Gamma Factory

Novel opportunities for Atomic, Nuclear, and Applied Physics

ECFA Plenary Meeting, November 2020

Dmitry Budker

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*

FEATURE ARTICLE Ann. Phys. (Berlin) 2020, 2000204

annalen der physik

www.ann-phys.org

Atomic Physics Studies at the Gamma Factory at CERN

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

duality

Light Source ↔ Giant Ion Trap

Spectroscopy of PSI

PSI=HCI=Highly Charged Ions

Hydrogen-like Ions

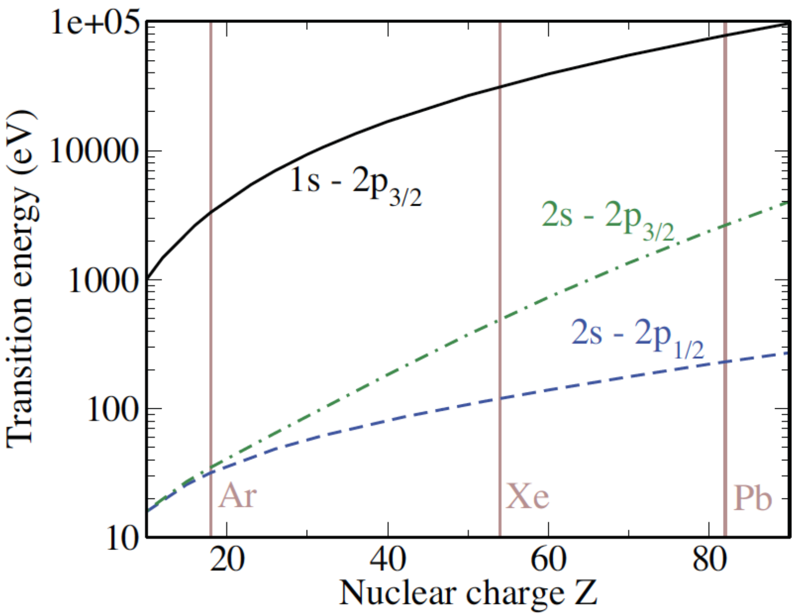
Transition energy $\Delta E_{nn'}$	$\propto (Z\alpha)^2$
Fine–structure splitting	$\propto (Z\alpha)^4$
Hyperfine–structure splitting	$\propto \alpha(Z\alpha)^3 m_e/m_p$
Lamb shift	$\propto \alpha(Z\alpha)^4$

Strong E-fields!

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

Schwinger critical field

$$E_s = m^2c^3/(e\hbar) \approx 1.3 \times 10^{16} \text{ V/cm}$$



H-like

Li-like

: direct excitation of heavy PSI with primary photons

Li-like ions

Ion	Transition energy	Reference
Pb^{79+}	230.823 (47)(4)	theory, [5]
	230.76(4)	theory, [6]
Bi^{80+}	235.809(53)(9)	theory, [5]
	235.72(5)	theory, [6]
U^{89+}	280.645(15)	experiment, [7]
	280.775(97)(28)	theory, [5]

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

PoP experiment

Parameter	**Value**
crossing angle	2.6°
Ion magnetic rigidity	787 T m
Ion γ factor	96.3
Ion beam horizontal RMS size at IP	1.3 mm
Ion beam vertical RMS size at IP	0.8 mm
Ion revolution frequency	43.4 kHz
Laser photon energy	1.2 eV
Laser frequency	40 MHz
Laser pulse energy	5 mJ
Ion $2s_{1/2} \rightarrow 2p_{1/2}$ transition energy	230.8 eV
Maximum energy of back scattered photon	44.5 keV

Projected 10^{-4} uncertainty in the PoP experiment: better than current theory state-of-the-art

