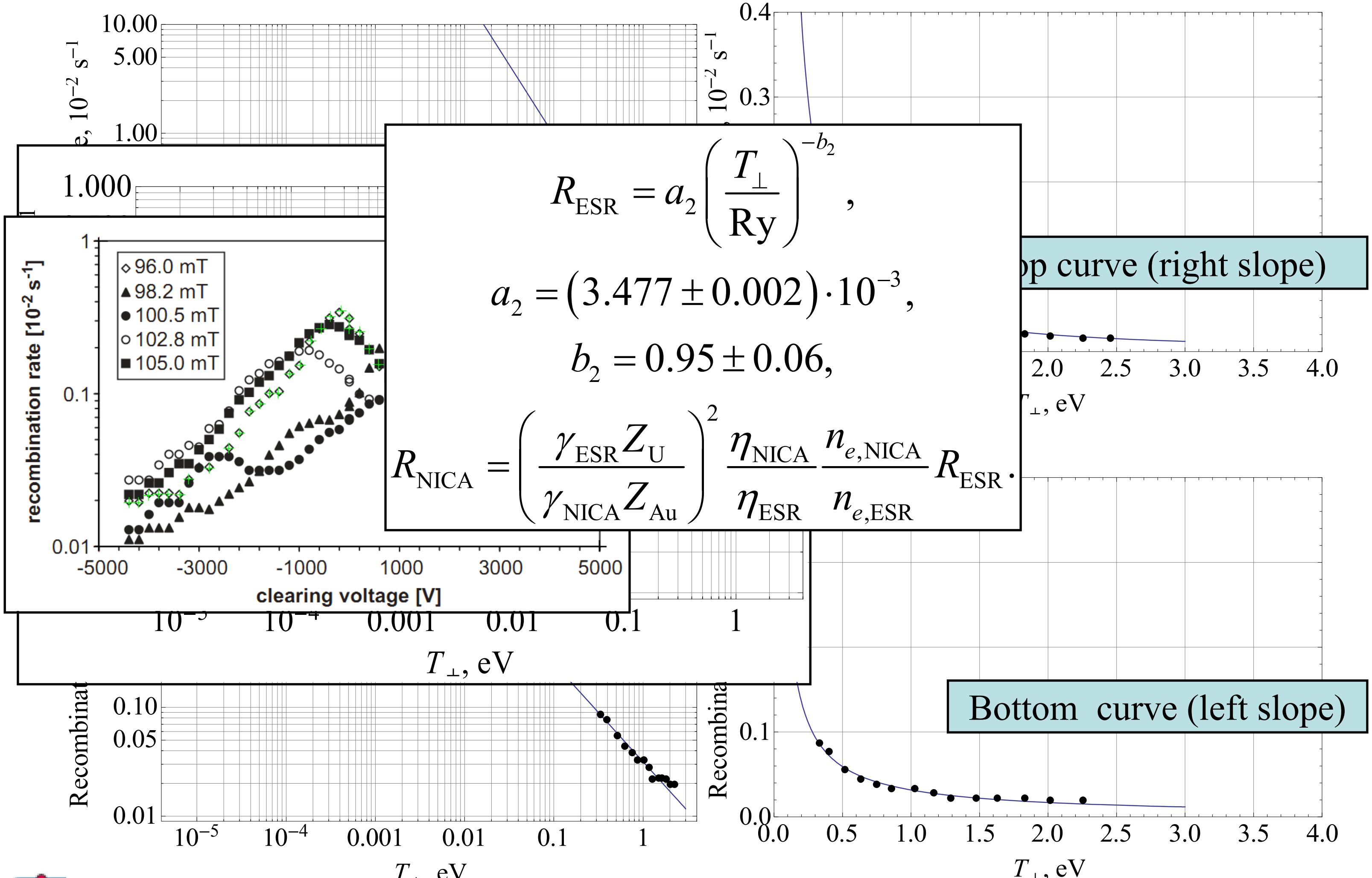
$$T_d\,[\mathrm{eV}] = \frac{m_e\,[\mathrm{g}]\,V_d^2\,[\mathrm{cm^2/s^2}]}{k_B\,[\mathrm{Erg/eV}]},$$

$$l = 10\ \mathrm{cm},\quad k_B = 1.6\cdot 10^{-12}\ \mathrm{Erg/eV},$$

$$T_\perp = T_d + T_{\text{cathode}},$$

$$T_{\text{cathode}} < 0.1\ \mathrm{eV}.$$

RR rates vs. transverse electron temperature $T_\perp$ experiment: ESR. [M. Steck. NIM A. 2004. V. 532. P. 427-432.]. Case B=96 mT.



