Beam-gas collisions at SPS and LHC

I. Tolstikhina and V.P. Shevelko

Lebedev Physical Institute, Moscow

CERN - LPI Moscow
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CONTENTS

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 HCl
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) - multiple-electron ionization of heavy ions at low and intermediate energies
- **RI CODE-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 $Z = 120$ (!).


3. Main interests:
   1. Ion beam lifetime and vacuum 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):
   \[ \chi^{q+} + A \nrightarrow \chi^{(q+m)+} + \Sigma A + me^{-}, \ m \geq 1 \]

2. multiple-electron non-radiative capture (NRC):
   \[ \chi^{q+} + A \nrightarrow \chi^{(q-k)+} + A^{+}, \ k \geq 1 \]

3. single-electron radiative capture (REC):
   \[ \chi^{q+} + A \nrightarrow \chi^{(q-1)+} + A^{+} + \hbar \omega \]

\[ \sigma_{\text{TOT(EC)}} = \sigma(\text{NRC}) + \sigma(\text{REC}) \]
Asymptotic behavior of EL and EC cross sections in fast non-relativistic collisions:

\[ \sigma_{EL} \sim Z_T^2 \ln E / (q^2 E) \]
\[ \sigma_{NRC} \sim q^5 Z_T^5 / E^{5.5} \]
\[ \sigma_{REC} \sim q^4 Z_T / E^2 \]
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.
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 $c$.

\[
M_{fi} = \langle f | (1 - \beta \alpha_z) e^{iqr} | i \rangle,
\]

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

\[
\sigma_{EL} \sim \text{const} \sim Z_T^2 I_p^{-0.0q} \text{ by neutrals (semi-empirical estimate)}
\]

\[
\sigma_{EL} \sim Z_i^2 \ln \gamma \text{ by ions, } \gamma - \text{the relativistic Lorentz factor}
\]

\[
\sigma_{EC} \ll \sigma_{EL} \text{ (very important!)}
\]
The RICODE-M code for calculation single-electron relativistic EL cross sections

\[ \chi^{q+}(n_l, N_{nl}, I_{nl}) + A \leftrightarrow \chi^{(q+1)+} + A + e^-(\varepsilon, \lambda) \]

\[ \sigma_{ion}(v) = \frac{8\pi}{(\beta c)^2} \sum_{n_l} N_{nl} \sum_{\lambda} \int_{0}^{\infty} \frac{dQ}{Q^3} \left[ Z_T^2(Q)F_{nl}(Q) + Z_T^2(Q') \frac{\beta^2(1-Q_0/Q^2)}{(1-\beta^2 Q_0/Q^2)^2} G_{nl}(Q) \right] \]

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

\( F_{nl}(Q) \): ‘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)
For **molecular** targets, the Bragg’s additivity rule is used, e.g., $\sigma(H_2) = 2\sigma(H)$. 
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.

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

\[ t_0 \ [s] = \left[ \rho \beta c \ \Sigma_T[Y_T \sigma_{EC} + Y_T \sigma_{EL}] \right]^{-1} \]

\[ v_{ion} = \beta c, \text{ relativistic ion velocity in cm/s} \]
\[ c \quad \text{speed of light, } \sim 3 \times 10^{10} \text{ cm/s} \]
\[ \text{sEC and s EL charge-changing cross sections} \]

**Vacuum conditions:**
\[ \text{rest-gas density, part/cm}^{-3} \]
\[ Y_T \quad \text{rest-gas fractions:} \]
\[ \Sigma_T Y_T = 1 \]
Examples

$U^{28+} + \text{rest gas}$

$\rho = 2.7 \times 10^6 \text{ part/cm}^3$

**exp, SIS18 and SIS, GSI:**

rest gas:
- $H_2$: 75.8%
- He: 3.4%
- $CH_4$: 11.9%
- $H_2O$: 4.9%
- CO: 2.6%
- $CO_2$: 0.2%
- $O_2$: 0.4%
- Ar: 0.8%