⬇

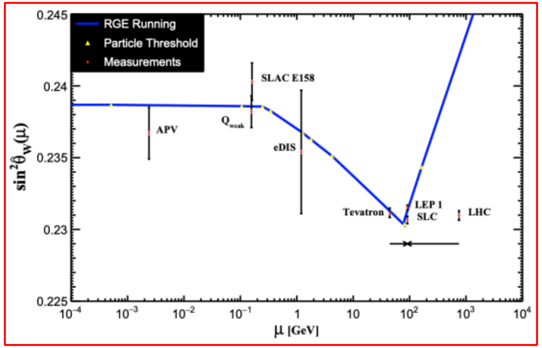
⬇⬇⬇Atomic Physics already in PoP!⬇□

Fundamental symmetry tests at the

VOLUME 78, NUMBER 25 PHYSICAL REVIEW LETTERS 23 JUNE 1997

Parity Nonconservation in Relativistic Hydrogenic Ions

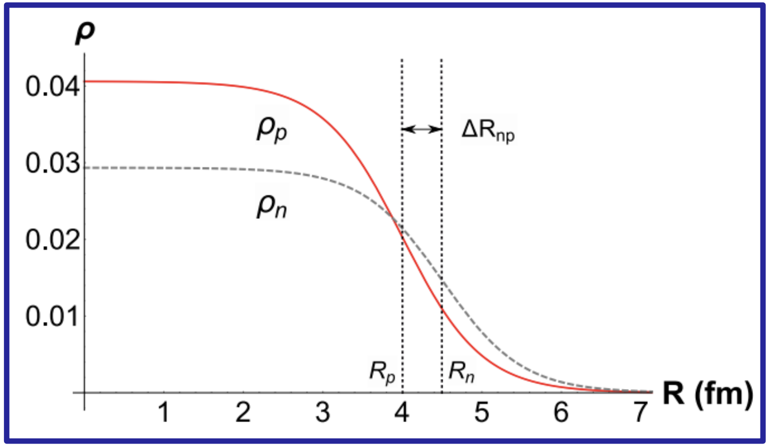
M. Zolotorev and D. Budker

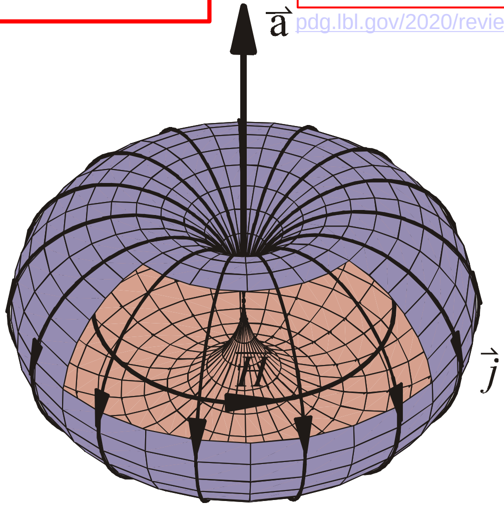


pdg.lbl.gov/2020/reviews/rpp2020-rev-standard-model.pdf

Why ?

- New physics (e.g. Z' bosons)
- Neutron skins
- Nuclear anapoles





VOLUME 78, NUMBER 25 PHYSICAL REVIEW LETTERS 23 JUNE 1997

F Izrailev

Parity Nonconservation in Relativistic Hydrogenic Ions

M. Zolotorev and D. Budker

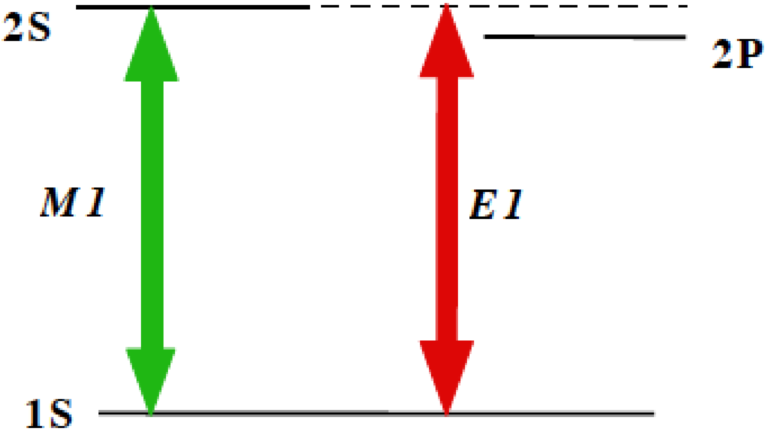


Fig. 1. The 1S→2S transition in a hydrogenic system.

level-mixing

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

☞ circular dichroism

Table 2. Parameters of relativistic ion storage rings.