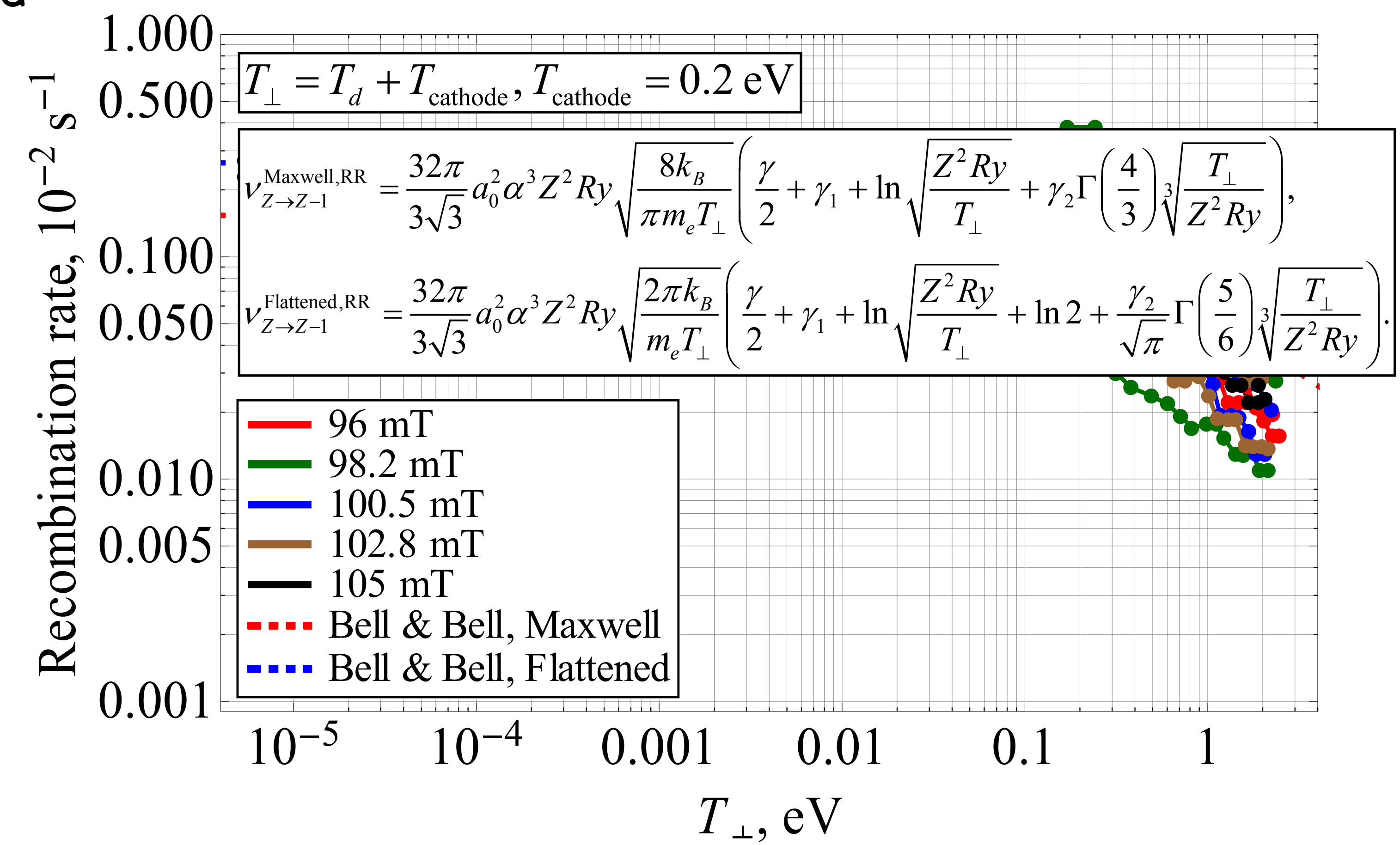
$$R_{\rm ESR} = a_2 \left(\frac{T_\perp}{\rm Ry} \right)^{-b_2},$$

$$a_2 = (3.477 \pm 0.002) \cdot 10^{-3},$$

$$b_2 = 0.95 \pm 0.06,$$

$$R_{\rm NICA} = \left(\frac{\gamma_{\rm ESR} Z_{\rm U}}{\gamma_{\rm NICA} Z_{\rm Au}} \right)^2 \frac{\eta_{\rm NICA}}{\eta_{\rm ESR}} \frac{n_{e,\rm NICA}}{n_{e,\rm ESR}} R_{\rm ESR}.$$

RR rates vs. transverse electron temperature $T_\perp$ experiment: ESR (Bell & Bell comparison). RR spectra of U^{92+} measured for a different drift temperature T_d, I_e=250 mA. Red dashed line — Maxwell, blue dashed line — flattened



$$\nu^{\rm Maxwell,RR}_{Z\to Z-1} = \frac{32\pi}{3\sqrt{3}} a_0^2 \alpha^3 Z^2 Ry \sqrt{\frac{8k_B}{\pi m_e T_\perp}} \left(\frac{\gamma}{2} + \gamma_1 + \ln\sqrt{\frac{Z^2 Ry}{T_\perp}} + \gamma_2 \Gamma\left(\frac{4}{3}\right) \sqrt[3]{\frac{T_\perp}{Z^2 Ry}} \right),$$

$$\nu^{\rm Flattened,RR}_{Z\to Z-1} = \frac{32\pi}{3\sqrt{3}} a_0^2 \alpha^3 Z^2 Ry \sqrt{\frac{2\pi k_B}{m_e T_\perp}} \left(\frac{\gamma}{2} + \gamma_1 + \ln\sqrt{\frac{Z^2 Ry}{T_\perp}} + \ln 2 + \frac{\gamma_2}{\sqrt{\pi}} \Gamma\left(\frac{5}{6}\right) \sqrt[3]{\frac{T_\perp}{Z^2 Ry}} \right).$$

1 ANALYSIS OF EXPERIMENTAL DATA OF RR RATES FOR BARE NUCLEI [M. Bell and J.S. Bell. Particle Accelerators. 1982. V. 12. P. 49-52.] [M. Steck. NIM A. 2004. V. 532. P. 427-432.] (Contnd)

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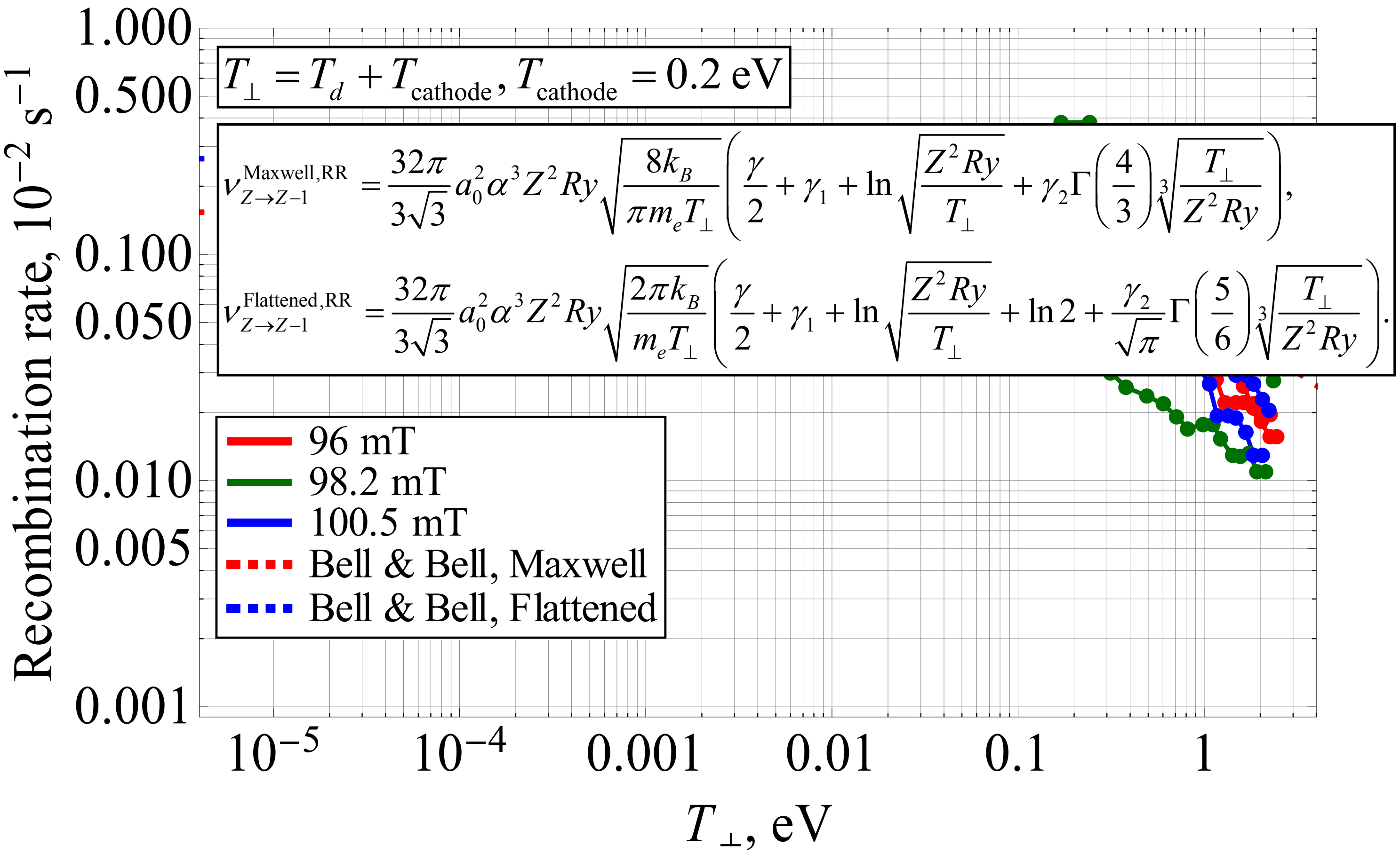

