Beam-gas collisions at SPS and LHC

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1. Charge-changing atomic processes due to interaction of PSI with the rest-gas atoms.

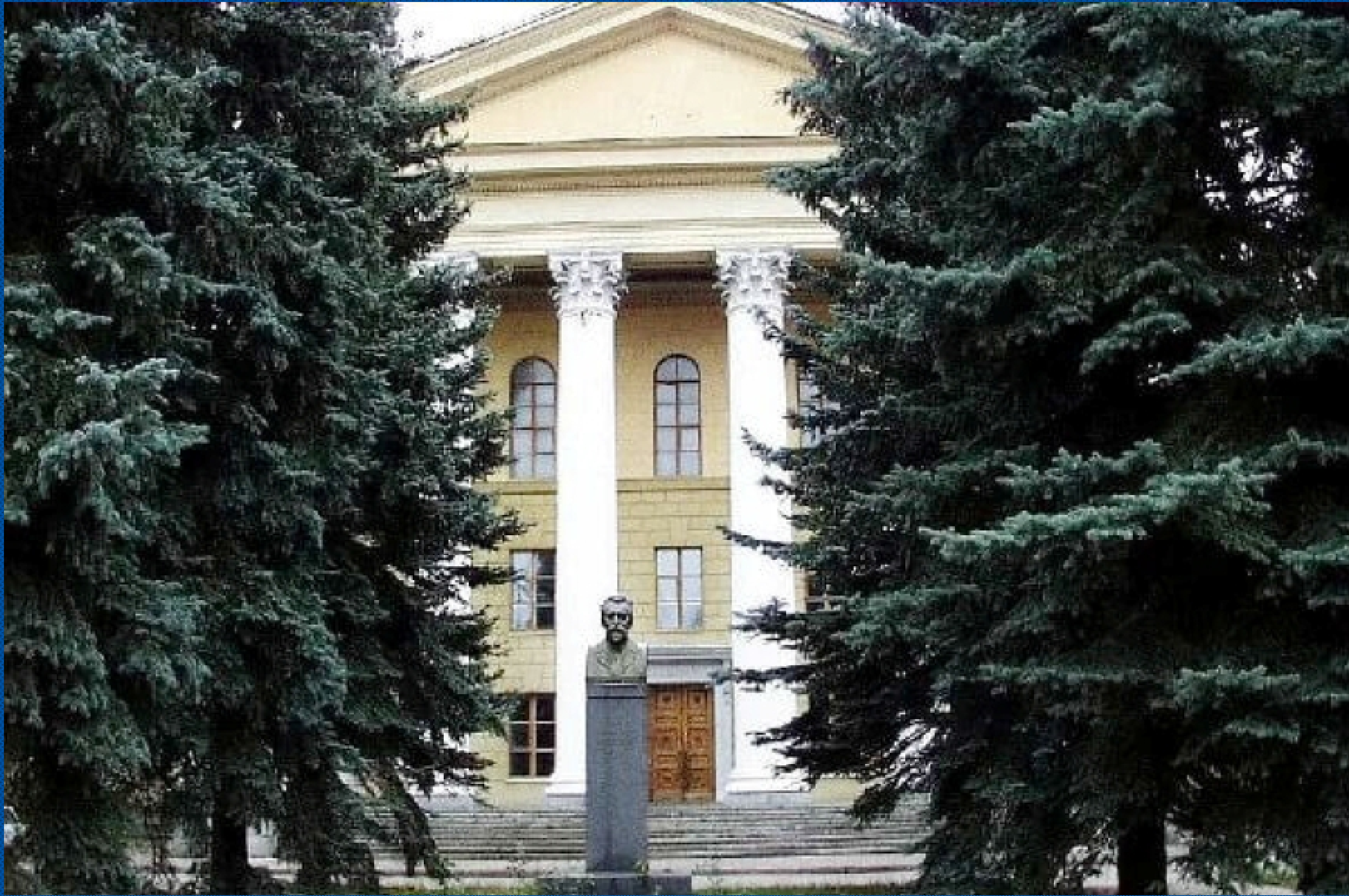
2. The role of electron-loss processes at relativistic energies. The RICODE-M computer code.

3. Ion-bean lifetimes and vacuum conditions.

4. Comparison of calculated ion-beam lifetimes with measured ones at SPS and LHC accelerators.

Conclusion

P.N. Lebedev Physical Institute (**LPI**), Moscow, since **1934**



Theoretical group in Laboratory for spectroscopy since 1961.
Theoretical group in 2018:

Leonid Vainshtein

Inga Tolstikhina

Viacheslav Shevelko

The main research topic -

Physics of Highly Charged Ions:

1. **X-ray and VUV spectra of HCI**
2. **Electronic and atomic collisions**
3. **Charge-exchange processes and isotopic effects in cold plasmas**
4. **Diagnostics of laser-produced plasmas**
5. **Interaction of fast heavy ions with gases, solids and plasmas**
6. **Dynamics of charge-state fractions in accelerators and storage rings**

and others

MAIN COMPUTER CODES:

- **ATOM** (L.A.Vainshtein: 1955) - interaction with electrons and photons
- **CAPTURE** (I.Tolstikhina, V.Shevelko: 2000) – capture processes
- **ARSENY** (E.Soloviev: 2001) - capture and ionization at very low energies
- **FAC** (M.F.Gu: 2003) – interaction with electrons and photons
- **CDW** (D. Belkic: 2005) – capture processes at low and intermediate energies
- **DEPOSIT** (M.Litsarev, V.Shevelko: 2008 - 2010) - mutiple-electron ionization of heavy ions at low and intermediate energies
- **RICODE-M** (I.Tolstikhina, I.Tupitsyn, V.Shevelko, S.N. Andreev: 2016) – relativistic ionization with relativistic w.f. and interaction
- **BREIT** (N. Winckler, A. Rybalchenko, V. Shevelko, M. Al-Turany, T. Kollegger, Th. Stöhlker: 2017) - charge-state fractions of heavy-ion beams in matter

INTERACTION OF FAST HEAVY IONS WITH MATTER

1. Heavy ions: Ar, Xe, Bi, Au, U at energies E > 1 MeV/u
   Superheavy ions up to Z = 120 (!).

2. Atomic physics approach: based on knowledge of atomic charge-changing cross sections and balance rate equations for charge-state fractions.

3. Main interests:
   1. Ion beam lifetime and vacum conditions
   2. Dynamics of charge-state fractions
      as a function of the target thickness.

Main charge-changing processes in gas/solid targets:

1. **multiple-electron ionization of projectiles (loss EL):**

   X^{q+} + A à $X^{(q+m)+}$ + ΣA + me^{-}, $m \geq 1$

2. **multiple-electron** non-radiative capture **(NRC):**

   X^{q+} + A à $X^{(q-k)+}$ + A^{+}, $k \geq 1$

3. **single-electron radiative capture** (R**EC):**

   X^{q+} + A à $X^{(q-1)+}$ + A^{+} + $\hbar\omega$

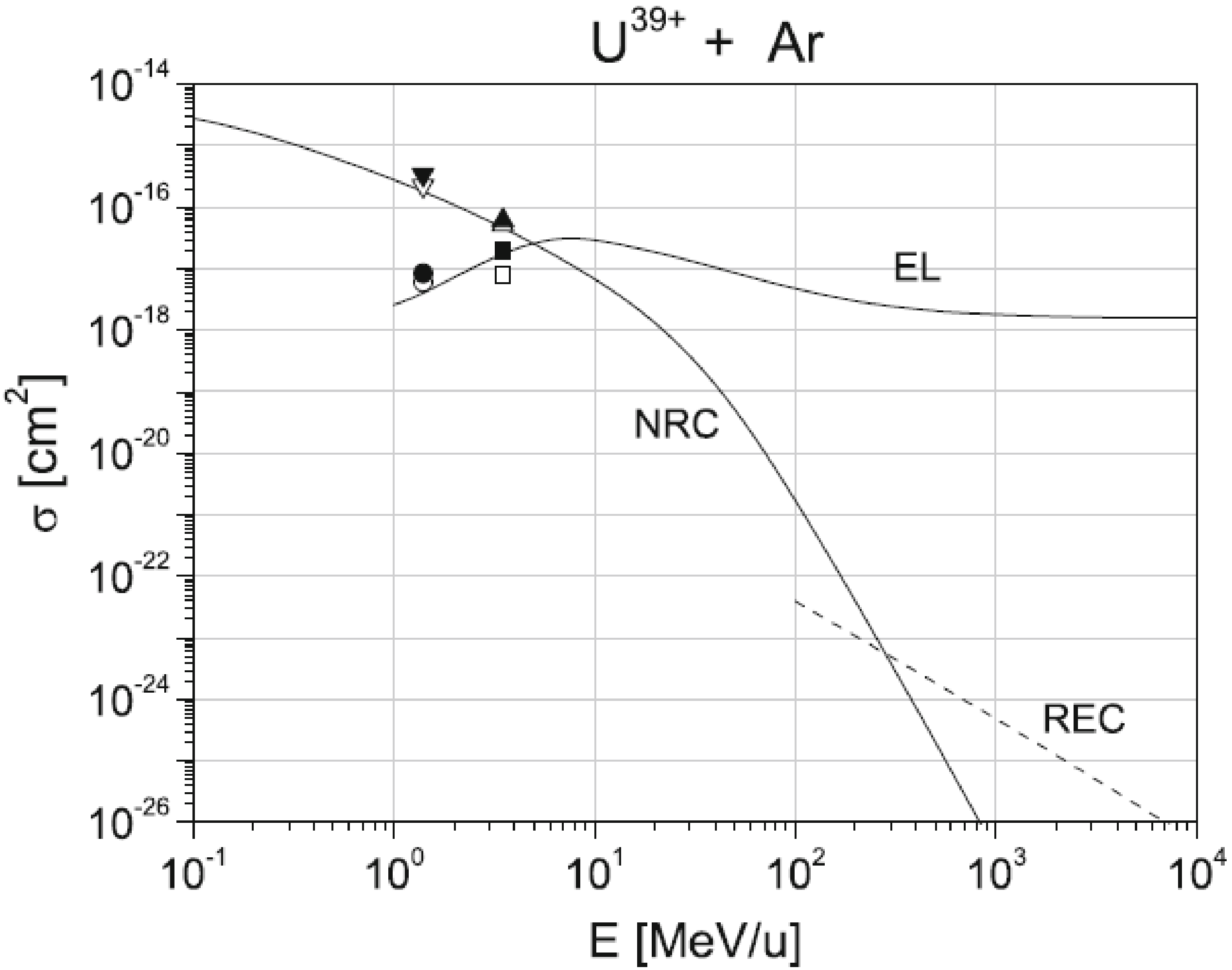
$\sigma_{TOT}(EC) = \sigma(NRC) + \sigma(REC)$