Parameter	RHIC	SPS	LHC
γ_{max} for protons[a]	250	450	7000
Number of ions/ring[b]	$\sim 5\cdot 10^{11}$	$\sim 2\cdot 10^{11}$	$\sim 5\cdot 10^{10}$
Number of bunches/ring	57	128	500-800
R.m.s bunch length	84 cm	13 cm	7.5 cm
Circumference	3.8 km	6.9 km	26.7 km
Energy spread w/o laser cooling	$2\cdot 10^{-4}$	$4.5\cdot 10^{-4}$	$2\cdot 10^{-4}$
Normalized Emittance (N.E.)	$\approx 4\ \pi\cdot\mu m\cdot rad$	$\approx 4\ \pi\cdot\mu m\cdot rad$	$\approx 4\ \pi\cdot\mu m\cdot rad$
Dipole field	3.5 T	1.5 T	8.4 T
Vacuum, cold	$<10^{-11}$ Torr (H_2, He)	-	$<10^{-11}$ Torr (H_2, He)

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

[b] Estimated from proton and heavy ion data.

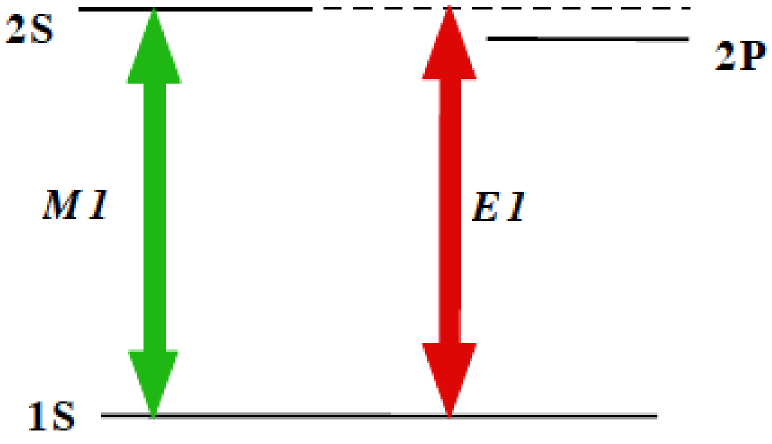


Fig. 1. The 1S→2S transition in a hydrogenic system.

Table 1: Z-dependence of atomic characteristics for hydrogenic ions. In the given expressions, α is the fine structure constant, $\hbar$=c=1, m_e is the electron mass, G_F is the Fermi constant, θ_w is the Weinberg angle, and *A* is the ion mass number.

Parameter	Symbol	Approximate Expression
Transition Energy	$\Delta E_{n-n'}$	$\frac{1}{2}\left(\frac{1}{n^2}-\frac{1}{n'^2}\right)\alpha^2 m_e \cdot Z^2$
Lamb Shift	ΔE_{2S-2P}	$\frac{1}{6\pi}\alpha^5 m_e \cdot Z^4 \cdot F(Z)^a$
Weak Interaction Hamiltonian	$\hat{H}_w$	$i\sqrt{\frac{3}{2}}\cdot\frac{G_F m_e^3\alpha^4}{64\pi}\cdot\left\{(1-4\sin^2\theta_w)-\frac{(A-Z)}{Z}\right\}\cdot Z^5$
Electric Dipole Amplitude (2S→2P$_{1/2}$)	$E1_{2S\to 2P}$	$\sqrt{\frac{3}{\alpha}}\cdot m_e^{-1}\cdot Z^{-1}$
Electric Dipole Amplitude (1S→2P$_{1/2}$)	$E1$	$\frac{2^7}{3^5}\sqrt{\frac{2}{3\alpha}}\cdot m_e^{-1}\cdot Z^{-1}$
Forbidden Magn. Dipole Ampl. (1S→2S)	$M1$	$\frac{2^{5/2}\alpha^{5/2}}{3^4}\cdot m_e^{-1}\cdot Z^2$
Radiative Width	Γ_{2P}	$\left(\frac{2}{3}\right)^8\alpha^5 m_e \cdot Z^4$

[a] 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

measure in isonuclear chains

(+isotopic chains)

