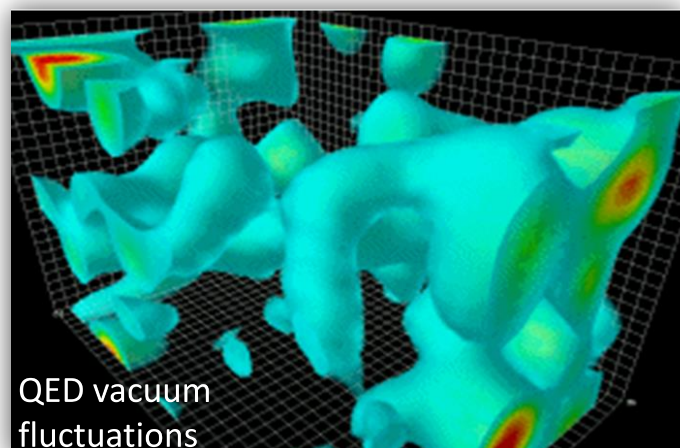
Photon-matter interaction in the extreme relativistic regime

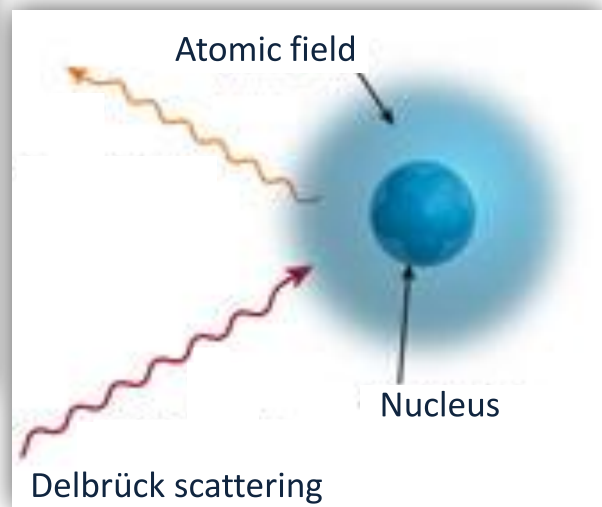
Andrey Surzhykov
Helmholtz Institite Jena

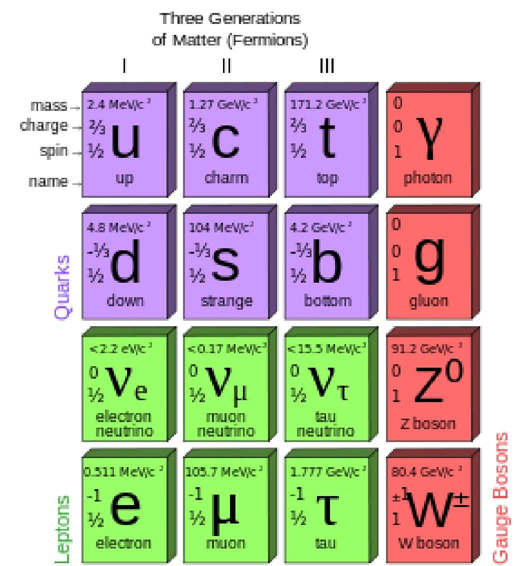
Physics of strong EM fields

Strong electromagnetic fields provide a unique tool for studying a large number of fundamental problems in modern physics:

- Structure of matter under extreme conditions
- Non-linear phenomena in light-matter interaction
- Search for a new physics beyond the Standard Model





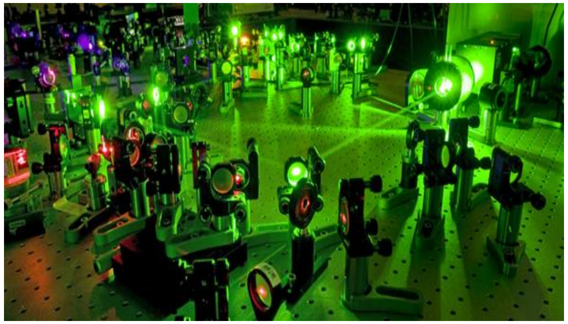


What is beyond the Standard Model?

