Gamma Factory

Novel opportunities for Atomic, Nuclear, and Applied Physics

ECFA Plenary Meeting, November 2020

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Helmholtz Institute Mainz, JGU Excellence Cluster PRISMA+, and UC Berkeley
Outline of the talk

- Opportunities with primary, secondary, and tertiary beams
- Atomic physics at the GF @ LHC and GF @ SPS
- Nuclear photophysics with fixed targets
- Applied physics examples
- Conclusions
Atomic Physics Studies at the Gamma Factory at CERN

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duality

Light Source ↔ Giant Ion Trap
Spectroscopy of PSI

PSI = HCl = Highly Charged Ions

Hydrogen-like Ions

Transition energy $\Delta E_{nn'} \propto (Z\alpha)^2$

Fine-structure splitting $\propto (Z\alpha)^4$

Hyperfine-structure splitting $\propto \alpha(Z\alpha)^3 m_e/m_p$

Lamb shift $\propto \alpha(Z\alpha)^4$

Strong E-fields!

$\text{Pb}^{81^+} : \ 10^{16} \ \text{V/cm}$

Schwinger critical field

$$E_s = m^2 c^3 / (e\hbar) \approx 1.3 \times 10^{16} \ \text{V/cm}$$
: direct excitation of heavy PSI with primary photons
Li-like ions

<table>
<thead>
<tr>
<th>Ion</th>
<th>Transition energy</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb(^{79+})</td>
<td>(230.823 \pm 0.047) ((47)(4))</td>
<td>theory, [5]</td>
</tr>
<tr>
<td></td>
<td>(230.76(4))</td>
<td>theory, [6]</td>
</tr>
<tr>
<td>Bi(^{80+})</td>
<td>(235.800(53)(9))</td>
<td>theory, [5]</td>
</tr>
<tr>
<td></td>
<td>(235.72(5))</td>
<td>theory, [6]</td>
</tr>
<tr>
<td>U(^{89+})</td>
<td>(280.645(15))</td>
<td>experiment, [7]</td>
</tr>
<tr>
<td></td>
<td>(280.775(97)(28))</td>
<td>theory, [5]</td>
</tr>
</tbody>
</table>

TABLE III. Energies (eV) of the \(1s^2 2s^2 S_{1/2} \rightarrow 1s^2 2p^2 P_{1/2}\) transition in heavy lithium-like ions.

PoP experiment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>crossing angle</td>
<td>2.6°</td>
</tr>
<tr>
<td>Ion magnetic rigidity</td>
<td>787 Tm</td>
</tr>
<tr>
<td>Ion (\gamma) factor</td>
<td>96.3</td>
</tr>
<tr>
<td>Ion beam horizontal RMS size at IP</td>
<td>1.3 mm</td>
</tr>
<tr>
<td>Ion beam vertical RMS size at IP</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Ion revolution frequency</td>
<td>43.4 kHz</td>
</tr>
<tr>
<td>Laser photon energy</td>
<td>1.2 eV</td>
</tr>
<tr>
<td>Laser frequency</td>
<td>40 MHz</td>
</tr>
<tr>
<td>Laser pulse energy</td>
<td>5 mJ</td>
</tr>
<tr>
<td>Ion (2s_{1/2} \rightarrow 2p_{1/2}) transition energy</td>
<td>230.8 eV</td>
</tr>
<tr>
<td>Maximum energy of back scattered photon</td>
<td>44.5 keV</td>
</tr>
</tbody>
</table>
Projected $10^{-4}$ uncertainty in the PoP experiment: better than current theory state-of-the-art

Atomic Physics already in PoP!
Fundamental symmetry tests at the GF
Parity Nonconservation in Relativistic Hydrogenic Ions