PR ST 12, 084201 (2009)
G. Weber et al
$U^{28+}$ beam lifetime at SIS18/GSI, 2016

- **Theory**: Theoretical curve
- **Exp**: Experimental data points

Rest-gas density:
- $5.3 \times 10^5$ part/cm$^3$

Fractions:
- H$_2$: 63%
- CH$_4$: 21%
- H$_2$O: 5%
- CO: 3%
- CO$_2$: 2%
- Ar: 7%

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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

<table>
<thead>
<tr>
<th>Atom, molecule</th>
<th>Concentration</th>
<th>Atom, molecule</th>
<th>Concentration</th>
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<tbody>
<tr>
<td>H</td>
<td>0.223</td>
<td>O₂</td>
<td>0.0773</td>
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<tr>
<td>H₂</td>
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<td>CO</td>
<td>0.00208</td>
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<tr>
<td>HO</td>
<td>0.0437</td>
<td>CO₂</td>
<td>0.0229</td>
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<tr>
<td>H₂O</td>
<td>0.0833</td>
<td>CO/N₂</td>
<td>0.0583</td>
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<tr>
<td>C</td>
<td>0.0385</td>
<td>F</td>
<td>0.0229</td>
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<tr>
<td>N</td>
<td>0.0219</td>
<td>Ar</td>
<td>0.00106</td>
</tr>
<tr>
<td>O</td>
<td>0.216</td>
<td>Xe</td>
<td>0.00106</td>
</tr>
</tbody>
</table>

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

Lifetime of Xe\(^{39+}\) beam

\[ \tau(Xe^{39+}) \text{ exp } = 2.550 \pm 0.085 \text{ s} \]
Beam lifetimes for collisions of Pb ions with the residual gas in the SPS accelerator

Lifetimes of Pb ions

\[
\begin{align*}
\tau(Pb80^+) \text{ exp } &= 350 \pm 50 \text{ s} \\
\tau(Pb81^+) \text{ exp } &= 660 \pm 30 \text{ s}
\end{align*}
\]
Lifetimes of Pb81+ ions in LHC at high vacuum

Lifetime of Pb81+ ions

- **set 1**
  - $\rho = 2.2 \times 10^6$ mol/cm$^3$
  - H$_2$ 92%
  - H$_2$O 3%
  - CO 4%
  - CH$_4$ 1%

- **set 2**
  - $\rho = 2.2 \times 10^6$ mol/cm$^3$
  - H$_2$ 88%
  - H$_2$O 5%
  - CO 5%
  - CH$_4$ 2%

Decay time of Pb81+ ions: $t(\text{Pb81+}) \exp = 38$ 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. The 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 confirms indirectly a quasi-constant behavior of the loss cross sections in the relativistic domain, predicted by the relativistic theory.
Influence of atomic processes on charge states and fractions of fast heavy ions passing through gaseous, solid, and plasma targets

I Yu Tolsikhina, V P Shevelko

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Contents

1. Introduction. Role of atomic interactions in the passage of ions through targets
   1.1 Gaseous targets; 1.2 Solid targets (solids); 1.3 Plasma targets; 1.4 Liquid targets
2. Characteristics of ion beams interacting with the medium
   2.1 Kinetic energy loss; 2.2 Angular straggling; Radiation length; 2.3 Penetration depth (ion range)
3. Stopping power of matter
   3.1 Definition of stopping power; 3.2 Effective charge of an incident ion. Stopping power tables; 3.3 Dependence of the mass stopping power on ion energy; 3.4 Bragg peak; 3.5 Stopping power in plasmas; 3.6 Influence of the target-density effect on the stopping power
4. Equations of charge state balance
   4.1 Charge-state balance equations in the passage of ions through matter. Average charge state and equilibrium
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Spasibo !

Lebedev Physical Institute, Moscow

Emails:

tolstikhinaiy@lebedev.ru
shevelkovvp@lebedev.ru
v.chevelko@gsi.de