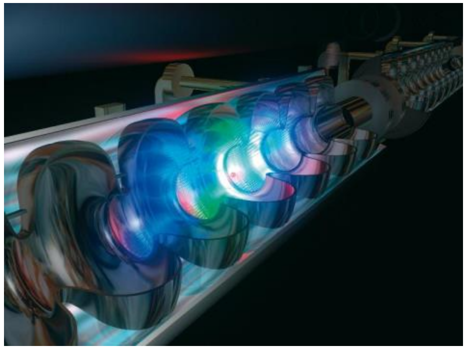
HELMHOLTZ GEMEINSCHAFT

Helmholtz-Institut Jena

Sources of strong EM fields

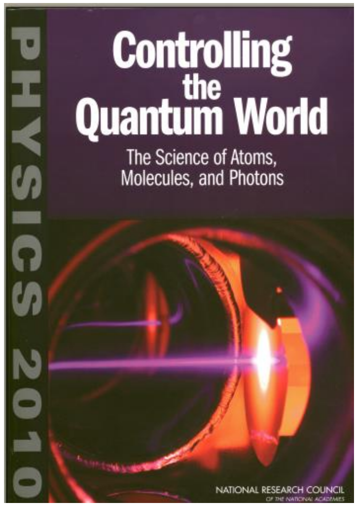


Novel intense laser sources (e.g. Vulcan facility in UK, POLARIS at FSU, DRACO at FZD)



Free electron lasers (e.g. DESY)

Advanced particle acceleration facilities (e.g. GSI and FAIR, DESY)



"... Thus the technologies are complementary [intense light sources and ion beams] and both are likely to lead to new insights in high-intensity science."

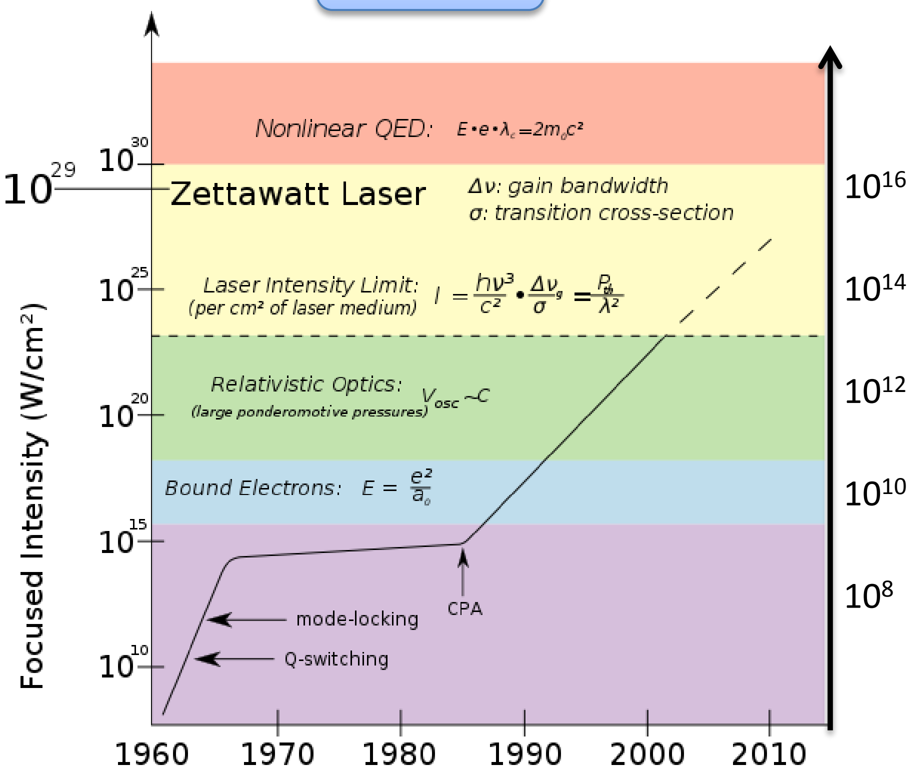
National Research Council, US on **AMO** Physics, 2008