M. Zolotorev and D. Budker

Why?
- New physics (e.g. Z’ bosons)
- Neutron skins
- Nuclear anapoles

\[ \rho \]

\[ \rho_p \]

\[ \rho_n \]

\[ \Delta R_{np} \]

\[ R_p \]

\[ R_n \]

pdg.lbl.gov/2020/reviews/rpp2020-rev-standard-model.pdf
Parity Nonconservation in Relativistic Hydrogenic Ions

M. Zolotorev and D. Budker

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

level-mixing

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

circular dichroism
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 \text{m} \cdot \text{rad} )</td>
<td>( \approx 4 \pi \cdot \mu \text{m} \cdot \text{rad} )</td>
<td>( \approx 4 \pi \cdot \mu \text{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 ( (\text{H}_2, \text{He}) )</td>
<td>-</td>
<td>( &lt;10^{-11} ) Torr ( (\text{H}_2, \text{He}) )</td>
</tr>
</tbody>
</table>

\( ^a \) For hydrogenic ions, \( \gamma_{\text{max}}^{\text{ions}} = \gamma_{\text{max}}^{p} \cdot Z / A \)

\( ^b \) 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, $\hbar=\epsilon=1$, $m_e$ 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>$\dot{H}_W$</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 $(2S\rightarrow 2P_{1/2})$</td>
<td>$E1_{2S\rightarrow 2p}$</td>
<td>$\sqrt{\frac{3}{\alpha}} \cdot m_e^{-1} \cdot Z^{-1}$</td>
</tr>
<tr>
<td>Electric Dipole Amplitude $(1S\rightarrow 2P_{1/2})$</td>
<td>$E1$</td>
<td>$\frac{2^7}{3^5} \sqrt{\frac{2}{3\alpha}} \cdot m_e^{-1} \cdot Z^{-1}$</td>
</tr>
<tr>
<td>Forbidden Magn. Dipole Ampl. $(1S\rightarrow 2S)$</td>
<td>$M1$</td>
<td>$\frac{2^{5/2}}{3^4} \alpha^{5/2} \cdot m_e^{-1} \cdot Z^2$</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.
Unique to \( \mathcal{P}_2 \text{gf} \):

measure in \textbf{isonuclear} chains

(+\textit{isotopic chains})

\[ \downarrow \]

control of systematics for \textbf{neutron-skins}
Not only hydrogenic ions are interesting for parity violation!

Level-crossing in He-like ions

Parity-violating mixing

$$\eta = \frac{\langle \Psi_s | \hat{H}_w | \Psi_p \rangle}{E_p - E_s - i\Gamma/2}$$

Enhancement near level crossings

$$\propto Z^5$$
Optical Pumping of PSI

- Single-path polarization via optical pumping
- Both electronic and nuclear polarization
- Will polarization survive a round trip?
- If yes ☞ measure static and oscillating EDM
- Regardless ☞ nuclear-spin dependent parity violation
More atomic physics at the

- Laser cooling of PSI in the ring: enabling technology!
- Twisted light (gamma)
- PSI in strong external fields (also for parity violation)
- Tests of special relativity
- Scattering of gamma rays on ions (Thompson, Delbrück, …)
- …
Expanding Nuclear Physics Horizons with Gamma Factory

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(Dated: November 13, 2020)
Nuclear physics at the $p^2$GF:

- Physics opportunities with primary, secondary and tertiary beams with previously unattainable parameters
- Direct measurements of astrophysical S-factors at relevant energies
- Spectroscopy of nuclear gamma transitions on par with laser spectroscopy of atoms
- Gamma polarimetry at the $10^{-5}$ to $10^{-6}$ rad level
- Precision measurement of parity violation in hadronic and nuclear system at previously inaccessible asymmetry
- Production of high-intensity, monoenergetic and small-emittance tertiary beams: neutrons, muons, neutrinos, etc.
- ...
Nuclear physics at the \( \pi^0 \): examples

- Direct nuclear-transition spectroscopy of stored nuclei (or PSI)
- Interplay of atomic and nuclear d.o.f.
- \((\gamma, \pi)\) reactions to probe halo nuclei
- Photoproduction of pionic(kaonic) atoms, e.g., \(\gamma + ^3H \rightarrow (^3He + \pi^-)_{ns}\)