Asymptotic behavior of EL and EC cross sections in fast non-relativistic collisions:

$$s_{EL} \sim Z_T^2 \ln E / (q^2 E)$$

$$s_{NRC} \sim q^5 Z_T^5 / E^{5.5}$$

$$s_{REC} \sim q^4 Z_T / E^2$$

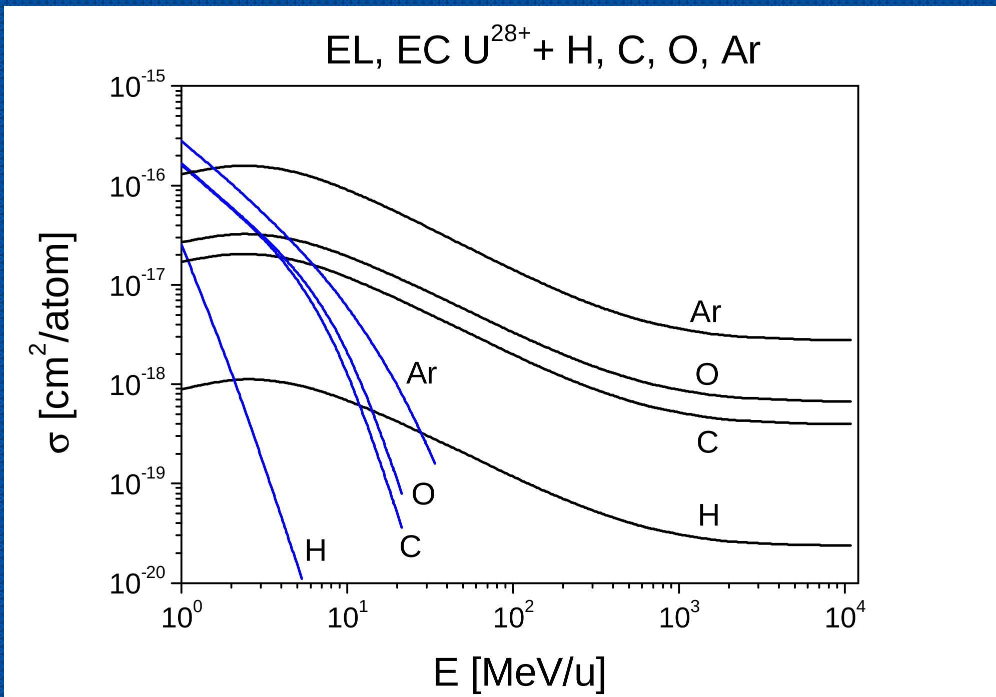


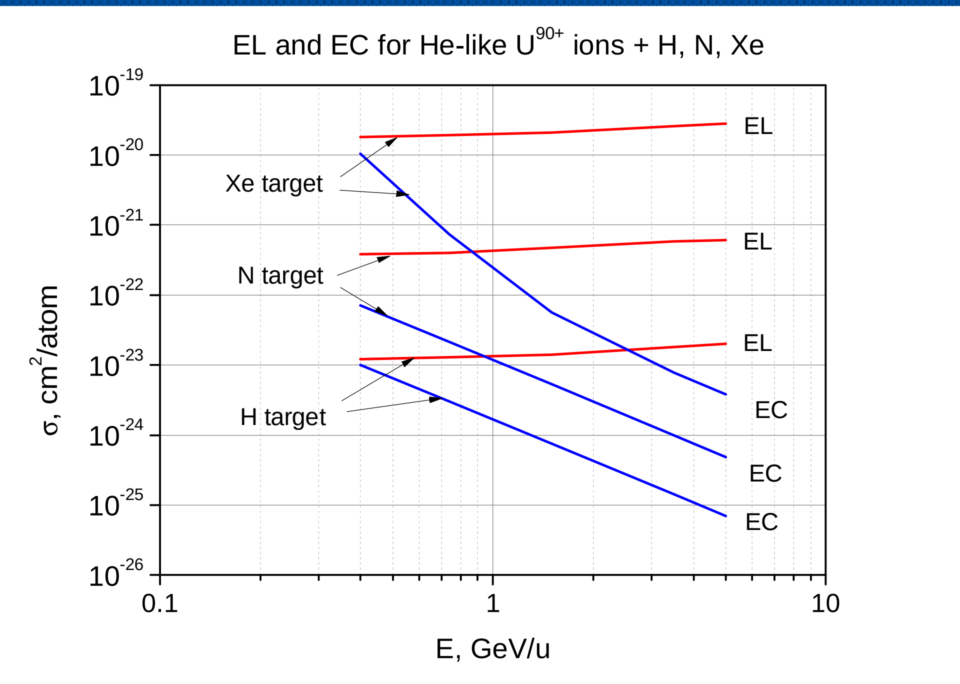
Exp.: GSI, Darmstadt and Texas University

Theory: VPS et al., NIMB 269 (2011) 1455

Relativistic collisions

At relativistic energies only single-electron loss processes play a role because electron-capture cross sections decrease very rapidly.





RELATIVISTIC EL CROSS SECTIONS

$$M_{fi} = \langle f|(1-\beta\alpha_z)e^{i\mathbf{qr}}|i\rangle,$$

$$\beta\alpha_z \sim \frac{v}{c}\frac{\langle p_e\rangle}{m_e c} \sim \frac{v}{c}\frac{v_e}{c}$$

The influence of magnetic interaction is very large if both the ion velocity v and projectile-electron velocity v_e are close to the speed of light *c*.

$s_{EL} \sim const \sim Z_T^2\, I_P^{-0.0q}$ *by neutrals* (semi-empirical estimate)

$s_{EL} \sim Z_i^2 \ln g$ *by ions*, g *– the relativistic Lorentz factor*

$s_{EC} << s_{EL}$ (very important!)

The RICODE-M code for calculation single-electron relativistic EL cross sections

$X^{q+}(nl,\ N_{nl},\ I_{nl}) + A$ à $X^{(q+1)+} + A + e^{-}(\varepsilon, \lambda)$

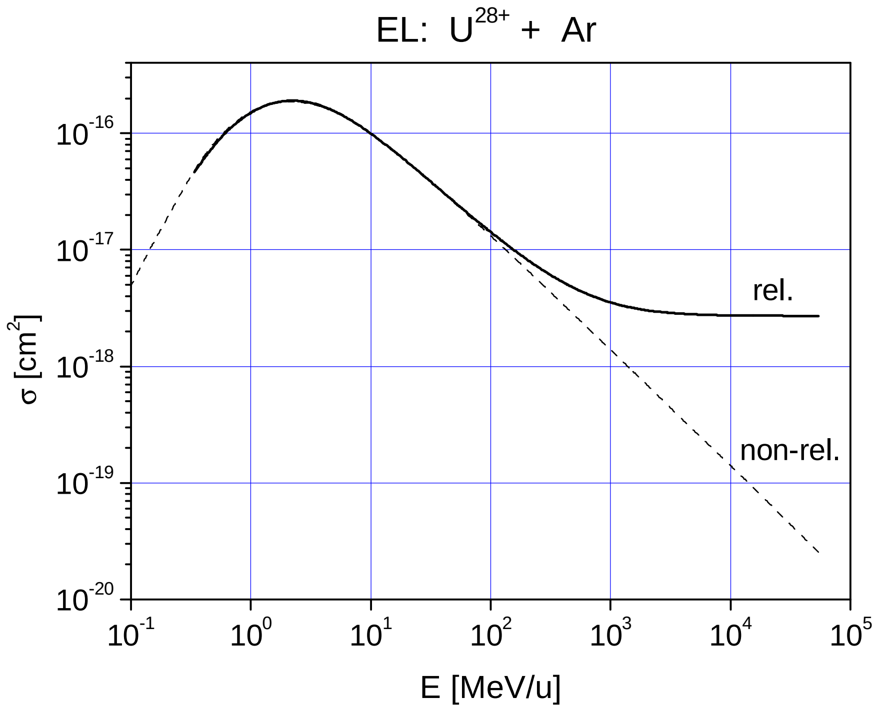
$$\sigma_{\rm ion}(v) = \frac{8\pi}{(\beta c)^2}\sum_{nl} N_{nl}\sum_{\lambda}\int_0^{\infty} d\varepsilon \int_{Q_0}^{\infty}\frac{dQ}{Q^3}\left[Z_T^2(Q)F_{nl}^2(Q) + Z_T^2(Q')\frac{\beta^2(1-Q_0^2/Q^2)}{(1-\beta^2 Q_0^2/Q^2)^2}G_{nl}^2(Q)\right]$$