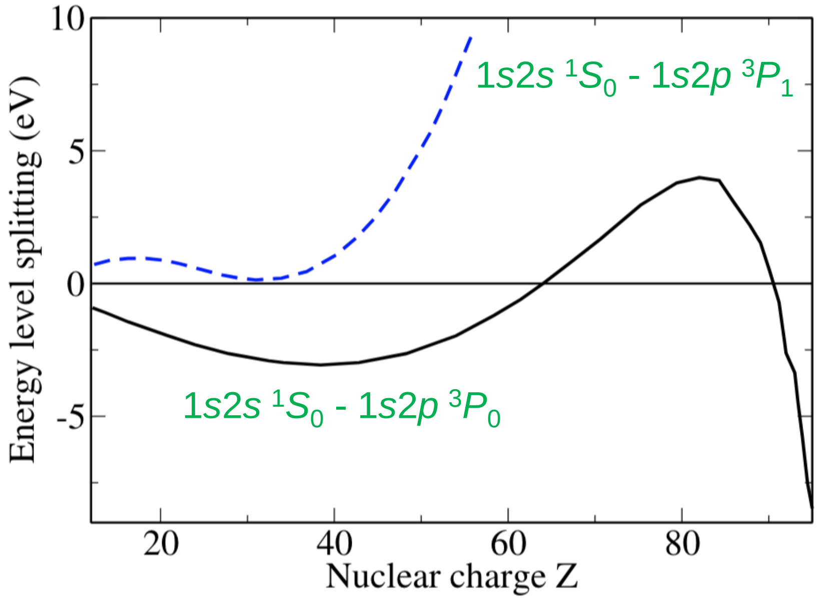
⬇

control of systematics

for neutron-skins

Not only hydrogenic ions are interesting for parity violation!

Level-crossing in He-like ions



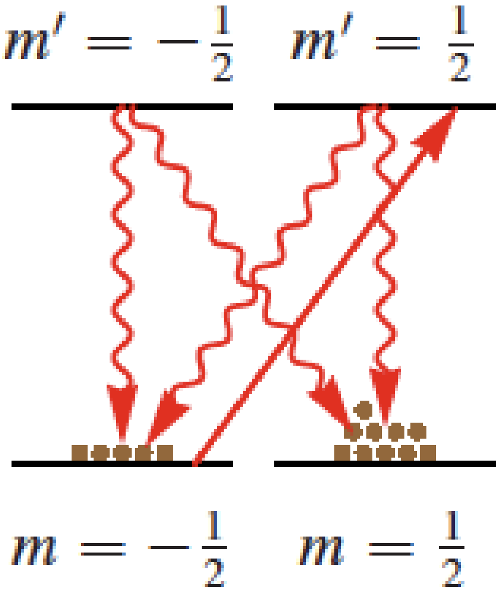
Parity-violating mixing

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

$\propto Z^5$

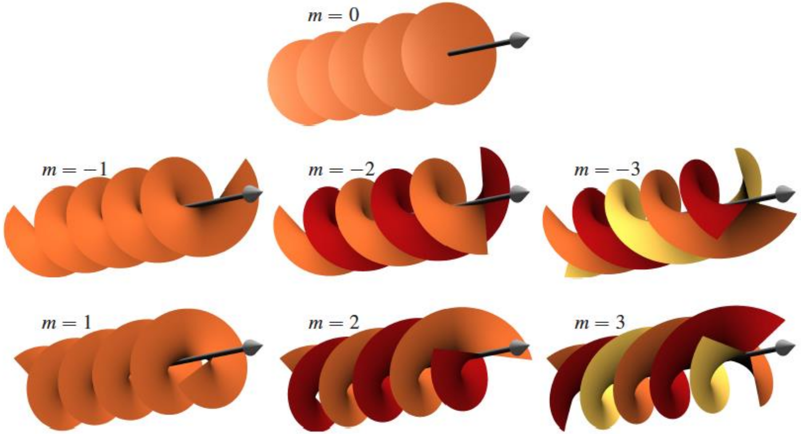
Enhancement near level crossings

Optical Pumping of PSI

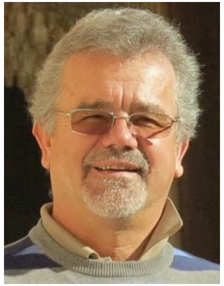


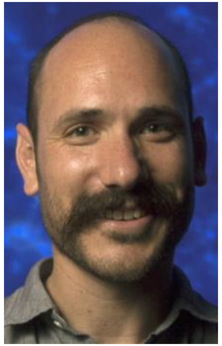
- Single-path polarization via optical pumping
- Both electronic and nuclear polarization
- Will polarization survive a round trip?
- If yes ☞ measure static and oscillating **EDM**
- Regardless ☞ nuclear-spin dependent parity violation

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

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 Gorshteyn
Johannes Gutenberg-Universitat Mainz, 55128 Mainz, Germany