<table>
<thead>
<tr>
<th>Isotope</th>
<th>(I_\gamma^P)</th>
<th>Transition energy</th>
<th>(I_e^P)</th>
<th>Excitation lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{129}\text{Xe})</td>
<td>1/2+</td>
<td>39.578 keV</td>
<td>3/2+</td>
<td>12.8 ns</td>
</tr>
<tr>
<td>(^{229}\text{Th})</td>
<td>5/2+</td>
<td>29.19 keV</td>
<td>(5/2+)</td>
<td>30 ns</td>
</tr>
<tr>
<td>(^{161}\text{Dy})</td>
<td>5/2+</td>
<td>25.651 keV</td>
<td>5/2-</td>
<td>95.7 ns</td>
</tr>
<tr>
<td>(^{118}\text{Sn})</td>
<td>1/2+</td>
<td>23.871 keV</td>
<td>3/2+</td>
<td>109 ns</td>
</tr>
<tr>
<td>(^{151}\text{Eu})</td>
<td>5/2+</td>
<td>21.541 keV</td>
<td>7/2+</td>
<td>275 ns</td>
</tr>
<tr>
<td>(^{57}\text{Fe})</td>
<td>1/2-</td>
<td>14.412 keV</td>
<td>3/2-</td>
<td>940 ns</td>
</tr>
<tr>
<td>(^{73}\text{Ge})</td>
<td>9/2+</td>
<td>13.3 keV</td>
<td>5/2+</td>
<td>3.3 msec</td>
</tr>
<tr>
<td>(^{45}\text{Sc})</td>
<td>7/2-</td>
<td>12.4 keV</td>
<td>3/2+</td>
<td>201 sec</td>
</tr>
<tr>
<td>(^{205}\text{Pb})</td>
<td>5/2-</td>
<td>2.3 keV</td>
<td>1/2-</td>
<td>3 hours</td>
</tr>
<tr>
<td>(^{235}\text{U})</td>
<td>7/2-</td>
<td>76.7 eV</td>
<td>1/2+</td>
<td>(10^{17}) years</td>
</tr>
<tr>
<td>(^{229}\text{Th})</td>
<td>5/2+</td>
<td>8.28 eV</td>
<td>(3/2+)</td>
<td>(~10) min</td>
</tr>
</tbody>
</table>
Nuclear physics at the $^{21}$: examples

- High-resolution spectroscopy of $\gamma$-resonances
- Fano effect in $\gamma$-resonances
- Giant resonances, pigmy resonances
- $(\gamma, \alpha)$ reactions: astrophysical S-factors
- Nuclear E1 polarizabilities, e.g., $^{208}\text{Pb}(\gamma, \gamma')$
- Parity-violating photophysics
- Lepton-pair photoproduction ($e^+, e^-$ and $\mu^+, \mu^-$)
Fixed-target experimental configurations

Excited ions

Laser pulse

Ion bunch

Targets

$\theta_1$

Gamma-ray pulses

Parallel Spectroscopy
Fixed-target experimental configurations

a) Short laser pulses
   - Excited ions
   - Ion bunch
   - Gamma-ray pulses
   - Target

b) X-ray mirror

Pump-Probe Spectroscopy
Applied physics and enabling technologies

- Production of medical isotopes and isomers
- Nuclear waste disposal
- Gamma-ray lasers
- Precision gamma polarimetry
- …
Virtual MITP Workshop

Physics Opportunities with the Gamma Factory

30 November – 4 December 2020

- Accelerator developments
- Atomic and fundamental physics
- Search for Dark Matter
- Nuclear and particle physics
- Rare isotopes and isomers
- Nuclear-physics applications
- Studies with primary, secondary and tertiary beams
- Gamma Factory in a global landscape

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Conclusion