Gamma-Ray Sources with Partially Stripped Ions

basics

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1. I am a GF enthusiast:

My is gamma factory!

2. Co-authored: Atomic physics with highly-charged heavy ions and atomic-physics inspired nuclear physics at the Gamma Factory with A. Derevianko, M. Zolotorev, V. Flambaum, S. Pustelny, and A. Surzhykov

3. Provided critique of the draft of the Bessonov et al paper

4. Co-authored a related paper 22 years ago!
Parity Nonconservation in Relativistic Hydrogenic Ions

M. Zolotorev and D. Budker

Parity Violation
☞ level-mixing
☞ circular dichroism

\[ |2S\rangle \Rightarrow |2S\rangle + i\eta |2P\rangle, \quad i\eta = \frac{\langle 2P | \hat{H}_w | 2S \rangle}{E_{2S} - E_{2P}} \]

Fig. 1. The 1S→2S transition in a hydrogenic system.
Table 2. Parameters of relativistic ion storage rings.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RHIC</th>
<th>SPS</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{\text{max}}$ for protons$^a$</td>
<td>250</td>
<td>450</td>
<td>7000</td>
</tr>
<tr>
<td>Number of ions/ring$^b$</td>
<td>$\sim 5 \cdot 10^{11}$</td>
<td>$\sim 2 \cdot 10^{11}$</td>
<td>$\sim 5 \cdot 10^{10}$</td>
</tr>
<tr>
<td>Number of bunches/ring</td>
<td>57</td>
<td>128</td>
<td>500-800</td>
</tr>
<tr>
<td>R.m.s bunch length</td>
<td>84 cm</td>
<td>13 cm</td>
<td>7.5 cm</td>
</tr>
<tr>
<td>Circumference</td>
<td>3.8 km</td>
<td>6.9 km</td>
<td>26.7 km</td>
</tr>
<tr>
<td>Energy spread w/o laser cooling</td>
<td>$2 \cdot 10^{-4}$</td>
<td>$4.5 \cdot 10^{-4}$</td>
<td>$2 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>Normalized Emittance (N.E.)</td>
<td>$\approx 4 \pi \cdot \mu$m \cdot \text{rad}$</td>
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<td>$\approx 4 \pi \cdot \mu$m \cdot \text{rad}$</td>
</tr>
<tr>
<td>Dipole field</td>
<td>3.5 T</td>
<td>1.5 T</td>
<td>8.4 T</td>
</tr>
<tr>
<td>Vacuum, cold</td>
<td>$&lt;10^{-11}$ Torr (H$_2$, He)</td>
<td>-</td>
<td>$&lt;10^{-11}$ Torr (H$_2$, He)</td>
</tr>
</tbody>
</table>

$^a$ For hydrogenic ions, $\gamma_{\text{ions}}^{\gamma_{\text{max}}} = \gamma_{\text{max}}^{p} \cdot Z - 1/A$

$^b$ Estimated from proton and heavy ion data.
Table 1: Z-dependence of atomic characteristics for hydrogenic ions. In the given expressions, $\alpha$ is the fine structure constant, $\hbar=\varepsilon=1$, $m_e$ is the electron mass, $G_F$ is the Fermi constant, $\theta_w$ is the Weinberg angle, and $A$ is the ion mass number.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Approximate Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transition Energy</td>
<td>$\Delta E_{n\rightarrow n'}$</td>
<td>$\frac{1}{2} \left( \frac{1}{n^2} - \frac{1}{n'^2} \right) \alpha^2 m_e \cdot Z^2$</td>
</tr>
<tr>
<td>Lamb Shift</td>
<td>$\Delta E_{2S\rightarrow 2P}$</td>
<td>$\frac{1}{6\pi} \alpha^5 m_e \cdot Z^4 \cdot F(Z)^a$</td>
</tr>
<tr>
<td>Weak Interaction Hamiltonian</td>
<td>$\hat{H}_w$</td>
<td>$i \sqrt{\frac{3}{2}} \cdot \frac{G_F m_e^3 \alpha^4}{64\pi} \cdot \left{ (1-4 \sin^2 \theta_w) - \frac{(A-Z)}{Z} \right} \cdot Z^3$</td>
</tr>
<tr>
<td>Electric Dipole Amplitude</td>
<td>$E_{1S\rightarrow 2P}$</td>
<td>$\frac{1}{\sqrt{\alpha}} \cdot m_e^{-1} \cdot Z^{-1}$</td>
</tr>
<tr>
<td>(2S→2P$_{1/2}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric Dipole Amplitude</td>
<td>$E_{1S\rightarrow 2P}$</td>
<td>$\frac{2^7}{3^5} \sqrt{\frac{2}{3\alpha}} \cdot m_e^{-1} \cdot Z^{-1}$</td>
</tr>
<tr>
<td>(1S→2P$_{1/2}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forbidden Magn. Dipole Ampl.</td>
<td>$M1$</td>
<td>$\frac{2^{5/2} \alpha^{5/2}}{3^4} \cdot m_e^{-1} \cdot Z^2$</td>
</tr>
<tr>
<td>(1S→2S)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiative Width</td>
<td>$\Gamma_{2P}$</td>
<td>$\left( \frac{2}{3} \right)^8 \alpha^5 m_e \cdot Z^4$</td>
</tr>
</tbody>
</table>