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

Felix Karbstein
Helmholtz-Institut Jena, Fröbelstieg 3, 07743 Jena, Germany and
Theoretisch-Physikalisches Institut, Abbe 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 Pascalutsa 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

Andrey Surzhykov
Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany and
Technische Universität Braunschweig, 38106 Braunschweig, Germany
(Dated: November 13, 2020)





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.
- (γ, π) reactions to probe halo nuclei
- Photoproduction of pionic(kaonic) atoms,

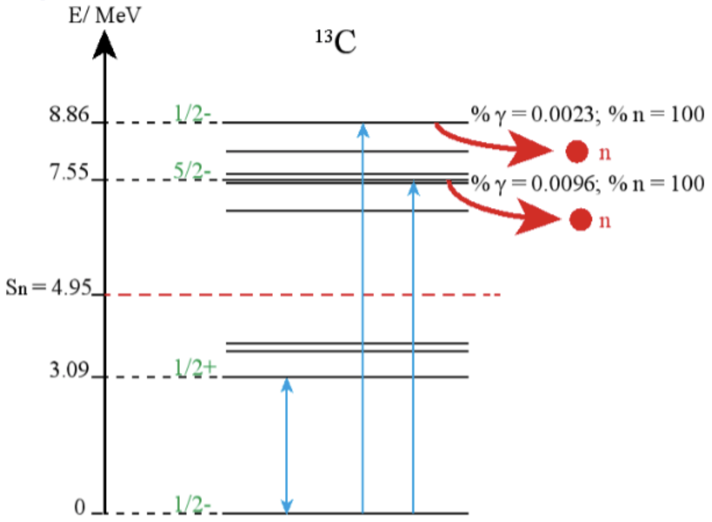
  e.g., $\gamma + {}^3\mathrm{H} \rightarrow ({}^3\mathrm{He} + \pi^-)_{ns}$

V.V.Flambaum, Junlan Jin, D.B., arXiv:2010.06912 (2020)

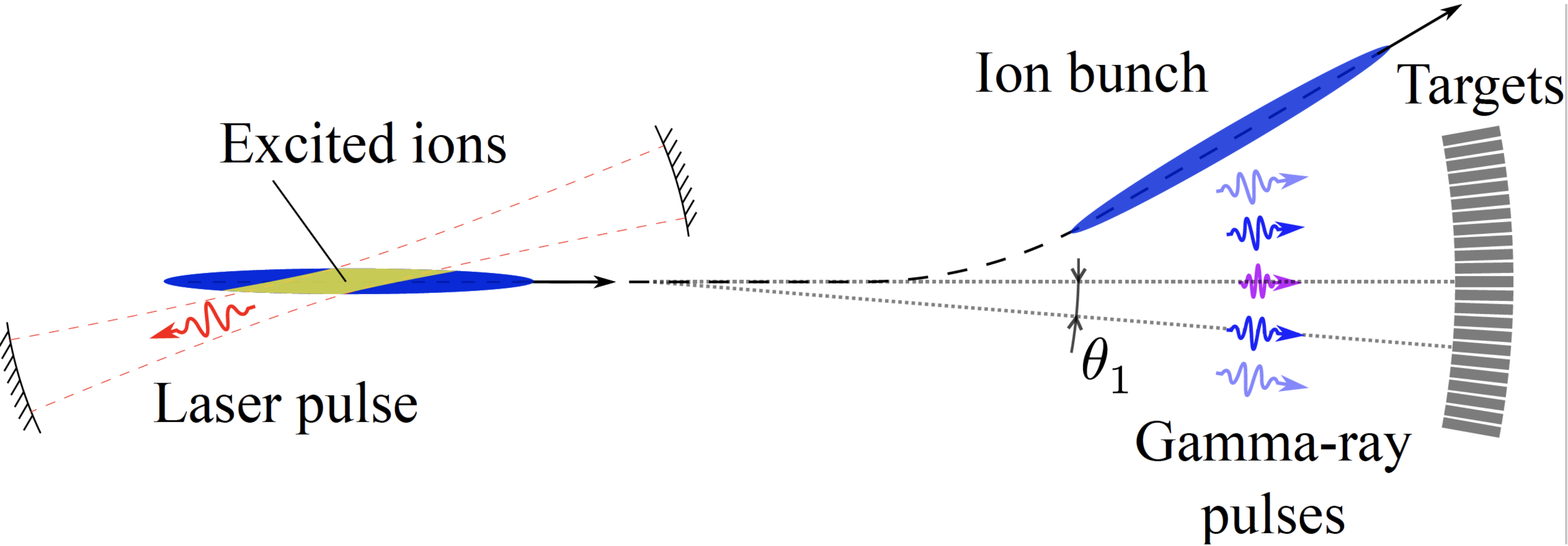
Isotope	I_g^P	Transition energy	I_e^P	Excitation lifetime
^{129}Xe	1/2+	39.578 keV	3/2+	12.8 ns
^{229}Th	5/2+	29.19 keV	(5/2+)	30 ns
^{161}Dy	5/2+	25.651 keV	5/2-	95.7 ns
^{119}Sn	1/2+	23.871 keV	3/2+	109 ns
^{151}Eu	5/2+	21.541 keV	7/2+	275 ns
^{57}Fe	1/2-	14.412 keV	3/2-	940 ns
^{73}Ge	9/2+	13.3 keV	5/2+	3.3 msec
^{45}Sc	7/2-	12.4 keV	3/2+	201 sec
^{205}Pb	5/2-	2.3 keV	1/2-	3 hours
^{235}U	7/2-	76.7 eV	1/2+	10^{17} years
^{229}Th	5/2+	8.28 eV	(3/2+)	$\sim$ 10 min

