Gamma Factory @ CERN

Novel opportunities for Atomic, Nuclear, and Applied Physics

Quantum Science Seminar, December 17, 2020

Dmitry Budker

Helmholtz Institute Mainz, JGU Excellence Cluster PRISMA+, and UC Berkeley
Photon scattering on relativistic ions

In the laboratory reference frame:

Before photon absorption

\[ \gamma m\nu \]

Excited ion

\[ \gamma m\nu + \hbar k \]

After photon emission

\[ \gamma m\nu + \hbar k - \hbar k_1 \]

\[ \gamma m\nu \gg \hbar k_1 \gg \hbar k \]

In the initial ion reference frame:

Before photon absorption

\[ \hbar k' \]

Excited ion

\[ \hbar k' \]

Excited ion is nonrelativistic, since \( \hbar k' \ll mc \)

After photon emission

\[ \hbar k' - \hbar k_1' \]

\[ k' = k_1' \]

Photon-energy boost: \( 2\gamma_L \times 2\gamma_L \)

backward emission angle: \( 1/\gamma_L \)

Photon-energy boost: \( 2\gamma_L \)
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, $E_{\gamma}$ (max) = 396 MeV
The expected magnitude of the $\gamma$-source intensity leap

**Electrons:**

$$\sigma_e = \frac{8\pi}{3} \times r_e^2$$

$r_e$ - classical electron radius

**Partially Stripped Ions:**

$$\sigma_{res} = \frac{\lambda_{res}^2}{2\pi}$$

$\lambda_{res}$ - photon wavelength in the ion rest frame

**Electrons:**

$$\sigma_e = 6.6 \times 10^{-25} \text{ cm}^2$$

**Partially Stripped Ions:**

$$\sigma_{res} = 5.9 \times 10^{-16} \text{ cm}^2$$

Numerical example: $\lambda_{laser} = 1540 \text{ nm}$

$\sim 9$ orders of magnitude difference in the cross-section

$\sim 7$ orders of magnitude increase of gamma fluxes

Witek Krasny
PSI @ LHC

Is this possible?
A major news from CERN! (July 2018)

During a special one-day run, LHC operators injected lead ‘atoms’ containing a single electron into the machine (Image: Maximilien Brice/Julien Ortan/CERN)

Protons might be the Large Hadron Collider’s bread and butter, but that doesn’t mean it can’t crave more exotic tastes from time to time. On Wednesday, 25 July, for the very first time, operators injected not just atomic nuclei but lead “atoms” containing a single electron into the LHC. This was one of the first proof-of-principle tests for a new idea called the Gamma Factory, part of CERN’s Physics Beyond Colliders project.
Gamma Factory PBC study group

90 scientists
35 institutes
>10 countries

A. Abramov¹, S.E. Alden¹, R. Alemany Fernandez², P.S. Antsiferov³, A. Apyan⁴, H. Bartosik², E.G. Bessonov⁵, N. Biancacci², J. Bion⁰, A. Bogacz⁷, A. Bosco¹, R. Bruce², D. Budker⁸, K. Cassou⁹, F. Castelli¹⁰, I. Chaikovska⁹, C. Curatoľ¹¹, P. Czodrowski², A. Dreevianko¹², K. Dupraz⁹, Y. Dutheil⁹, K. Dzierzęga⁶, V. Fedosseev⁷, N. Fuster Martinez², S. M. Gibson¹, B. Goddari¹², A. Gorzawski¹³², S. Hirlander⁷, J.M. Jowett², R. Kersevan², M. Kowalska², M.W. Krasny¹⁴², F. Kroeger¹⁵, D. Kuchler², M. Lamont², T. Lefevre², D. Manglunki², B. Marsh³, A. Martens⁶, J. Molson⁶, D. Nutarelli⁰, L. J. Nevay¹, A. Petrenko², V. Petrillo¹⁰, W. Placzek⁸, S. Redaelli², S. Pustelny⁶, S. Rochester², M. Sapinski¹⁶, M. Schaumann³, M. Scrivens², L. Serafini¹⁰, V.P. Shevelko⁵, T. Stoechler¹⁵, A. Surzhikov¹⁷, I. Tolstikhina⁵, F. Velotti², G. Weber¹⁵, Y.K. Wu¹⁸, C. Yin-Vallgren², M. Zanetti¹⁹¹¹, F. Zimmermann², M.S. Zolotorev²⁰ and F. Zomer⁰