$$T_\perp = T_d + T_{\text{cathode}},\ T_{\text{cathode}} = 0.2\text{ eV}$$

$$\nu^{\text{Maxwell,RR}}_{Z\to Z-1} = \frac{32\pi}{3\sqrt{3}} a_0^2\alpha^3 Z^2 Ry \sqrt{\frac{8k_B}{\pi m_e T_\perp}} \left(\frac{\gamma}{2}+\gamma_1+\ln\sqrt{\frac{Z^2 Ry}{T_\perp}}+\gamma_2\Gamma\left(\frac{4}{3}\right)\sqrt[3]{\frac{T_\perp}{Z^2 Ry}}\right),$$

$$\nu^{\text{Flattened,RR}}_{Z\to Z-1} = \frac{32\pi}{3\sqrt{3}} a_0^2\alpha^3 Z^2 Ry \sqrt{\frac{2\pi k_B}{m_e T_\perp}} \left(\frac{\gamma}{2}+\gamma_1+\ln\sqrt{\frac{Z^2 Ry}{T_\perp}}+\ln 2+\frac{\gamma_2}{\sqrt{\pi}}\Gamma\left(\frac{5}{6}\right)\sqrt[3]{\frac{T_\perp}{Z^2 Ry}}\right).$$

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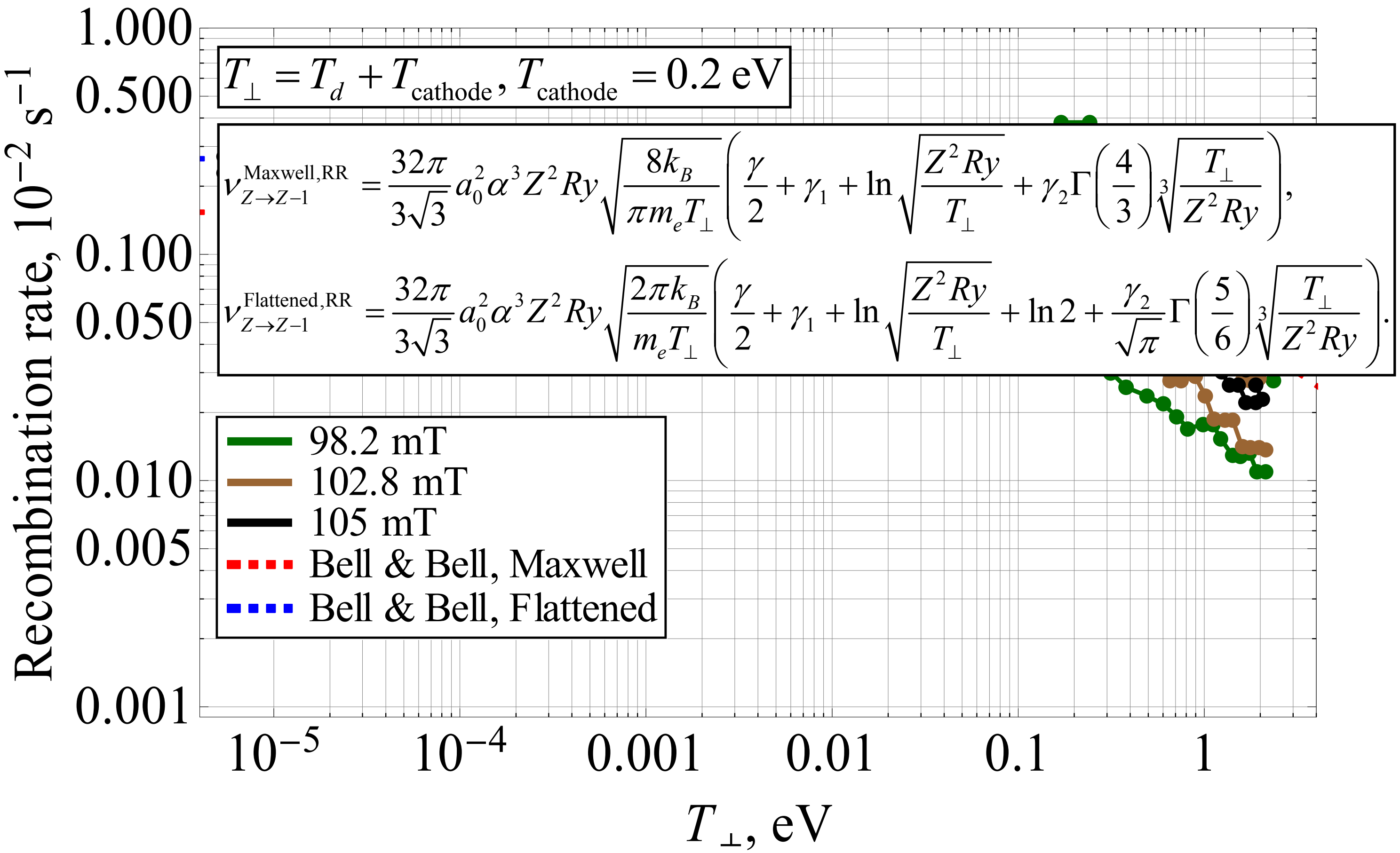
RR rates vs. transverse electron temperature $T_\perp$ experiment: ESR (Bell & Bell comparison). RR spectra of U^{92+} measured for a different drift temperature T_d, I_e=250 mA. Red dashed line — Maxwell, blue dashed line — flattened