HELMHOLTZ | GEMEINSCHAFT

Helmholtz-Institut Jena

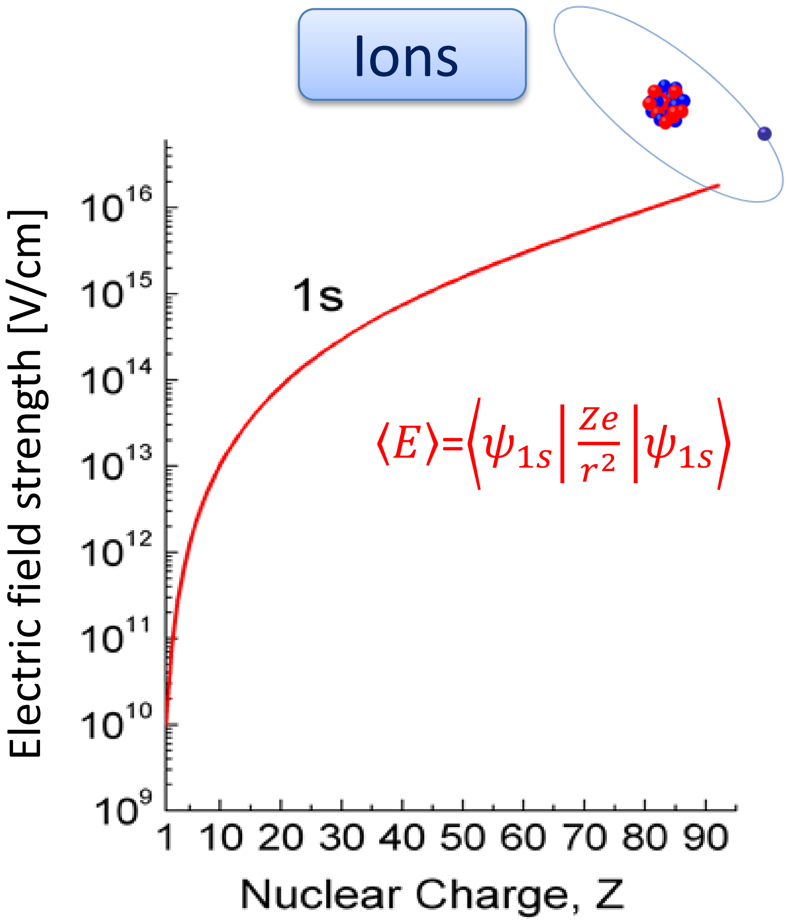
Lasers and Ions: Strong fields

Lasers



Macroscopic fields of strength $E \geq 10^{12}$ V/cm are available.

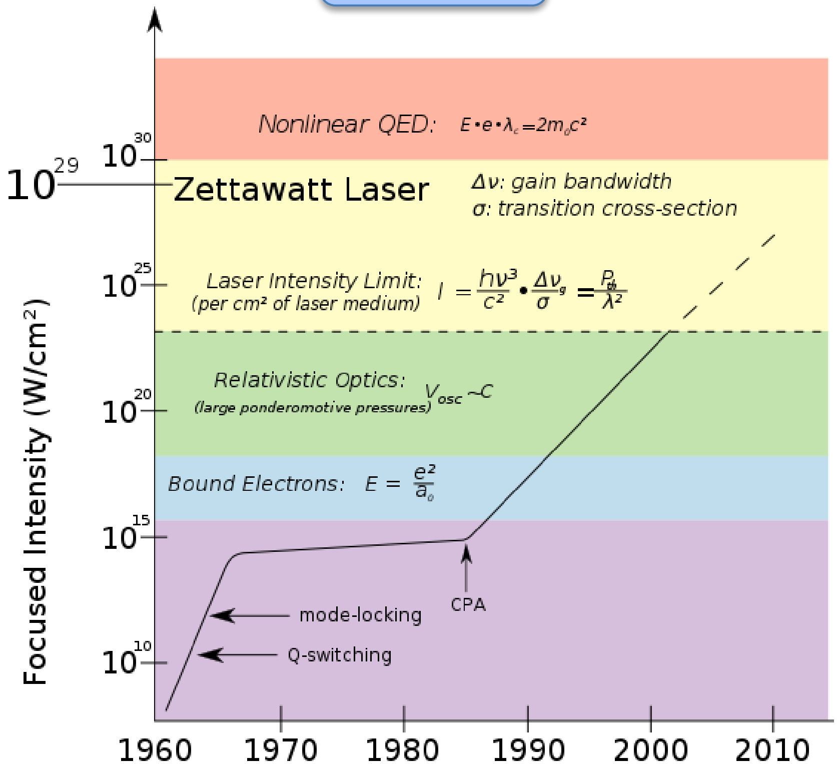
Ions



Electrons in the ground state of hydrogen-like uranium is exposed to the field of strength $E \geq 10^{16}$ V/cm.