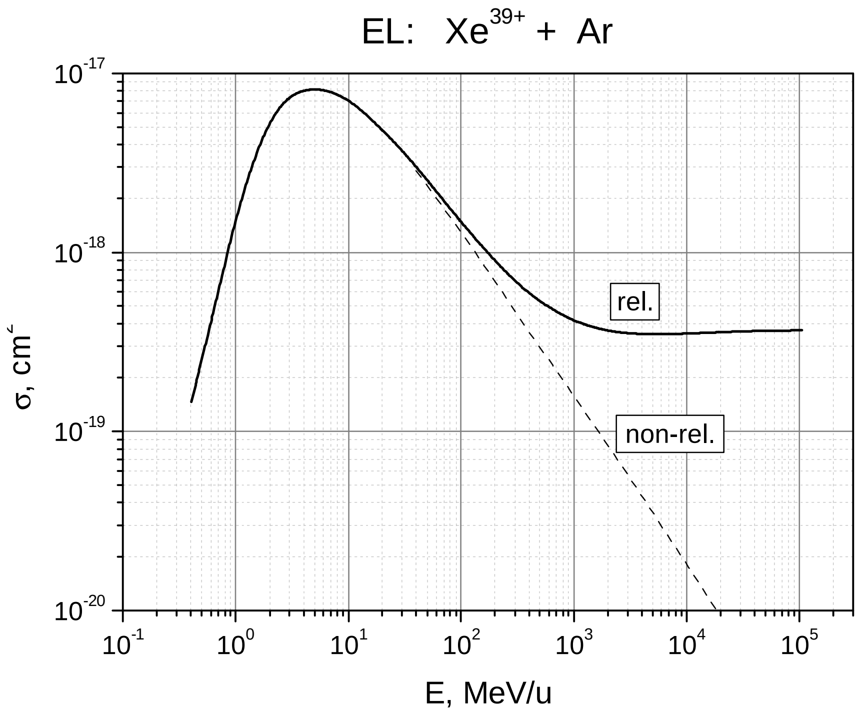
$$Q_0 = \frac{I_{nl}+\varepsilon}{v}, \quad Q' = \sqrt{Q^2-\beta^2 Q_0^2}$$

$F_{nl}(Q)$: ‘usual’ Born form-factor, Q: momentum transfer

RICODE-M: I. Tolstikhina et al., JETP, 1 (2014) 5

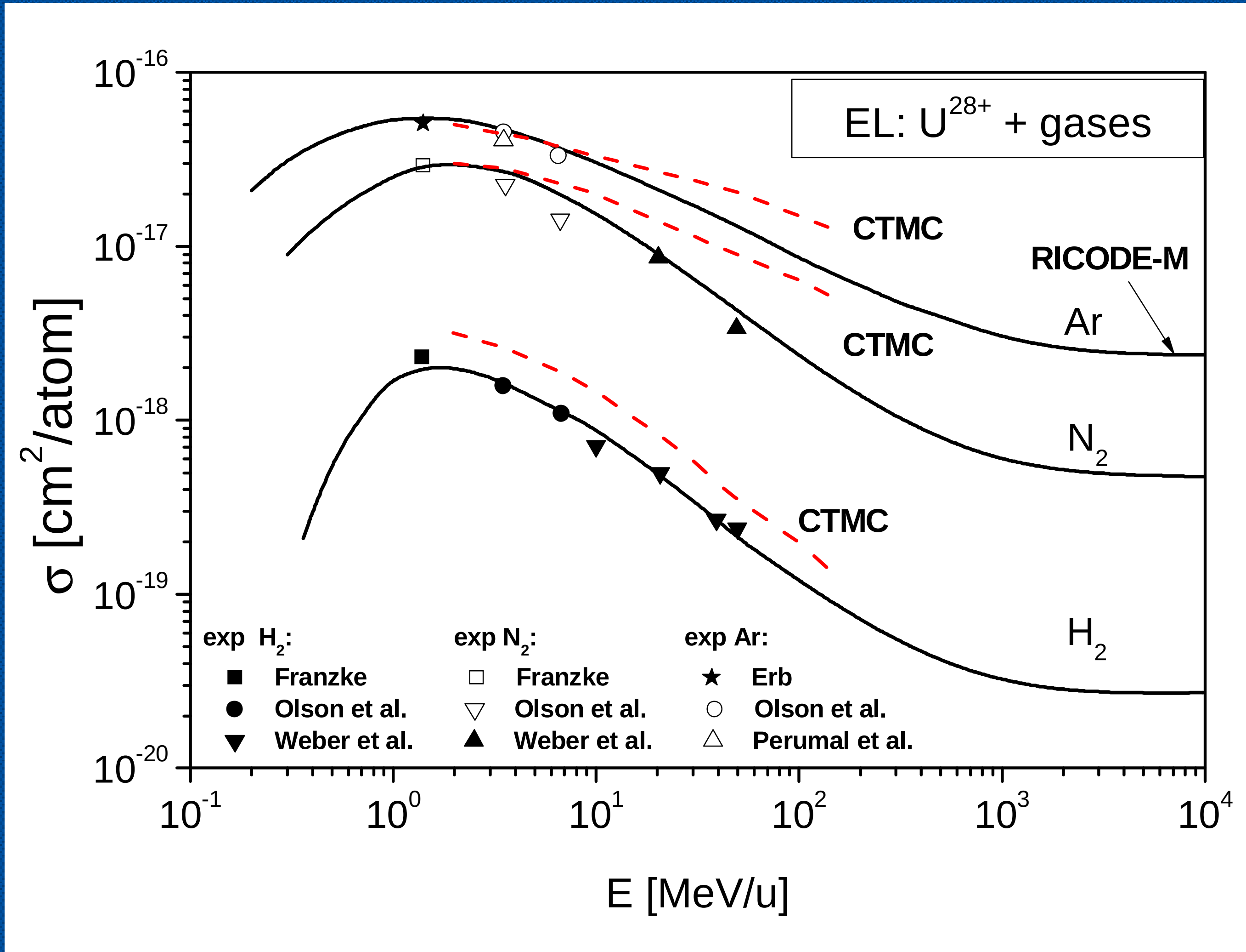
Influence of relativistic effects on EL cross sections





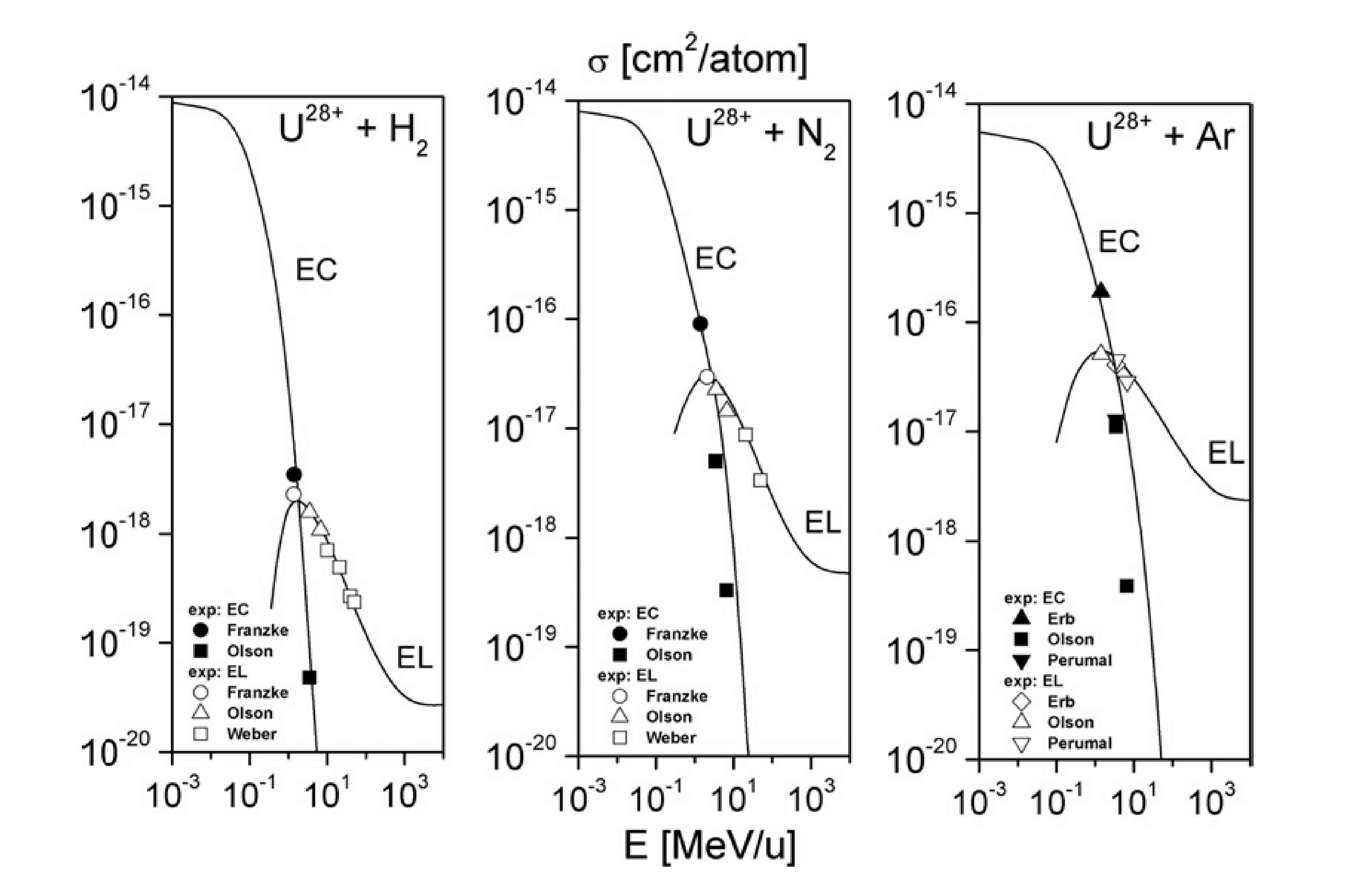
I. Tolstikhina et al., JETP (2014)