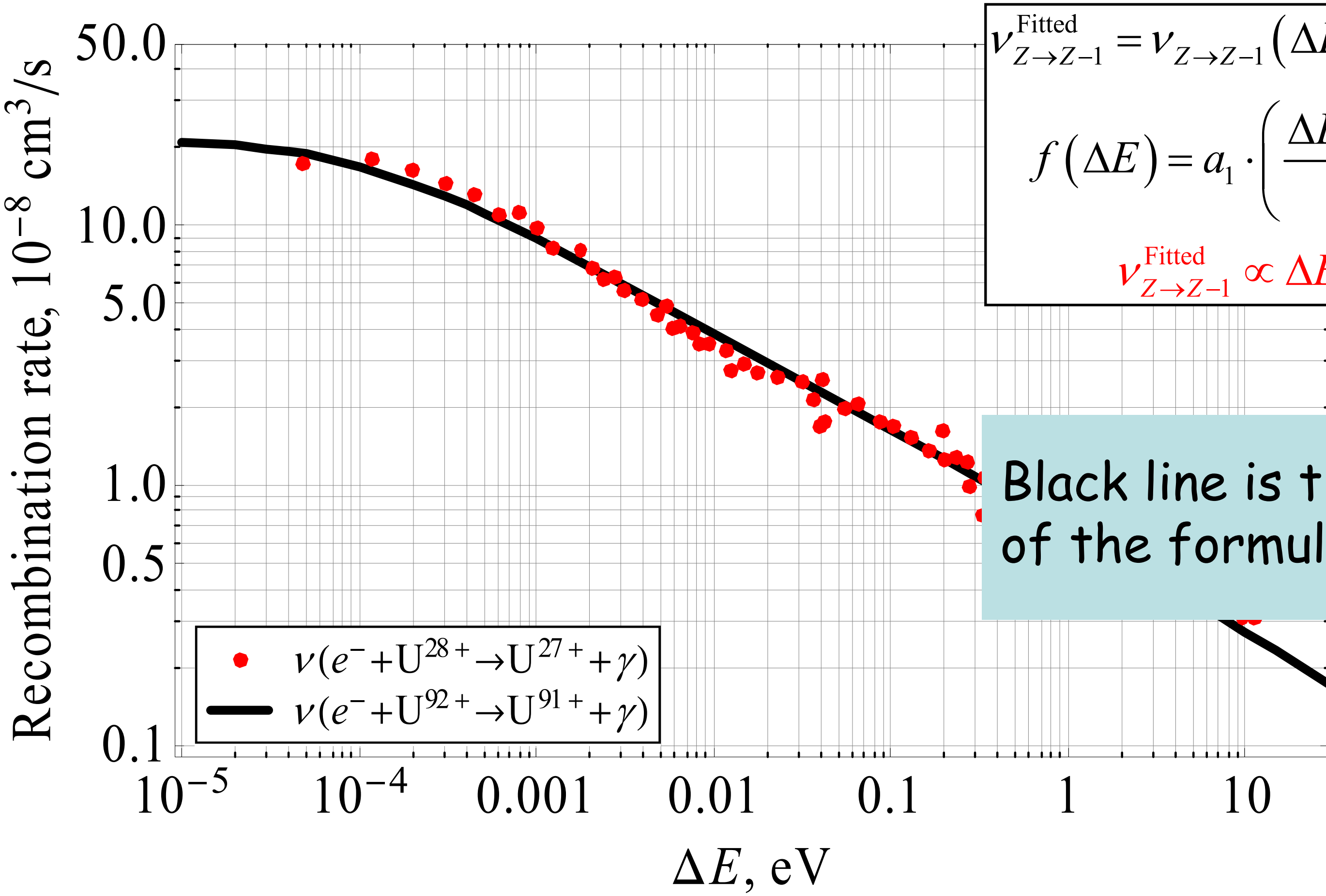


RR spectra of U^{28+} measured at ESR.
[A. Müller et al. Phys. Scr. 1991. V. T37. P. 62-65.]

$$\nu_{Z\to Z-1}^{\text{Fitted}} = \nu_{Z\to Z-1}(\Delta E)\cdot f(\Delta E),$$

$$f(\Delta E) = a_1 \cdot \left(\frac{\Delta E + b_1}{\text{Ry}}\right)^{1/8},$$

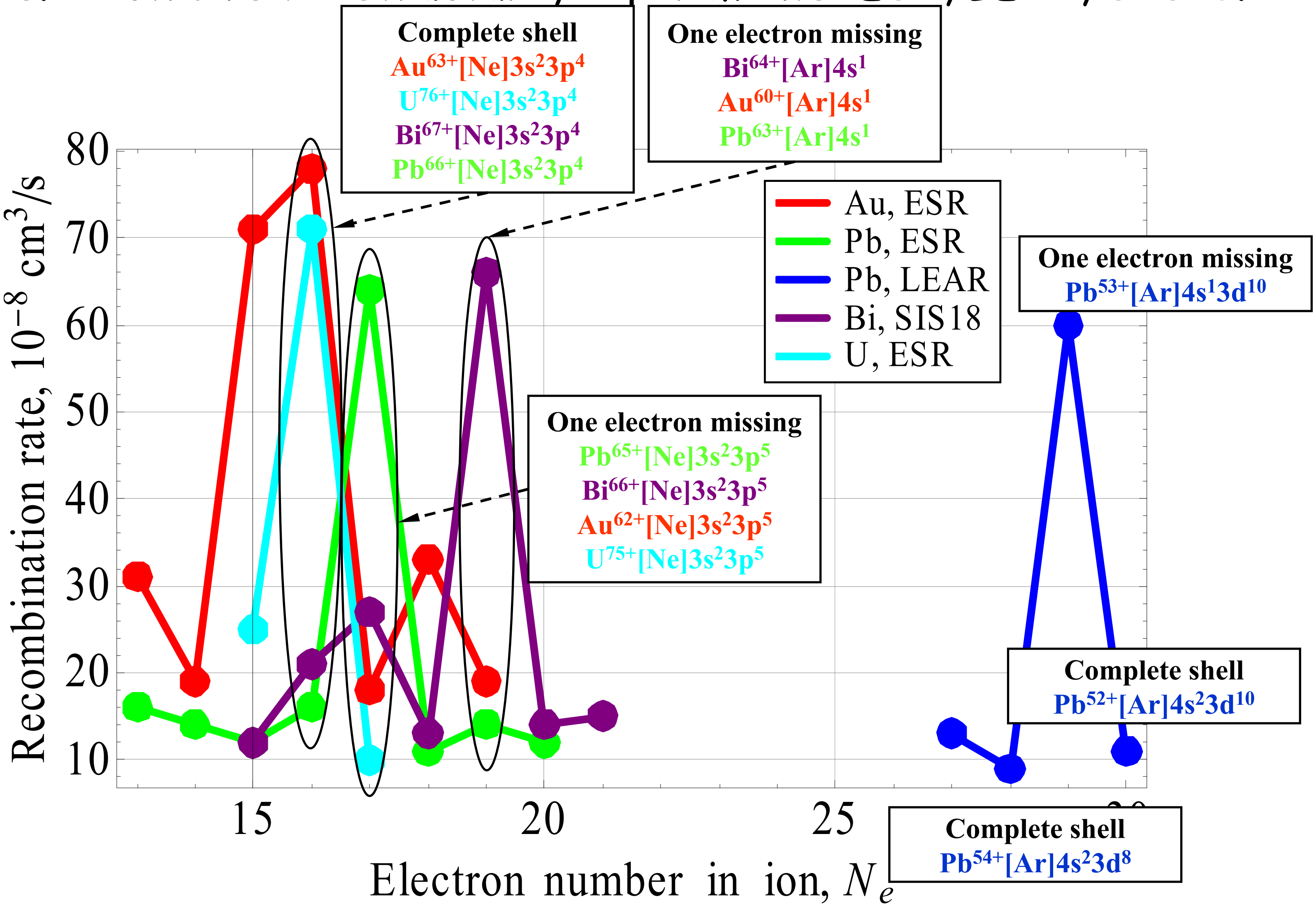
$$\nu_{Z\to Z-1}^{\text{Fitted}} \propto \Delta E^{-3/8}.$$