¹ Royal Holloway University of London, Egham, Surrey, TW20 0EX, United Kingdom
² CERN, Geneva, Switzerland
³ Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow Region, Russia
⁴ A.L. Alkhanyan National Science Laboratory, Yerevan, Armenia
⁵ P.N. Lebedev Physical Institute, Russian Academy of Sciences, Moscow, Russia
⁶ Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
⁷ Center for Advanced Studies of Accelerators, Jefferson Lab, USA
⁸ Helmholtz-Institute, Johannes Gutenberg University, Mainz, Germany
⁹ LAL, Univ. Paris-Sud, CNRS-IN2P3, Université Paris-Saclay, Orsay, France
¹⁰ Department of Physics, INFN–Milan and University of Milan, Milan, Italy
¹¹ INFN–Padua, Padua, Italy
¹² University of Nevada, Reno, Nevada 89557, USA
¹³ University of Malta, Malta
¹⁴ LPNHE, University Paris Sorbonne, CNRS-IN2P3, Paris, France
¹⁵ HI Jena, IQOQ FSU Jena and GSI Darmstadt, Germany
¹⁶ GSI, Helmholtzcenter für Schwerionenforschung, 64291 Darmstadt, Germany
¹⁷ Braunschweig University of Technology and Physikalisch-Technische Bundesanstalt, Germany
¹⁸ FEL Laboratory, Duke University, Durham, USA
¹⁹ University of Padua, Padua, Italy
²⁰ Center for Beam Physics, LBNL, Berkeley, USA

GF group is open to everyone willing to contribute to this initiative!
• Parity violation in relativistic ions
• Laser cooling @ RHIC, SPS, & LHC
• Optical stochastic cooling
• Atomic physics @ GF

Max S. Zolotorev
1941-2020
Atomic Physics Studies at the Gamma Factory at CERN

Dmitry Budker,* José R. Crespo López-Urrutia, Andrei Derevianko, Victor V. Flambaum, Mieczysław Witold Krasny, Alexey Petrenko, Szymon Pustelný, Andrey Surzhykov, Vladimir A. Yerokhin, and Max Zolotorev
duality

Light Source ↔ Giant Ion Trap
Expanding Nuclear Physics Horizons with Gamma Factory

Dmitry Budker
Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany
Helmholtz-Institut, GSI Helmholtzzentrum für Schwerionenforschung, 55128 Mainz, Germany and
Department of Physics, University of California, Berkeley, California 94720, USA

Julian C. Berengut
School of Physics, University of New South Wales, Sydney 2052, Australia and
Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

Victor V. Flambaum
School of Physics, University of New South Wales, Sydney 2052, Australia
Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany
Helmholtz-Institut, GSI Helmholtzzentrum für Schwerionenforschung, 55128 Mainz, Germany and
The New Zealand Institute for Advanced Study, Massey University Auckland, 0632 Auckland, New Zealand

Mikhail Gorshtein
Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany

Jianan Jin
Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China

Felix Karbstein
Helmholtz-Institut Jena, Freieleuht 3, 07743 Jena, Germany and
Theoretisch-Physikalisches Institut, Abt Center of Photonics,
Friedrich-Schiller-Universität Jena, Max-Wien-Platz 1, 07743 Jena, Germany

Mieczyslaw Witold Krasny
LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris; France and
CERN, Geneva, Switzerland

Adriana Pálffy and Hans A. Weidenmüller
Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

Vladimir Pascualtsa and Marc Vanderhaeghen
Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany

Alexey Petrenko
CERN, Geneva, Switzerland and
Budker Institute of Nuclear Physics, Novosibirsk, Russia

Audrey Surzhykov
Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany and
Technische Universität Braunschweig, 38106 Braunschweig, Germany

Vladimir Zelevinsky
Department of Physics and Astronomy, Michigan State University,
640 S. Shaw Lane, East Lansing, MI 48824, USA and
National Superconducting Cyclotron Laboratory, Michigan State University,
640 S. Shaw Lane, East Lansing, MI 48824, USA
(Dated: December 5, 2020)
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

Contacts
Web: https://indico.mitp.uni-mainz.de/event/214/overview
Email: POG2021@uni-mainz.de

Organizers
Dmitry Budker
Misha Gorshteyn
Witold Krasny
Adriana Palffy
Andrey Surzhykov

Workshop is sponsored by the Mainz Institute for Theoretical Physics
Special Issue

Physics Opportunities with the Gamma Factory

Submission deadline: April 1st, 2021

Scope:
- 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

Guest Editors
- Dmitry Budker
- Mikhail Gorshtein
- Witold Krasny
- Adriana Palffy
- Andrey Surzhykov

About the Journal:
Annalen der Physik (IF 3.317) is one of the world’s renowned physics journals with an over 225 years’ tradition of excellence. It comprises all areas of physics, from fundamental research to forefront applications including interdisciplinary fields. Research articles (ca. 6-8 pages): new results of general interest. Reviews (ca. 15-25 pages): a snapshot of recent progress and particularly relevant aspects with possibly open or controversially discussed questions.