Examples:

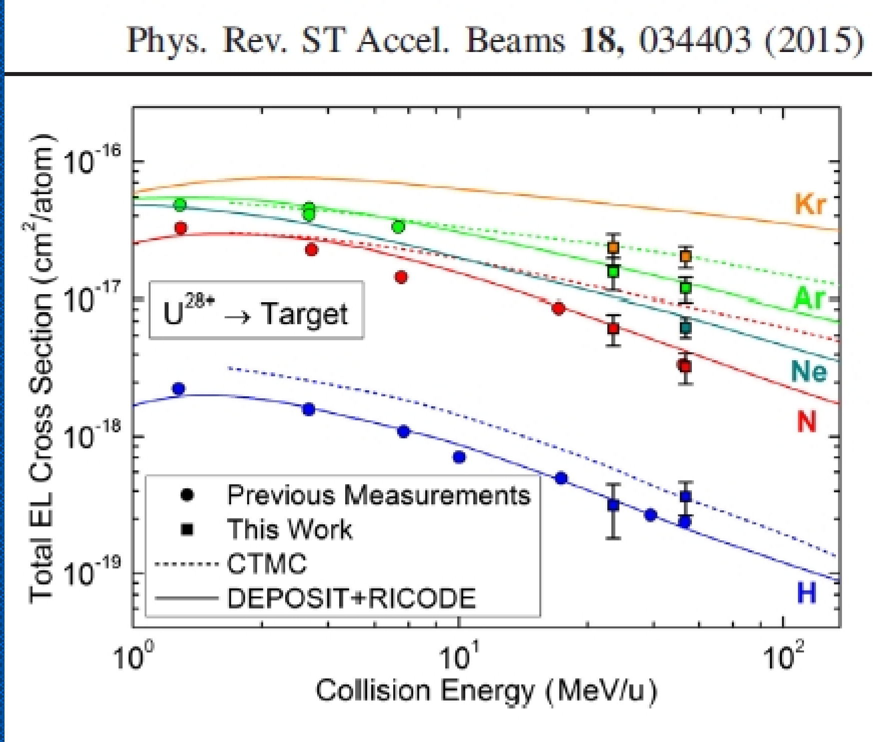


For molecular targets, the Bragg's additivity rule is used, e.g., σ(H2) = 2σ(H).

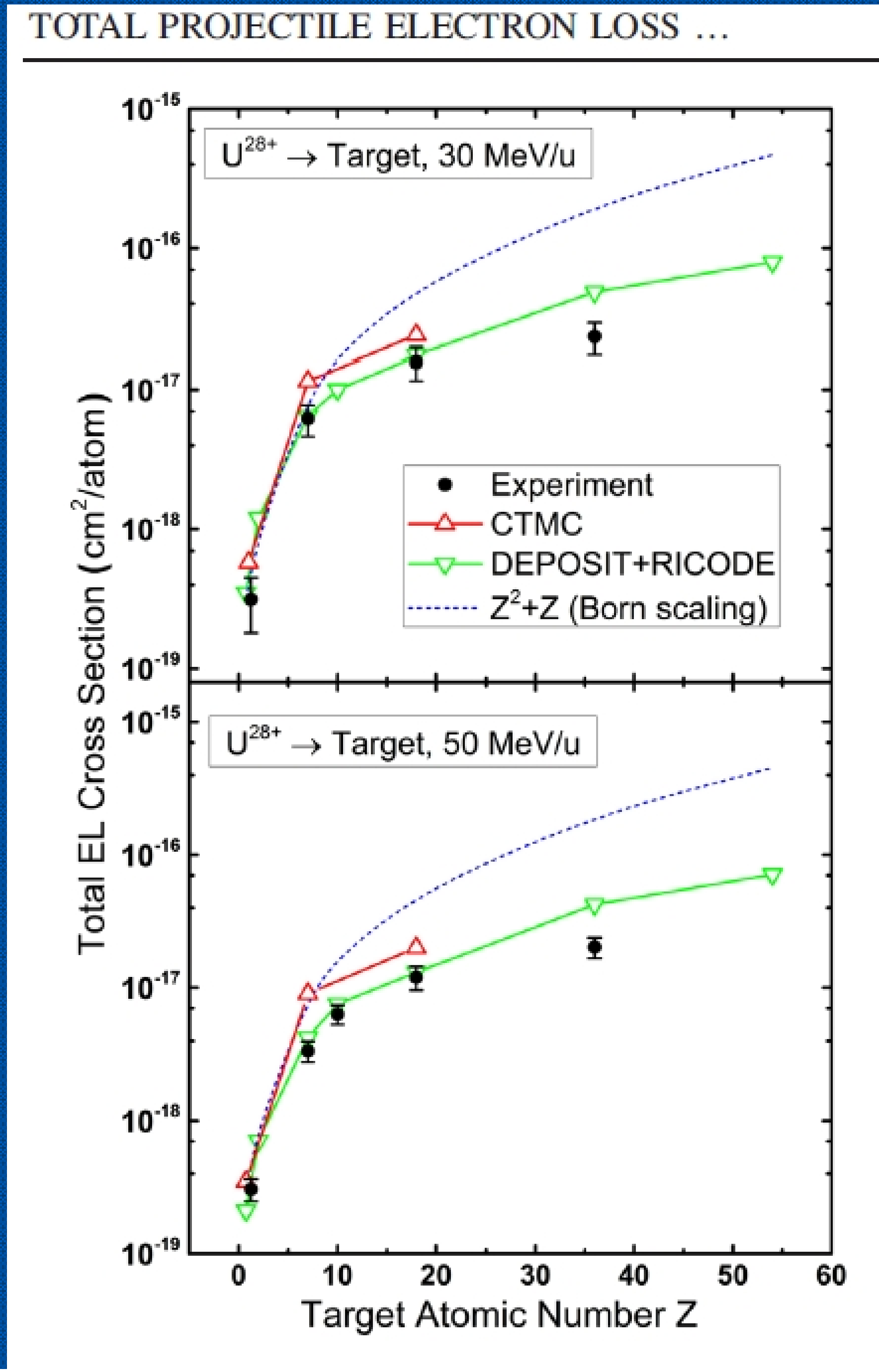
Recommended charge-changing cross sections



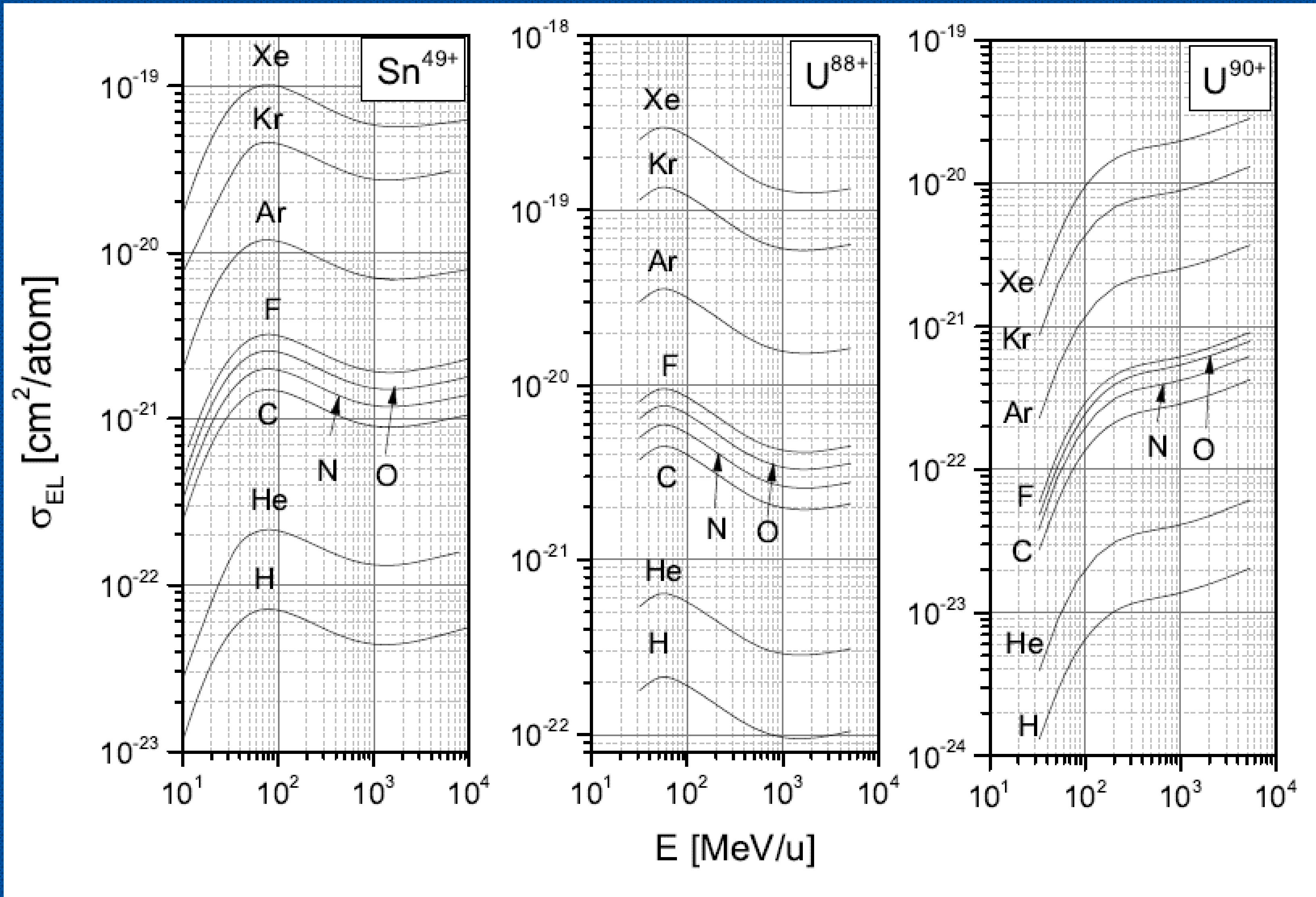
Exp: GSI and Texas A&M Cyclotron
Theory: NIMB 269 (2011) 1455