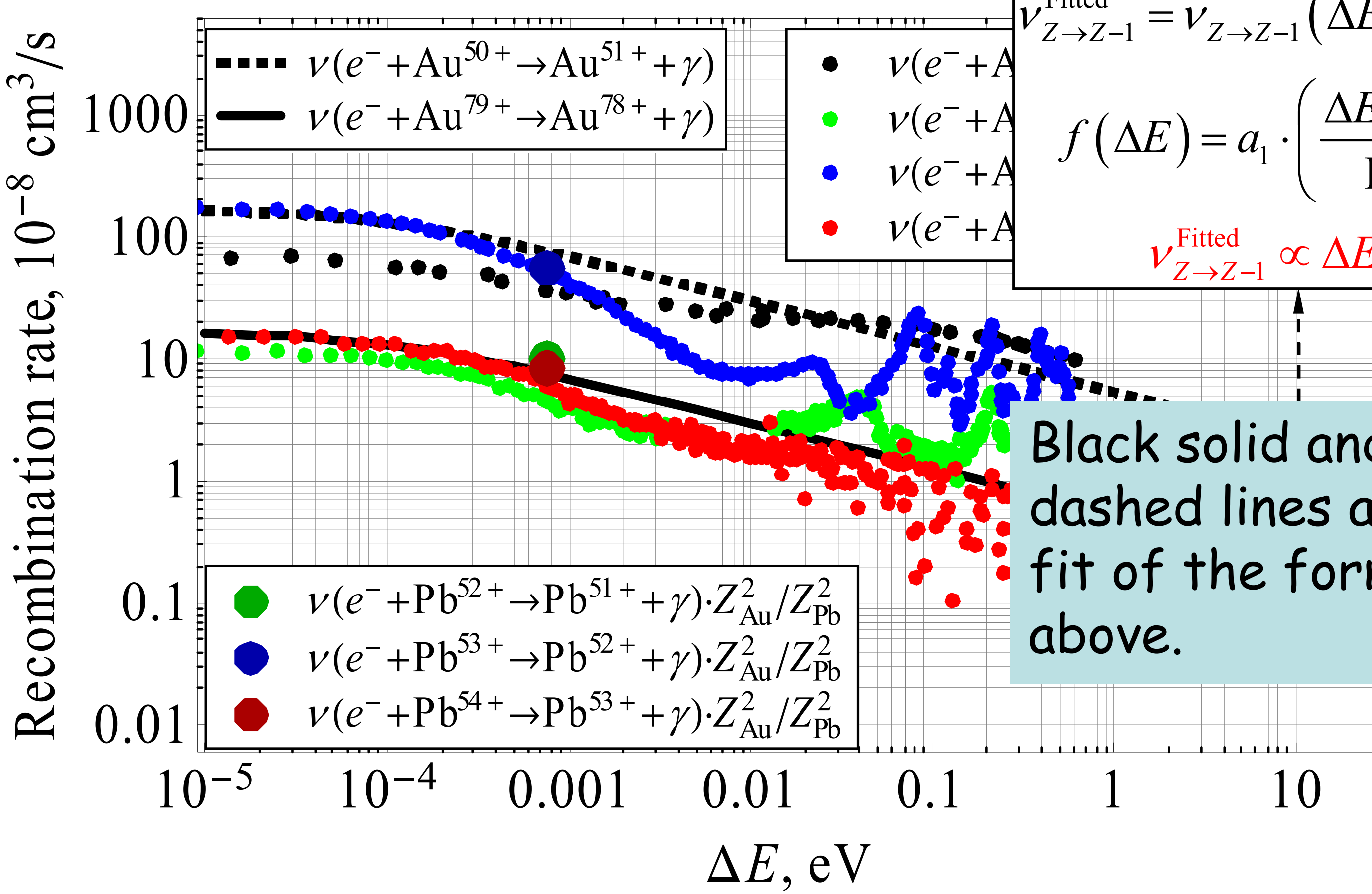
Black line is the fit of the formula above.

2 ANALYSIS OF EXPERIMENTAL DATA OF RR RATES FOR INTERMEDIATE CHARGE STATE OF IONS (Contnd)

RR rates vs. electron shell structure, experiments: ESR, LEAR, SIS18.



RR rates vs. electron shell structure, experiments: LEAR ($Pb^{52+, 53+, 54+}$), ESR (Au^{25+}), TSR ($Au^{49+, 50+, 51+}$). Au^{49+} and Pb^{52+} — $[Ar]4s^2 3d^{10}$, **Au^{50+} and Pb^{53+} — $[Ar]4s^1 3d^{10}$**, Au^{51+} and Pb^{54+} — $[Ar]4s^2 3d^8$.



$$\nu_{Z\to Z-1}^{\text{Fitted}} = \nu_{Z\to Z-1}(\Delta E) \cdot f(\Delta E),$$

$$f(\Delta E) = a_1 \cdot \left(\frac{\Delta E + b_1}{\text{Ry}}\right)^{1/8},$$

$$\nu_{Z\to Z-1}^{\text{Fitted}} \propto \Delta E^{-3/8}.$$

Black solid and dashed lines are the fit of the formula above.