* The function $F(Z)$ is tabulated in Ref. 12. Some representative values are: $F(1)=7.7$; $F(5)=4.8$, $F(10)=3.8$; $F(40)=1.5$. 

Fig. 1. The 1S→2S transition in a hydrogenic system.
Resonance condition:

With LHC ($\gamma \approx 3000$): up to $Z=48$ (Cd) 
(for $1s \rightarrow 2p$ in hydrogenic ion)
The $\gamma$-ray source scheme for CERN

Relativistic magic applied twice!
Gamma Factory @ CERN

Partially Stripped Ion beam as a light frequency converter

\[ \nu_{\text{max}} \rightarrow (4 \gamma_L^2) \nu_i \]

Tuning of the beam energy, the choice of the ion type, the number of left electrons and of the laser type allows to tune the \( \gamma \)-ray energy, at CERN, in the energy domain of 100 keV – 400 MeV.

Example (maximal energy):
LHC, Pb\(^{90+}\) ion, \( \gamma_L = 2887 \), \( n=1 \rightarrow 2 \), \( \lambda = 104.4 \) nm, \( E_\gamma (\text{max}) = 396 \) MeV
Basics of laser-driven transitions in PSI

• Resonant cross-section:

\[ \sigma_{abs} = \frac{\lambda^2}{2\pi} \cdot \frac{2J'+1}{2J+1} \cdot \frac{\Gamma_p}{\Gamma_{tot}} \]

Note: Rabi oscillations picture is equivalent!

• 1s→2p in PSI: \( \lambda \approx 122 \text{ nm/} Z^2 \)

• Transition rate: \( \sigma_{abs} \cdot \Phi = \sigma_{abs} \cdot \frac{\dot{N}_{\text{phot}}}{\lambda_{\text{laser}} \cdot \frac{z_R}{2}} = \frac{a^2 E^2}{\Gamma_p} \)

Example: \( \lambda_{\text{laser}} = 1 \text{ \mu m}, z_R = 1 \text{ m} \rightarrow \lambda_{\text{laser}} \cdot \frac{z_R}{2} \approx 0.5 \text{ mm}^2 \)
Basics of laser-driven transitions in PSI

- Doppler broadening: \( \Gamma_D = 2\delta \gamma \cdot \omega_{\text{laser}} = \frac{\delta \gamma}{\gamma} \cdot (2\gamma \omega_{\text{laser}}) = \frac{\delta \gamma}{\gamma} \cdot \omega_0 \)

- Fraction of resonant ions: \( \Gamma_p / \Gamma_D \) (for \( \Gamma_p < \Gamma_D \))

- 1s→2p in PSI: \( \frac{\Gamma_p}{\omega_0} \approx 4 \cdot 10^{-8} Z^2 \)

- Resonant-transition rate:
  \[
  \sigma_{\text{abs}} \cdot \Phi = \sigma_{\text{abs}} \cdot \frac{\dot{N}_{\text{phot}}}{\lambda_{\text{laser}} \cdot Z R / 2}
  \]
What happens if light is off resonance?

- There is still population in upper state:
  
  Off resonance: $\frac{d^2E^2}{4\Delta^2}$
  
  On resonance: $\frac{d^2E^2}{\Gamma_p}$

- Homogeneous and inhomogeneous broadening

![Diagram showing energy levels and transitions between states](image-url)
How to excite a distribution of PSI?