Nuclear physics at the GF: examples

- High-resolution spectroscopy of γ-resonances
- Fano effect in γ-resonances
- Giant resonances, pigmy resonances
- (γ, α) reactions: astrophysical S-factors
- Nuclear E1 polarizabilities, e.g., $^{208}\mathrm{Pb}(\gamma, \gamma')$
- Parity-violating photophysics
- Lepton-pair photoproduction (e^+,e^- and μ^+, μ^-)

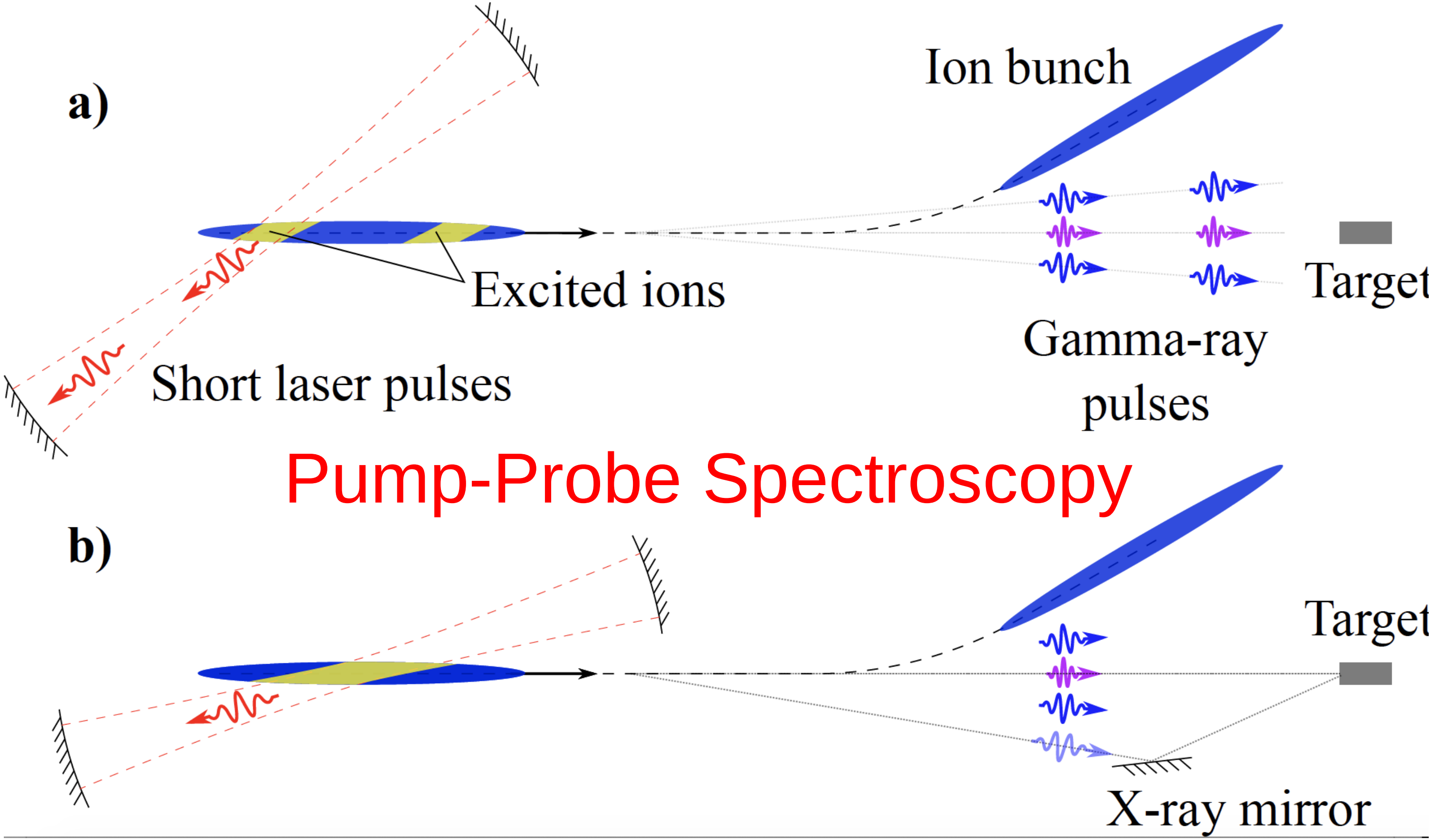


Fixed-target experimental configurations



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
- …

JOURNAL OF NUCLEAR SCIENCE AND TECHNOLOGY, 2016
VOL. 53, NO. 12, 2064–2071
http://dx.doi.org/10.1080/00223131.2016.1194776

Taylor & Francis
Taylor & Francis Group

ARTICLE

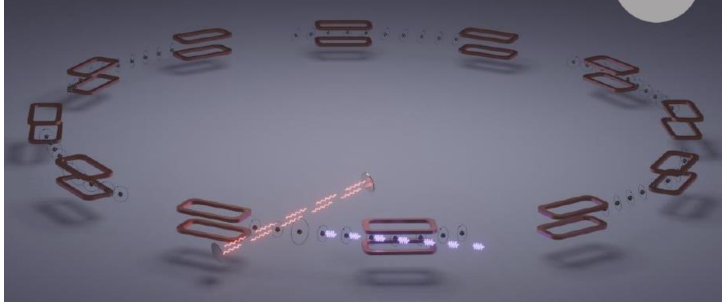
Proposal for selective isotope transmutation of long-lived fission products using quasi-monochromatic γ-ray beams