G. Weber et al. 2015



LOSS cross sections for HESR/GSI project



VPS et al., NIMB 421 (2018) 45–49

Ion-beam lifetimes due to interaction with the rest gas.

$$I(t) = I_0(t) \cdot e^{-t/t_0}$$

$$t_0[s] = \left[r\, b\, c\, \Sigma_T [Y_T s_{EC} + Y_T s_{EL}] \right]^{-1}$$

v_{ion} = βc, relativistic ion velocity in cm/s
c speed of light, ~ 3 x 10^{10} cm/s
sEC and s EL charge-changing cross sections

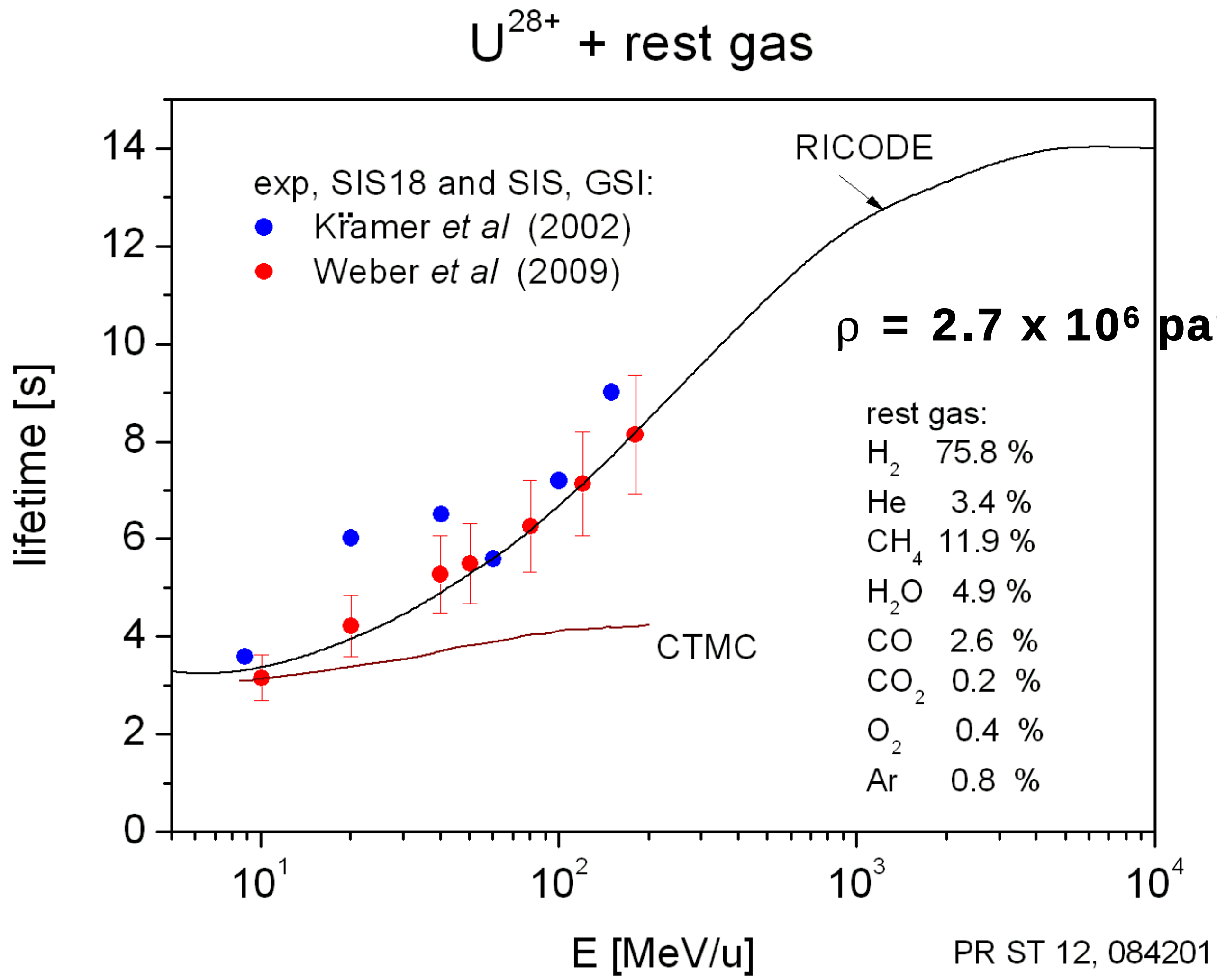
Vacuum conditions:

rest-gas density, part/cm^{-3}

Y_T rest-gas fractions:

$$\Sigma_T Y_T = 1$$

Examples

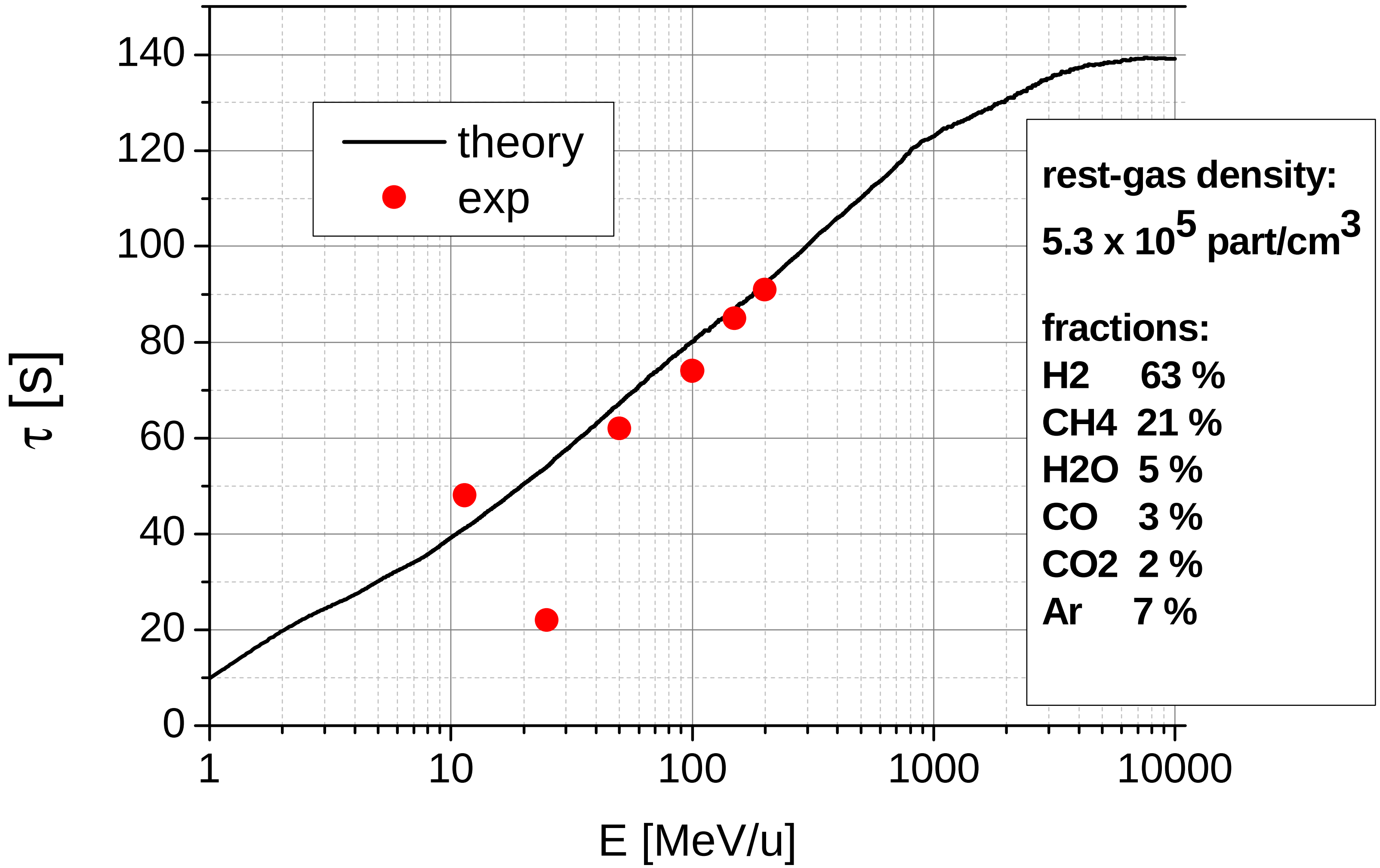


ρ **= 2.7 x 10^6 part/cm^3**

PR ST 12, 084201 (2009)