- With narrow-band light (good)
- With broadband light (better)
- With chirped light (the best)
- This was discussed by Simon Rochester
Let us talk about 1D optical molasses first.

Photon scattering rate:

\[ R_{\pm} = \frac{\kappa_0 \gamma_0}{1 + \left(1 \pm \frac{2\omega v}{\gamma_0 c}\right)^2} \]

Momentum kick:

\[ \Delta p_{\pm} = \pm \frac{\hbar \omega}{c} \]

Average force:

\[ \langle F \rangle = \Delta p_+ R_+ + \Delta p_- R_- = \frac{\kappa_0 \hbar \omega}{c} \left[ \frac{1}{1 + (1 + \beta)^2} - \frac{1}{1 + (1 - \beta)^2} \right] \]

Q: What is the final temperature?
Q: What is the final temperature?

When $\Gamma_D = \Gamma_p (= \gamma_0)$

But one can go much colder!
Doppler Limit

• Equilibrium temperature: balance of cooling and heating

\[
\bar{v} = \sqrt{\langle p^2 \rangle / M}
\]

\[
E = \frac{k_B T}{2} = \frac{\langle p^2 \rangle}{2M}
\]

\[
\frac{\partial E}{\partial t} \bigg|_{\text{cool}} = \langle F \rangle \bar{v} \approx -2\hbar \omega^2 \kappa \frac{\bar{v}^2}{c^2}
\]

\[
\frac{\partial E}{\partial t} \bigg|_{\text{heat}} = \kappa \gamma_0 \frac{\hbar^2 \omega^2}{Mc^2}
\]

\[
\frac{\partial}{\partial t} \langle p^2 \rangle_{\text{heat}} \approx 2\kappa \gamma_0 \frac{\hbar^2 \omega^2}{c^2}
\]

\[
\frac{1}{2} M \bar{v}^2 = \frac{\hbar \gamma_0}{4}
\]

• Doppler limit holds for PSI

\[
T_D = \frac{\hbar \gamma_0}{2k_B}
\]
Single-Photon-Recoil Limit

\[ T_\gamma \sim \frac{\hbar^2 \omega^2}{2k_B M c^2}, \]

\[ T_D = \frac{\hbar \gamma_0}{2k_B}, \]

\[ T^* \sim \gamma_0^2 \frac{M c^2}{2k_B \omega_0^2}. \]

\[ T_D^2 = T^* T_\gamma. \]
Cooling PSI

- Only one laser beam
- PSI are not free $\Rightarrow$ accelerator dynamics important
- It works! since 1990s
- Doppler Limit for PSI:
  
  \[
  \left( \frac{\Delta \gamma}{\gamma} \right)_D = \sqrt{\frac{\Gamma_{2P}}{M_{\text{ion}}}} \]
  
  scales as $Z^{3/2}$
- Cooling dilemma: avoid photoionization but overcome heating due to intrabeam scattering
Further reading on basics

Fundamentals of gamma-ray light sources (Gamma Factory) based on backward resonance scattering of laser photons from relativistic ion beams

E. Bessonov, P. Antsiferov, W. Krasny, A. Petrenko, D. Budker, S. Pustelny
Figure 1: The ion-laser pulse interaction in the laboratory reference frame.
Things to worry about with PSI

- Ionization on residual gas

\[ \sigma = 4\pi\alpha^2 a_B^2 \frac{Z_a(Z_a+1)}{Z^2} \]

- Field ionization

\[ \tau^{-1}_{f.i.} = 4 \frac{\alpha c}{a_B} Z^5 \frac{\varepsilon_{at}}{B_D} \exp \left( -\frac{2\varepsilon_{at} Z^3}{3\gamma B_D} \right) \]

- Photoionization from \( 2P \) (and for \( Z > 40 \), also \( 2S \))

Also

- Need laser cooling to reduce \( \frac{\Delta \gamma}{\gamma} \) \( \Rightarrow \) laser cooling

- Is the required laser realistic?
More things to worry about...

- How to detect the PV transition? Absorption cavity?
- Systematics due to stray $E$-field mixing
- $E$-field due to the ions’ space charge
- Laser cooling should be faster than intrabeam scatt.