Takehito Hayakawa[a], Shuji Miyamoto[b], Ryoichi Hajima[a], Toshiyuki Shizuma[a], Sho Amano[b], Satoshi Hashimoto[b] and Tsuyoshi Misawa[c]

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

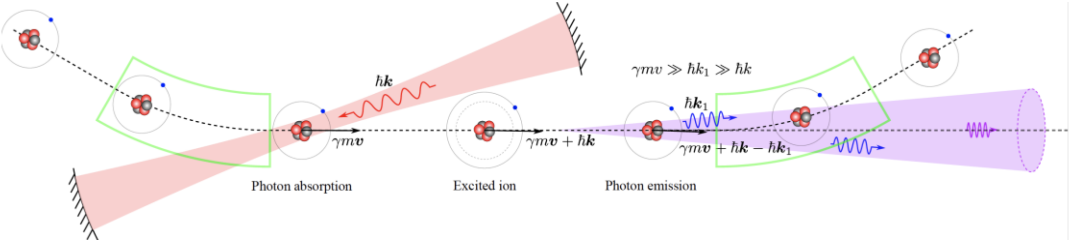
Email: POG2021@uni-mainz.de

Organizers

Dmitry Budker
Misha Gorshteyn
Witold Krasny
Adriana Palffy
Andrey Surzhykov

Workshop is sponsored by the Mainz Institute for Theoretical Physics

Conclusion



$\hbar \boldsymbol{k}$
$\gamma m \boldsymbol{v}$
$\gamma m \boldsymbol{v} + \hbar \boldsymbol{k}$
$\gamma m v \gg \hbar k_1 \gg \hbar k$
$\hbar \boldsymbol{k}_1$
$\gamma m \boldsymbol{v} + \hbar \boldsymbol{k} - \hbar \boldsymbol{k}_1$
Photon absorption
Excited ion
Photon emission