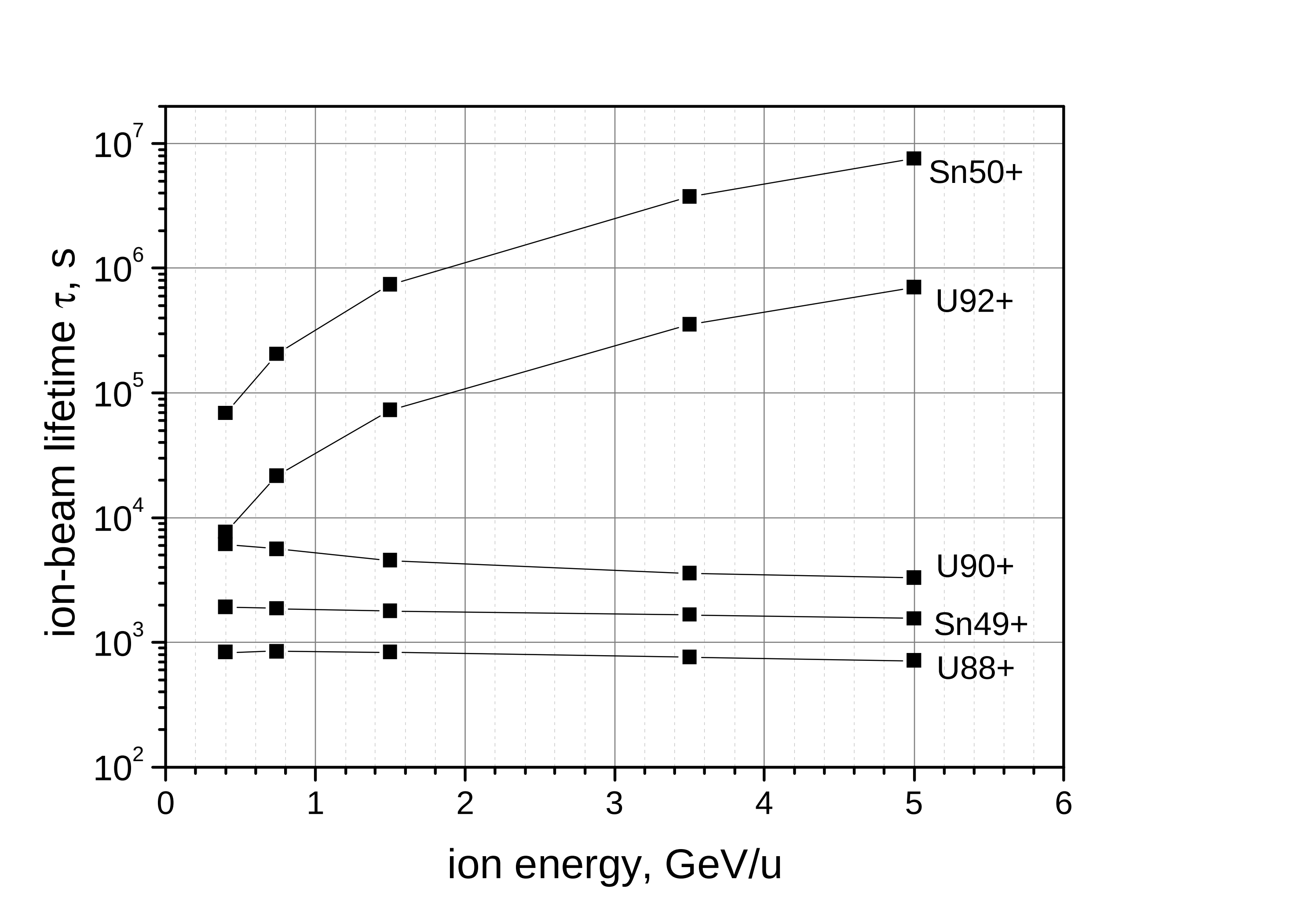
G. Weber et al

U^{28+} beam lifetime at SIS18/GSI, 2016



L. Bozyk et al. NIMB 372 (2016) 102

Ion-beam lifetimes for HESR/GSI project



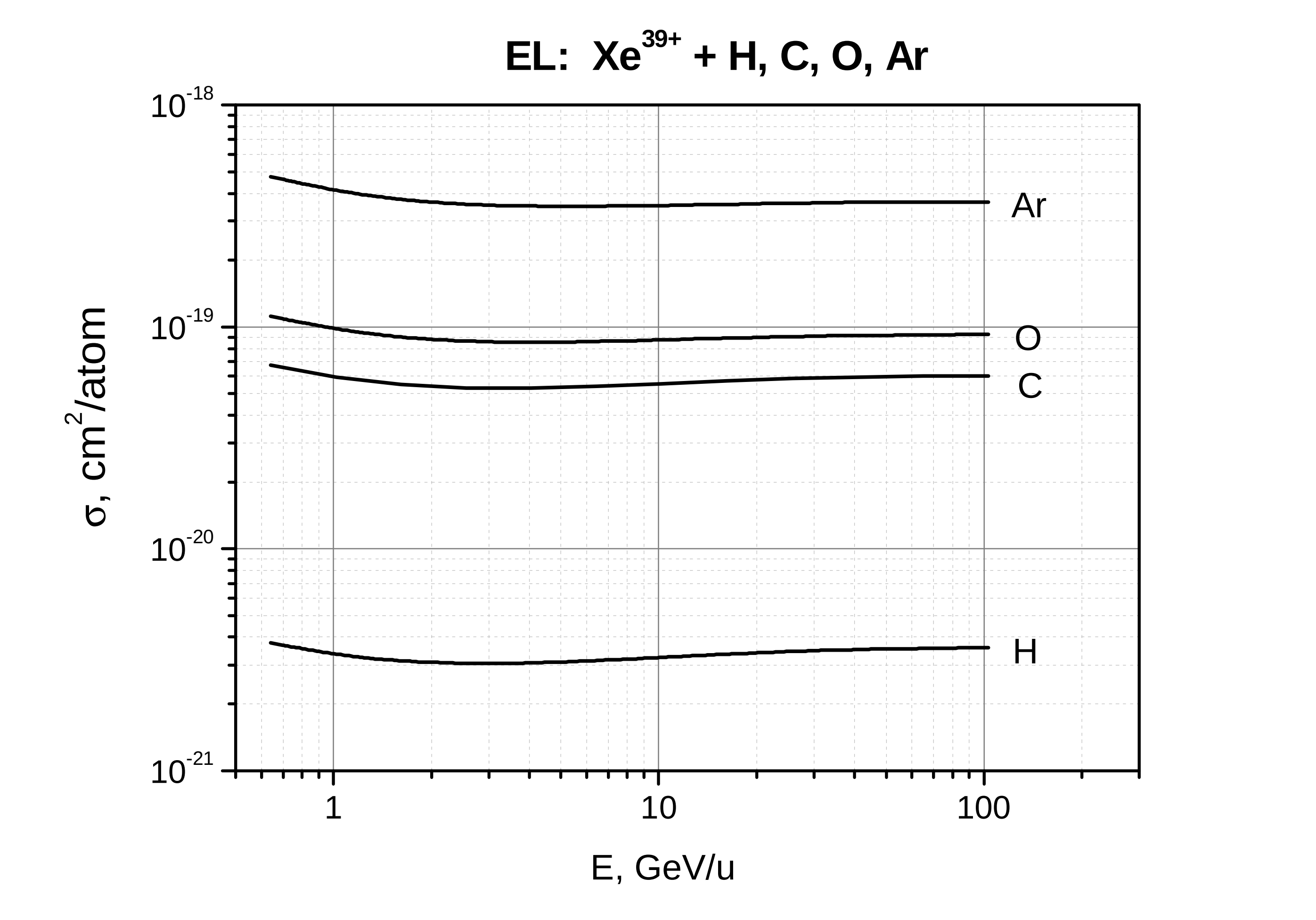
VPS et al., NIMB 421 (2018) 45–49

The rest-gas fractions used for HESR/GSI project

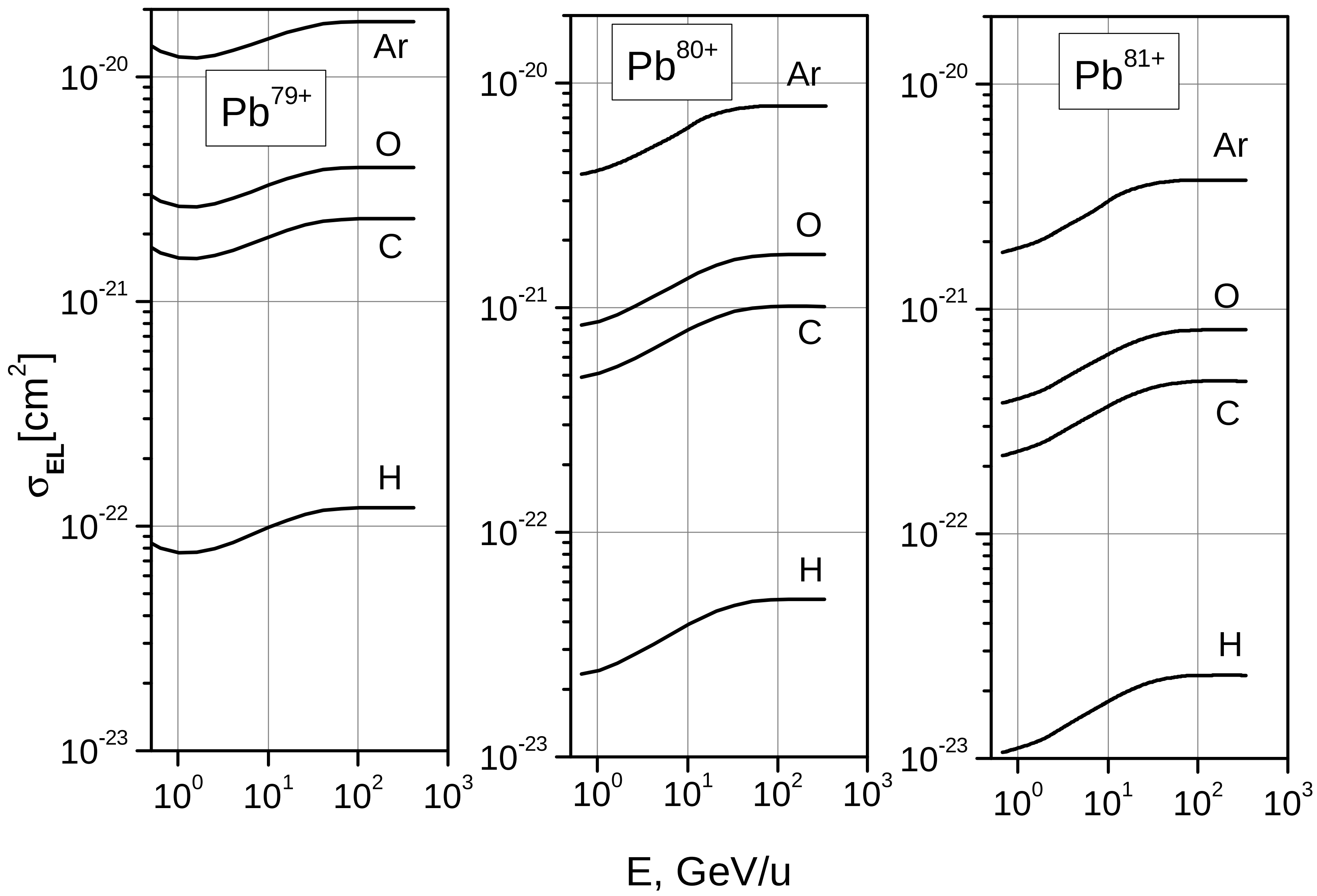
Atom, molecule	Concentration	Atom, molecule	Concentration
H	0.223	O_2	0.0773