3 RR BEAM LIFETIME AND COOLING TIME

RR beam lifetime in lab frame:

$$\tau^{\mathrm{RR}}_{Z\to Z-1}=\left(-\frac{1}{n_Z}\frac{dn_Z}{dt}\right)^{-1},\quad -\frac{1}{n_Z}\frac{dn_Z}{dt}=\frac{\nu^{\mathrm{RR}}_{Z\to Z-1}n_e\eta_{\mathrm{cool}}}{\gamma^2},\quad \nu^{\mathrm{RR}}_{Z\to Z-1}=\nu^{\mathrm{Fitted}}_{Z\to Z-1}.$$

We use well known Parkhomchuk formula for cooling time in lab frame:

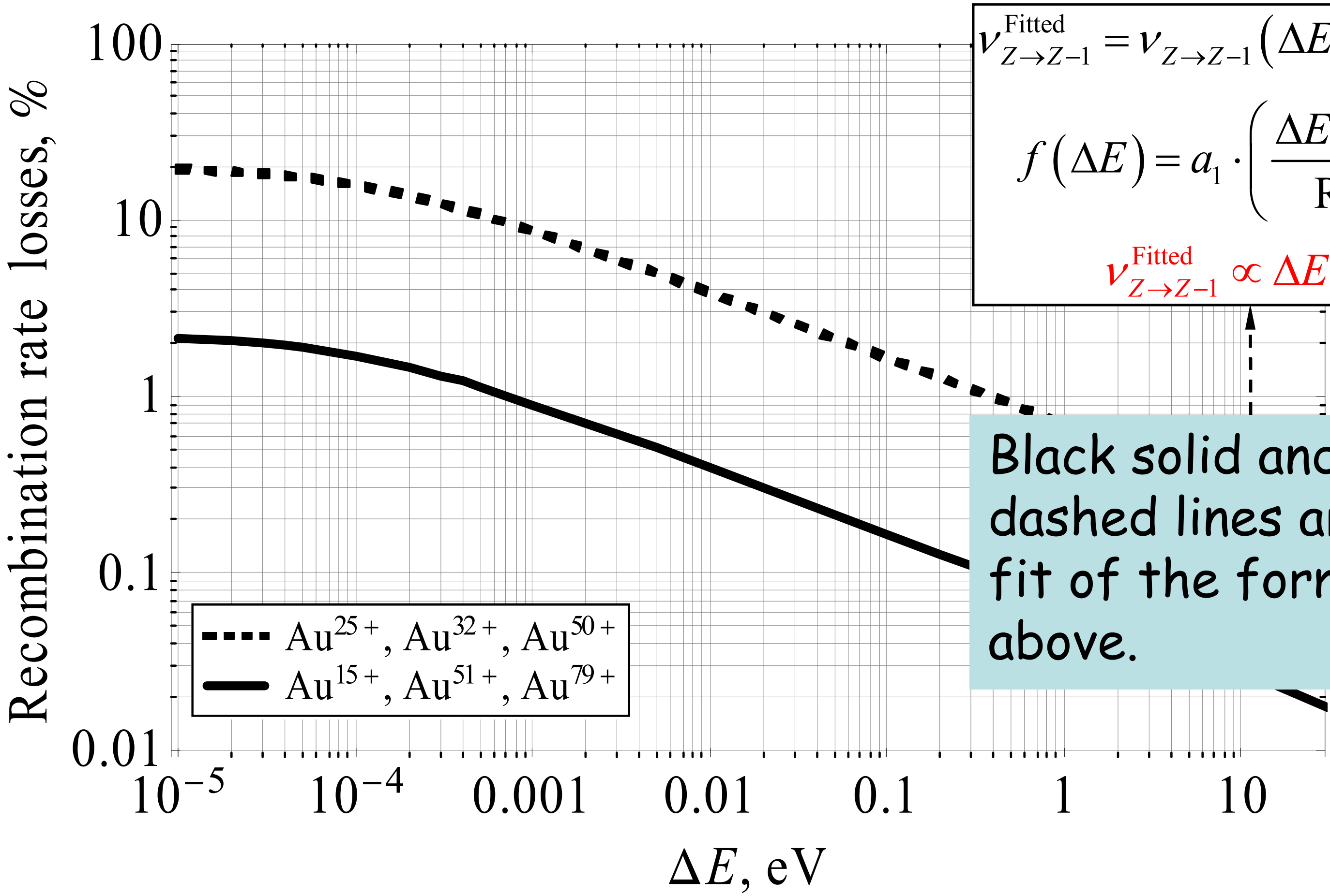
$$\tau^{\mathrm{cool}}_{Z/e}=\left(\frac{\nu^{\mathrm{cool}}_{Z/e}n_e\eta_{\mathrm{cool}}}{\gamma^2}\right)^{-1},\quad \nu^{\mathrm{cool}}_{Z/e}=\frac{4m_e}{Am_u}\left(\frac{e^2Z}{m_e}\right)^2\frac{\lambda_{Z/e}}{\left(V_\perp^2+V_\parallel^2+V_{\mathrm{eff}}^2\right)^{3/2}},\quad \lambda_{Z/e}=\ln\Lambda_{Z/e},$$

$$\Lambda_{Z/e}=\frac{\rho_{\max}+\rho_{\min}+\rho_L}{\rho_{\min}+\rho_L},\quad \rho_{\max}=\frac{l_{\mathrm{cool}}}{\gamma V_0}\sqrt{V_\perp^2+V_\parallel^2},\quad \rho_{\min}=\frac{e^2}{m_e}\frac{1}{V_\perp^2+\dfrac{k_B\Delta E}{m_e}},\quad \rho_L=\frac{m_ec}{qB}\sqrt{\frac{k_BT_\perp}{m_e}},$$

$$V_0=\beta c,\quad V_\perp=\gamma\beta c\sqrt{\frac{\varepsilon_\perp}{\beta_\perp}},\quad V_\parallel=10^{-3}\beta c,\quad V_{\mathrm{eff}}=\sqrt{\gamma^2\theta_B^2V_0^2+\frac{k_B\Delta E}{m_e}}.$$

All the units in CGS; q, Z — ion charge and nuclear number; m_u, m_e — unit of mass, electron mass; γ, β — Lorenz factor, beta; $\rho_{\max}$, $\rho_{\min}$ — impact parameter; ρ_L — electron Larmor radius; $V_\perp$, $V_{||}$ — $\perp$, $||$ ion velocity; V_{eff} — electron effective velocity; θ_B — magnetic field angular spread; B — magnetic field in Gs; ΔE — electron energy shift in eV; $\beta_\perp$, $\varepsilon_\perp$ — beta-function, emittance; l_{cool}, η_{cool} — length, relative length of cooling section; k_B=$1.6\cdot10^{-12}$ Erg/eV — Boltzmann constant; e — electron charge; c — speed of light.