Online submission at www.editorialmanager.com/adp-journal

Contact Editor: Nadezda Panarina

Wiley-VCH GmbH
Rotherstrasse 21
10245 Berlin, Germany
E-mail: ann-phys@wiley.com
Outline of the talk

- What is Gamma Factory (GF)
- Opportunities with primary, secondary, and tertiary beams
- Atomic physics at the GF
- Nuclear photophysics with fixed targets
- Applied physics examples
- Conclusions
Spectroscopy of PSI

PSI = HCl = Highly Charged Ions

Hydrogen-like Ions

<table>
<thead>
<tr>
<th>Property</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transition energy $\Delta E_{nn'}$</td>
<td>$\propto (Z\alpha)^2$</td>
</tr>
<tr>
<td>Fine-structure splitting</td>
<td>$\propto (Z\alpha)^4$</td>
</tr>
<tr>
<td>Hyperfine-structure splitting</td>
<td>$\propto \alpha(Z\alpha)^3 m_e/m_p$</td>
</tr>
<tr>
<td>Lamb shift</td>
<td>$\propto \alpha(Z\alpha)^4$</td>
</tr>
</tbody>
</table>

Strong E-fields!

Pb$^{81+}$: $10^{16}$ 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 (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 $1s^2\ 2s\ 2p^2 S_{1/2} \rightarrow 1s^2\ 2p^2 P_{1/2}$ transition in heavy lithium–like ions.

---

**Parameter**

<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 T m</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 D. Budker: Gamma Factory @ CERN
Parity Nonconservation in Relativistic Hydrogenic Ions

M. Zolotorev and D. Budker

Why?

• New physics (e.g. $Z'$ bosons)
• Neutron skins
• Nuclear anapoles
Parity Nonconservation in Relativistic Hydrogenic Ions

M. Zolotorev and D. Budker

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

level-mixing

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

☞ circular dichroism
<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</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>
<td>$\approx 4 \pi \cdot \mu m \cdot \text{rad}$</td>
<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, $\gamma_{\text{ions}}^{\text{max}} = \gamma_{\text{max}}^p \cdot Z - 1/A$

$^b$ 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, $h=c=1$, $m_e$ is the electron mass, $G_F$ is the Fermi constant, $\theta_w$ is the Weinberg angle, and $Z$ 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>$\Delta E_{n-n'}$</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>$\Delta E_{2S-2p}$</td>
<td>$\frac{1}{6\pi} \alpha^5 m_e \cdot Z^4 \cdot F(Z)$</td>
</tr>
<tr>
<td>Weak Interaction Hamiltonian</td>
<td>$\hat{H}_w$</td>
<td>$i \sqrt{\frac{3}{2}} \frac{G_F m_e^3 \alpha^4}{64\pi} \left[ (1 - 4 \sin^2 \theta_w) - \frac{(A-Z)}{Z} \right] Z^3$</td>
</tr>
<tr>
<td>Electric Dipole Amplitude (2S→2P&lt;sub&gt;1/2&lt;/sub&gt;)</td>
<td>$E1_{2S→2P}$</td>
<td>$\sqrt{\frac{3}{\alpha}} \cdot m_e^{-1} \cdot Z^{-1}$</td>
</tr>
<tr>
<td>Electric Dipole Amplitude (1S→2P&lt;sub&gt;1/2&lt;/sub&gt;)</td>
<td>$E1$</td>
<td>$\frac{2^7}{3^3} \sqrt{\frac{2}{3\alpha}} \cdot m_e^{-1} \cdot Z^{-1}$</td>
</tr>
<tr>
<td>Forbidden Magn. Dipole Ampl. (1S→2S)</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>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: $F(1)=7.7$; $F(5)=4.8$; $F(10)=3.8$; $F(40)=1.5$. *
Unique to $^{235}\text{U}$ measure in isonuclear chains (+isotopic chains)

control of systematics for 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

α \( Z^5 \)
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 GF:

- 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, …)
- …
Nuclear physics at the 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 GF: 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., $\gamma + ^3\text{H} \rightarrow (^3\text{He} + \pi^-)_{ns}$


<table>
<thead>
<tr>
<th>Isotope</th>
<th>$I_g^P$</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>$^{119}\text{Sn}$</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>$\sim 10$ min</td>
</tr>
</tbody>
</table>
Nuclear physics at the GF: 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., $^{208}$Pb($\gamma, \gamma'$)
- Parity-violating photophysics
- Lepton-pair photoproduction ($e^+, e^-$ and $\mu^+, \mu^-$)
Fixed-target experimental configurations

Parallel Spectroscopy
Fixed-target experimental configurations

Pump-Probe Spectroscopy
Applied physics and enabling technologies

- Production of medical isotopes and isomers
- Nuclear waste disposal
- Gamma-ray lasers
- Precision gamma polarimetry
- ...

ARTICLE
Proposal for selective isotope transmutation of long-lived fission products using quasi-monochromatic $\gamma$-ray beams

Takehito Hayakawa, Shuji Miyamoto, Ryoichi Hajima, Toshiyuki Shizuma, Sho Amano, Satoshi Hashimoto and Tsuyoshi Misawa
Conclusion