H_2	0.188	CO	0.00208
HO	0.0437	CO_2	0.0229
H_2O	0.0833	CO/N_2	0.0583
C	0.0385	F	0.0229
N	0.0219	Ar	0.00106
O	0.216	Xe	0.00106

VPS et al., NIMB 421 (2018) 45–49

Calculations for the GF project
EL cross sections for Xe and Pb ions

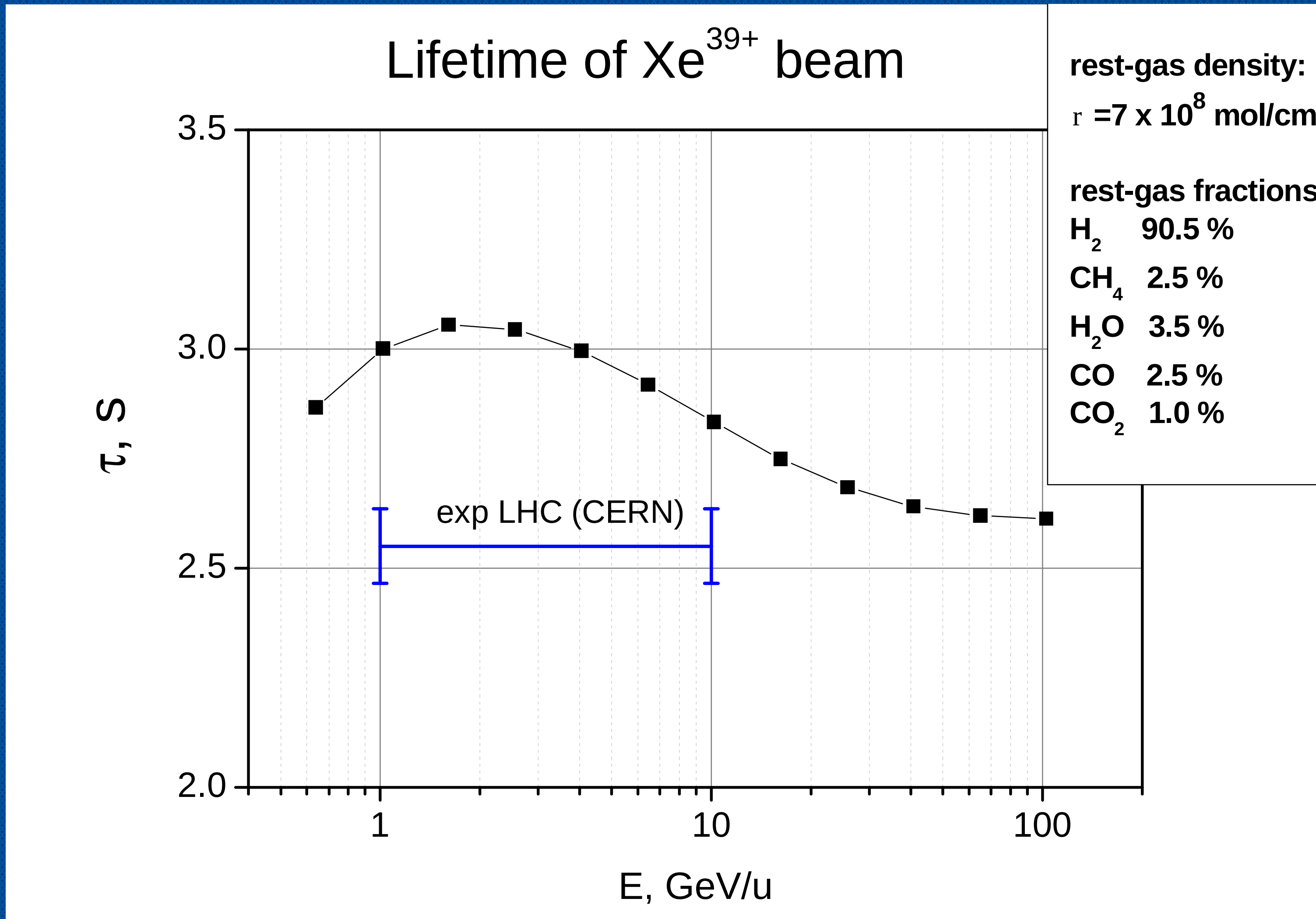


RICODE-M code



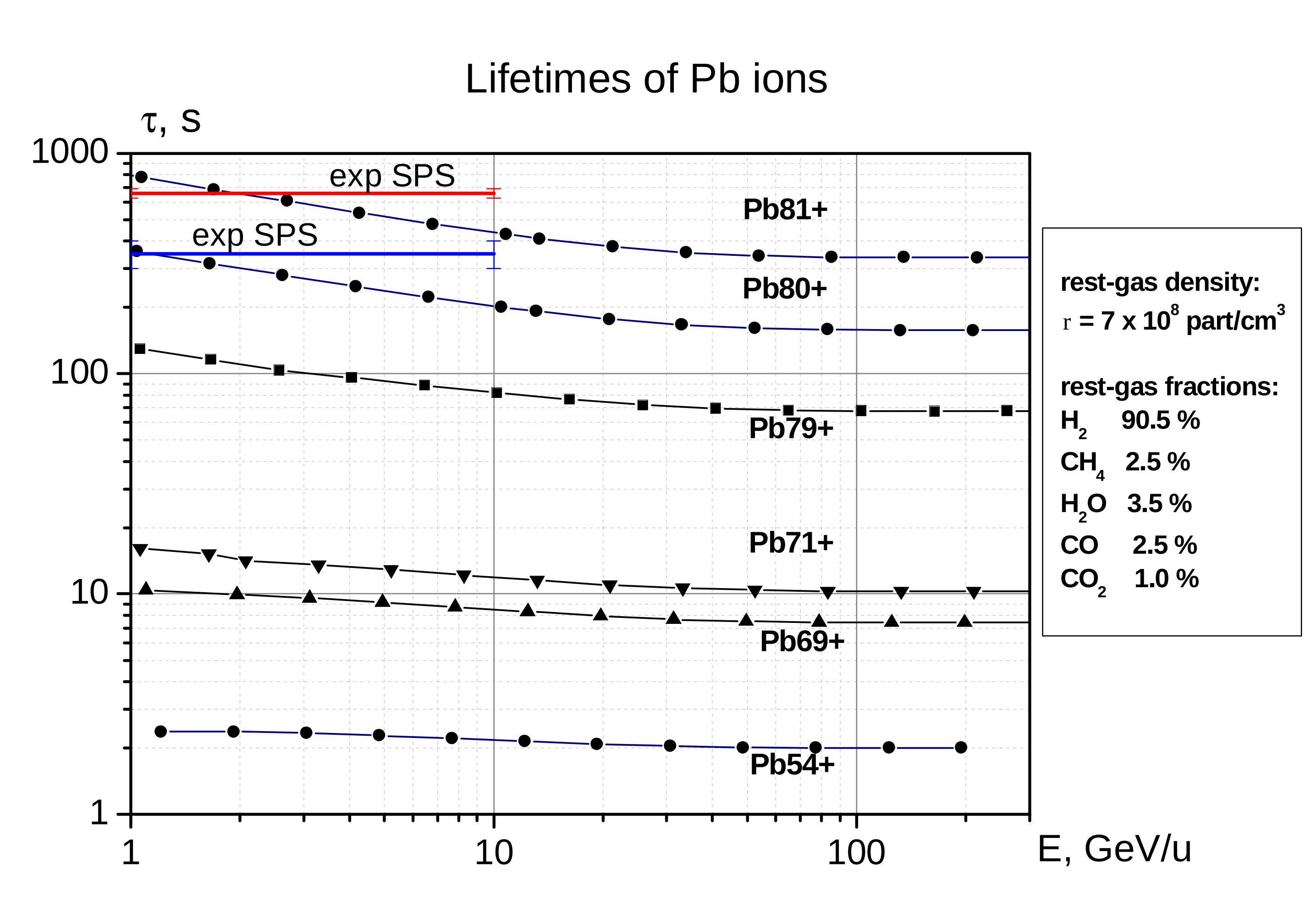
RICODE-M code

Beam lifetimes for collisions of Xe ions with the residual gas in the SPS accelerator