Estimation of gold ions beam losses in Booster.



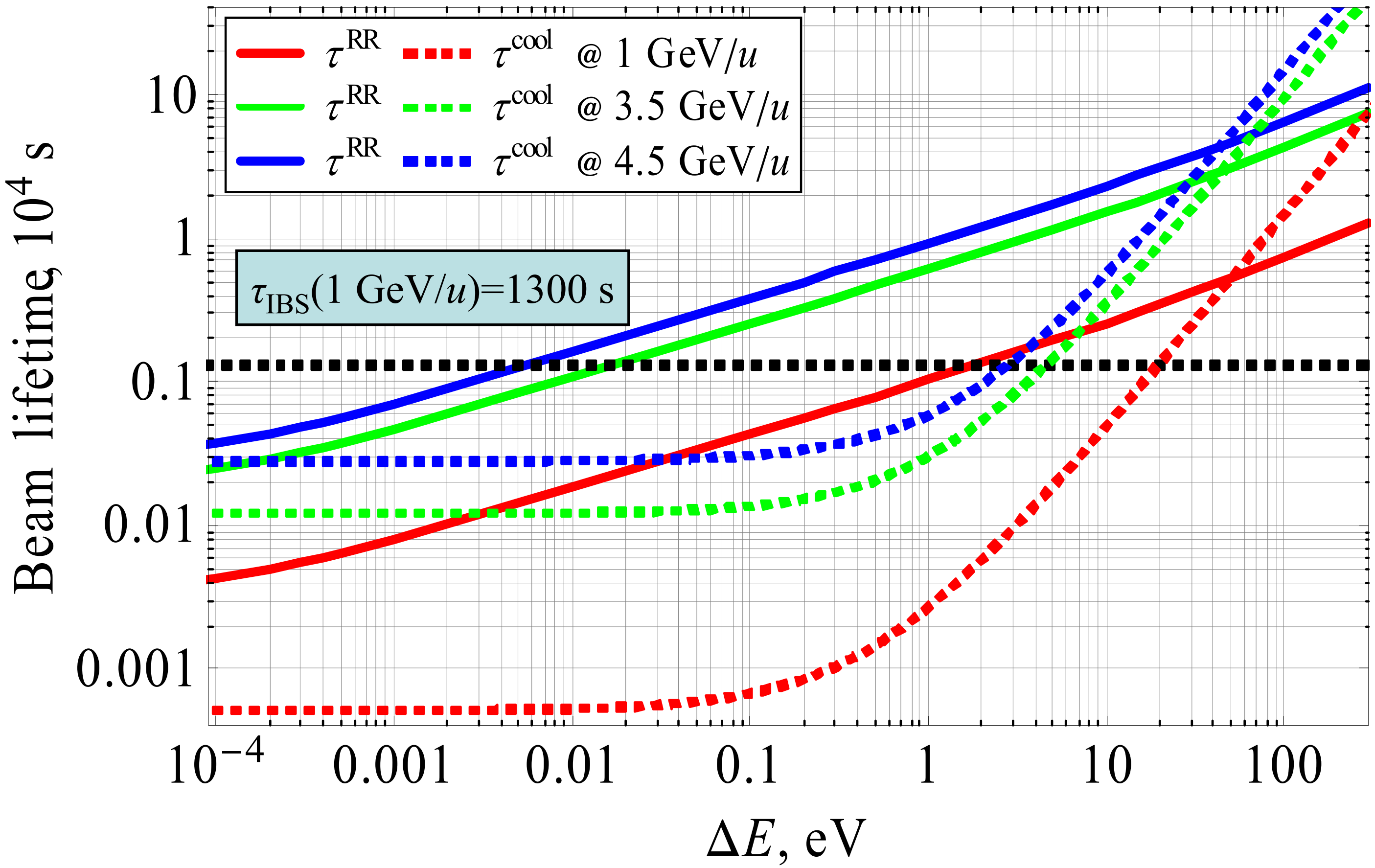
$$\nu_{Z\to Z-1}^{\text{Fitted}} = \nu_{Z\to Z-1}(\Delta E)\cdot f(\Delta E),$$