$\tau(Xe39+)$ exp = 2.550 ± 0.085 s

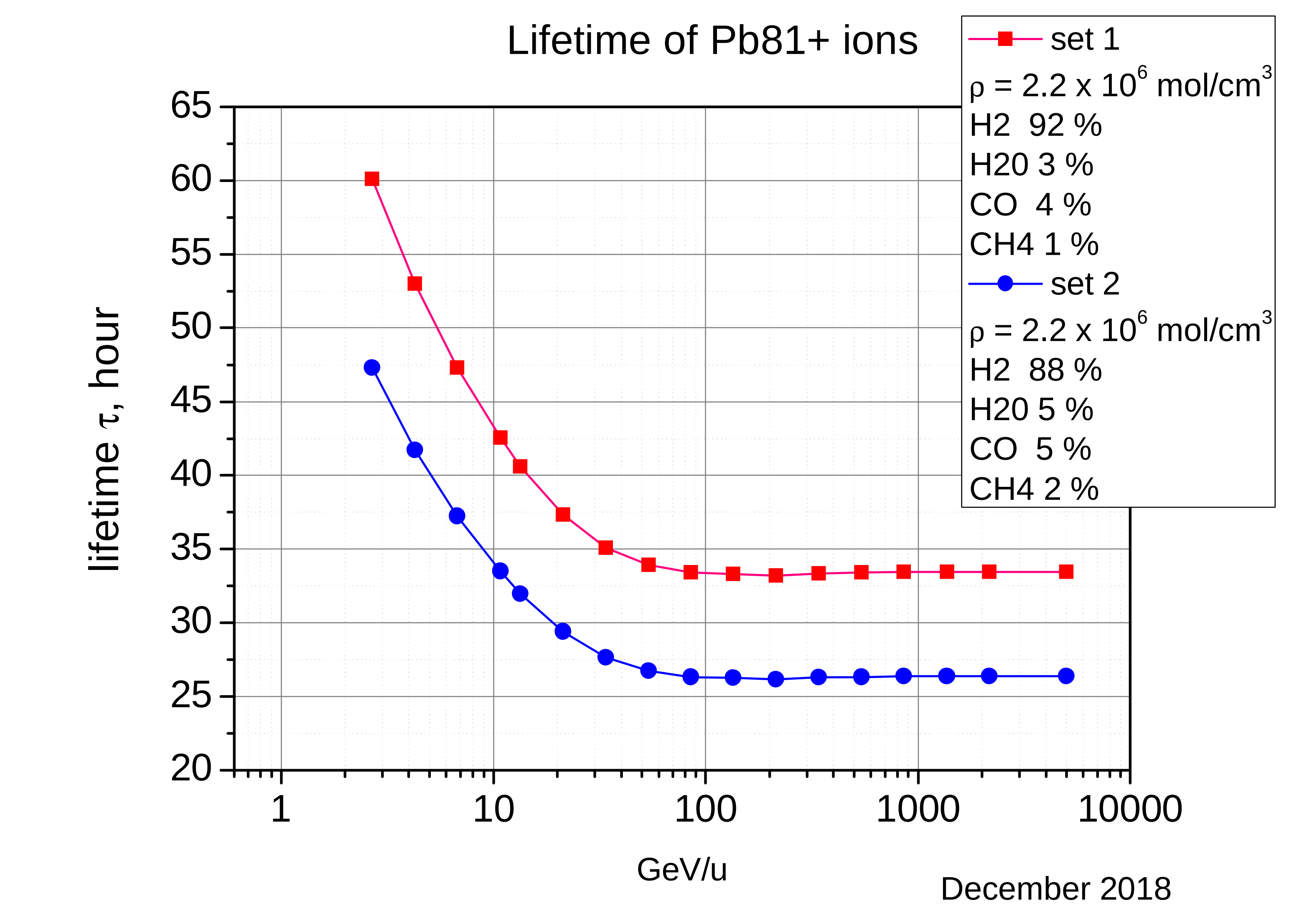
Beam lifetimes for collisions of Pb ions with the residual gas in the SPS accelerator



$\tau(Pb80+)$ exp = 350 ± 50 s

$t(Pb81+)$ exp = 660 ± 30 s

Lifetimes of Pb81+ ions in LHC at high vacuum



t(Pb81+) exp = 38 h

Conclusion

1. The observed in SPS and LHC lifetimes of Xe39+, Pb81+ and Pb80+ beams at energies E = 1 – 10 GeV/u are in a good agreement with calculated by the RICODE-M program values within the uncertainty of the density and molecular composition of the residual gas accelerators.

2. T**he ion losses at relativistic energies are mainly caused by ionization of projectiles by the rest-gas molecules. The estimated ion-beam lifetimes are nearly independent on ion energy in the range of *E* = 1 - 200 GeV/u because of influence of the relativistic effects on the electron-loss cross sections.**

3. A good agreement between theory and experiment for the first time **confurms indirectly** a quasi-constant behavior of the loss cross sections in the relativisic domain, predicted by the relativistic theory.

Our recent publications

Physics–Uspekhi **61** (3) 247–279 (2018)

REVIEWS OF TOPICAL PROBLEMS

PACS numbers: **34.10.**+x, 34.50.Fa, **34.70.**+e

Influence of atomic processes on charge states and fractions of fast heavy ions passing through gaseous, solid, and plasma targets

I Yu Tolstikhina, V P Shevelko

DOI: https://doi.org/10.3367/UFNe.2017.02.038071

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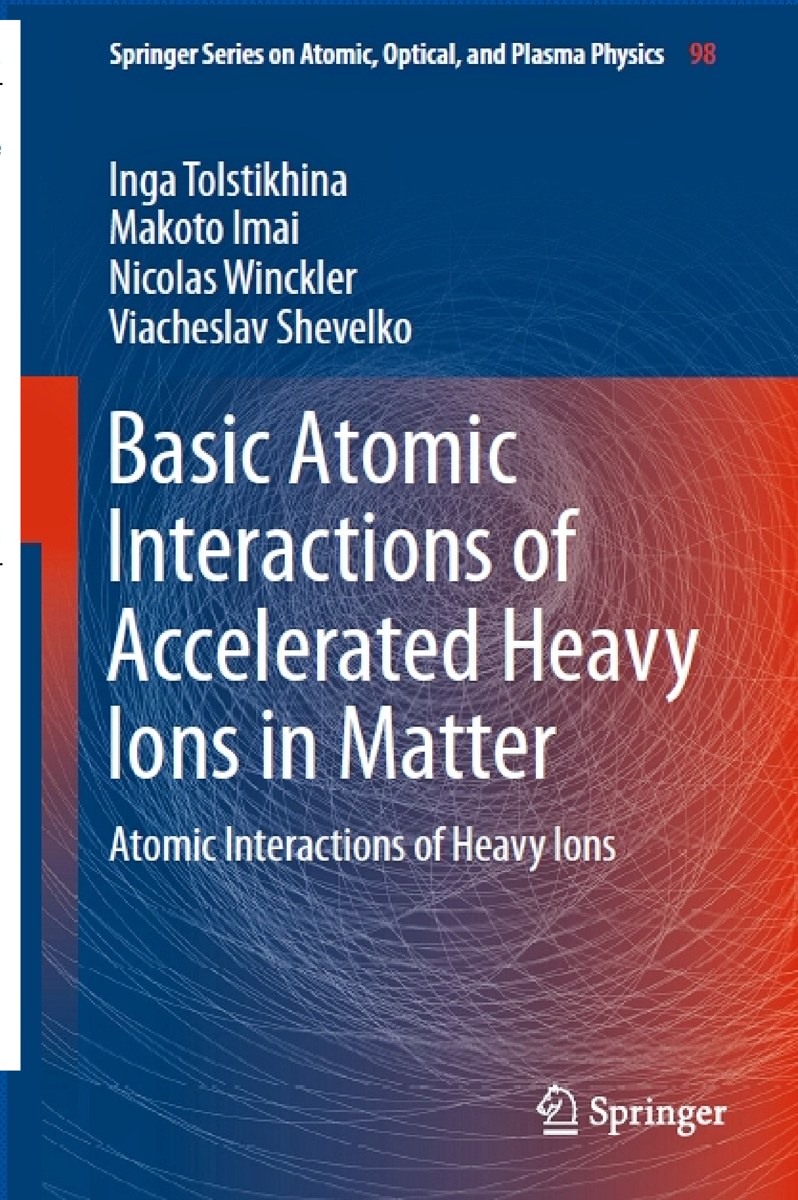

2018

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Spasibo !

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