$$f(\Delta E) = a_1 \cdot \left(\frac{\Delta E + b_1}{\text{Ry}}\right)^{1/8},$$

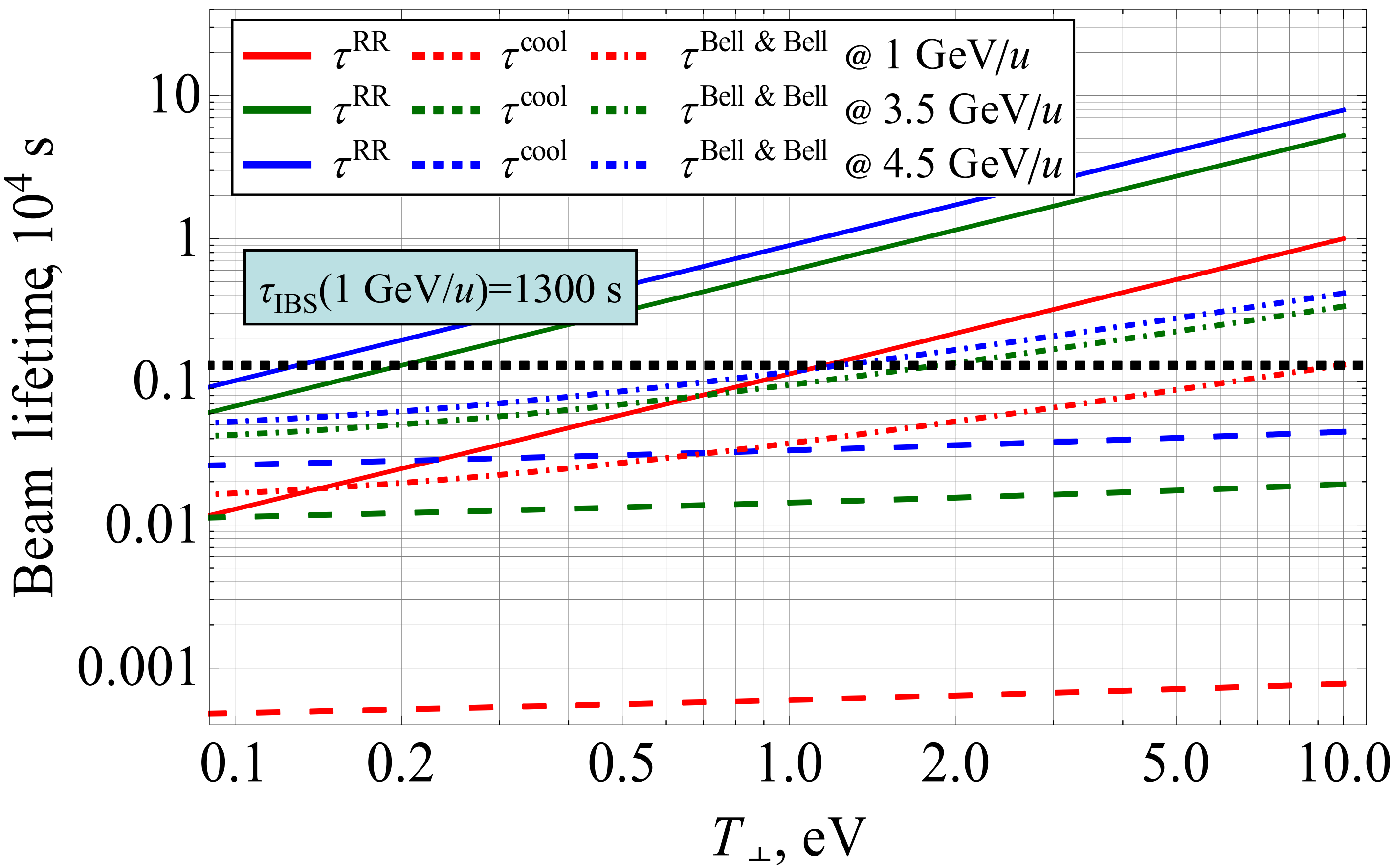
$$\nu_{Z\to Z-1}^{\text{Fitted}} \propto \Delta E^{-3/8}.$$

Black solid and dashed lines are the fit of the formula above.

Estimation of bare gold nucleus beam lifetime at NICA: I_e=1 A, r_e=1 cm, $T_\perp/T_\parallel$=0.2/5·10^{-3} eV, B=0.1 T. Intrabeam scattering (IBS) time ($\tau_{\rm IBS}$) — black dashed line.



Estimation of bare gold nucleus beam lifetime at NICA vs. transverse temperature: I_e=1 A, r_e=1 cm, B=0.1 T.



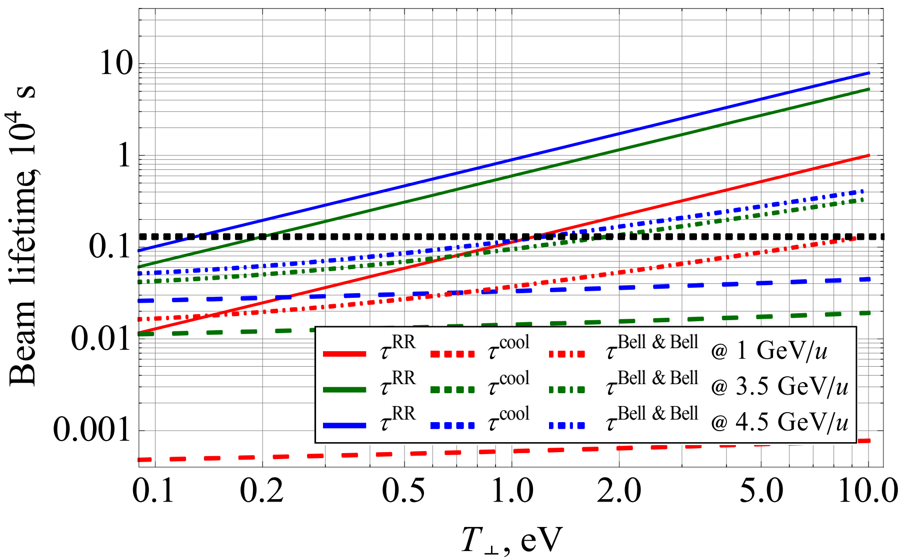
CONCLUSION

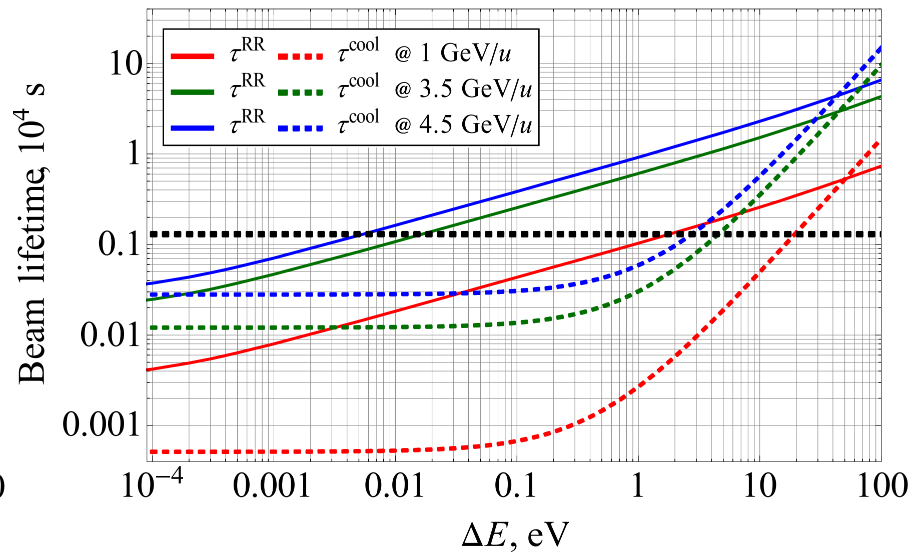
The RR process of gold bare nuclei in NICA cooling system can be suppressed in two methods:

- by choosing of optimal relative electron energy shift ΔE between ions and electrons beam,
- and by an artificial increase the transverse temperature $T_{\perp}$ of the electron beam (more preferable).

In order to suppress the RR process of intermediate gold ions charge state in the Booster cooling system during ions accumulation is required to avoided when using the ions with electron shell configuration which have one electron missing.

CONCLUSION (Contnd)





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Thank you for your attention!