Lasers and Ions: Short and intense pulses

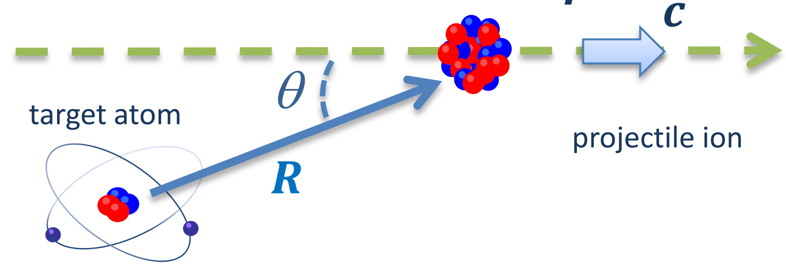
Lasers

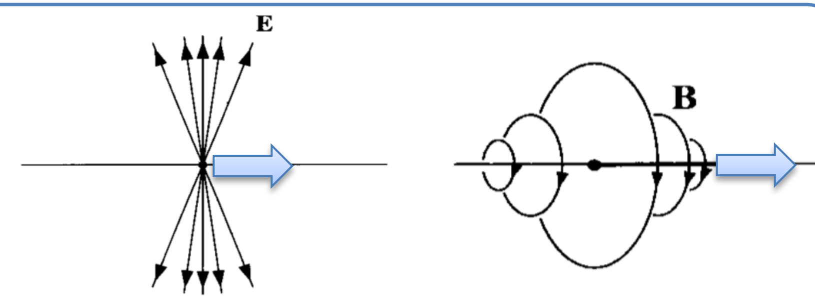


Advanced laser facilities can generate sub-femtosecond pulses with intensities $I \geq 10^{23}$ W/cm^2.

Ions

$\boldsymbol{\beta} = \dfrac{\boldsymbol{v}}{\boldsymbol{c}}$





$$\boldsymbol{E} = -\frac{Z_P\, e\, \boldsymbol{R}}{\gamma^2 R^3 (1-\beta^2 \sin^2\theta)^{\frac{3}{2}}} \qquad \boldsymbol{B} = \frac{\boldsymbol{v}}{\boldsymbol{c}^2} \times \boldsymbol{E}$$

Fast moving ions may produce extremely short, $\Delta t < 1\, zs$, and extremely intense, $I > 10^{28}$ W/cm^2 pulses.

Physics of strong fields: Lasers and Ions

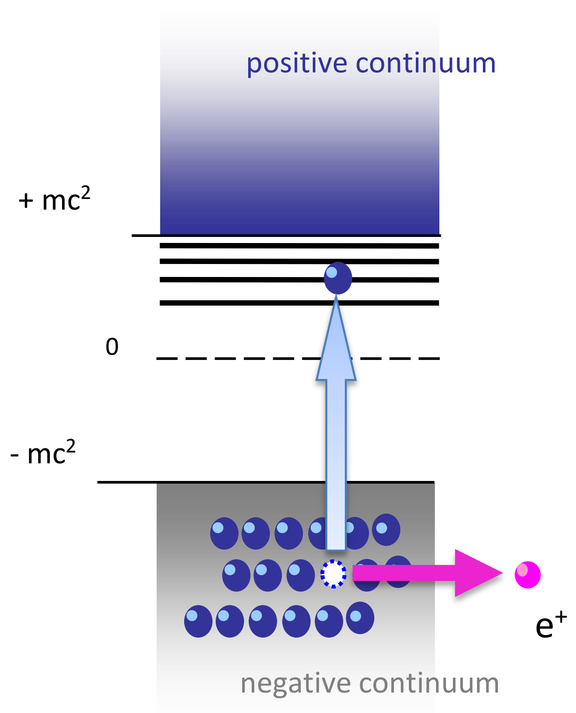
We will briefly recall two case studies in the strong-field physics:

- Pair production in strong electromagnetic fields
- Atomic structure studies and fundamental symmetries

HELMHOLTZ GEMEINSCHAFT

Helmholtz-Institut Jena

Electron-positron pair production



In order to produce electron-positron pairs we would need:

- High field strength of about

$$E_{crit} \approx mc^2 / e\lambda_C \approx 10^{16}\ \mathrm{V/cm}$$

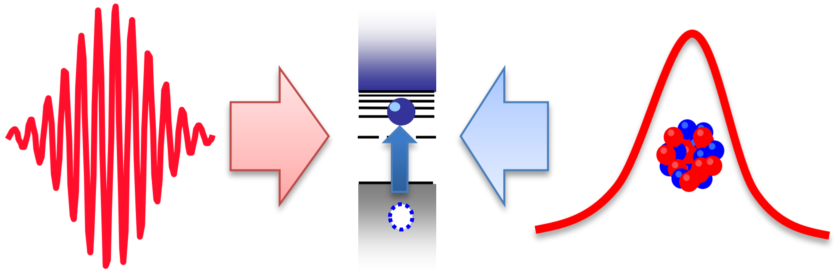
to induce tunneling, *Schwinger* mechanism

- Or high energy of about

$$\hbar\omega \approx 2mc^2 \approx 1 MeV$$

to induce *dynamical* pair production

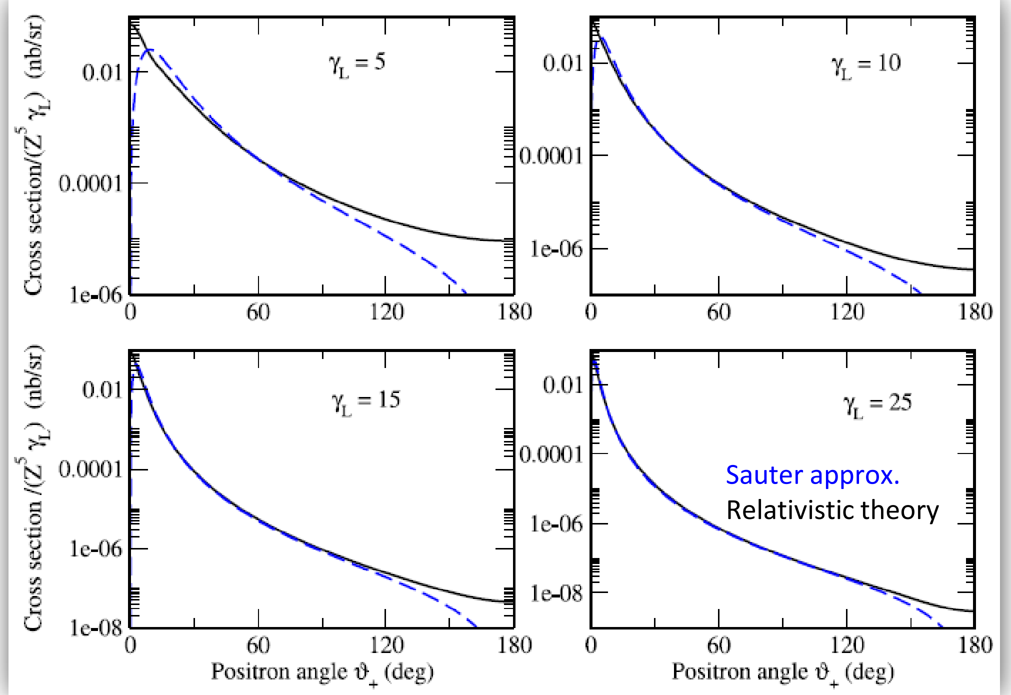
Bound-free pair production



- A number of studies is focused on the electron-positron pair production in ion-laser collisions.

$Pb^{82+} + \gamma \rightarrow Pb^{81+}(1s) + e^+$

- Recent attention is directed toward analysis of angular distributions of emitted positrons.

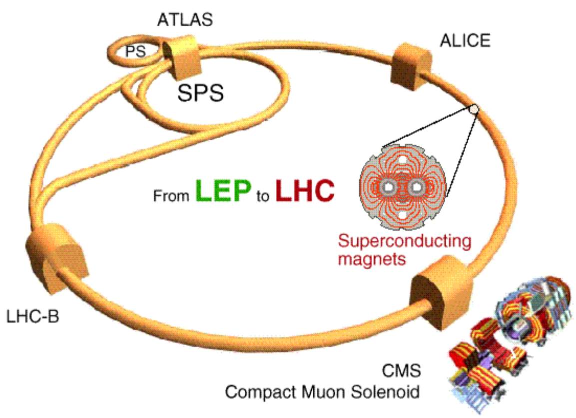


- Apart from Sauter approximation:

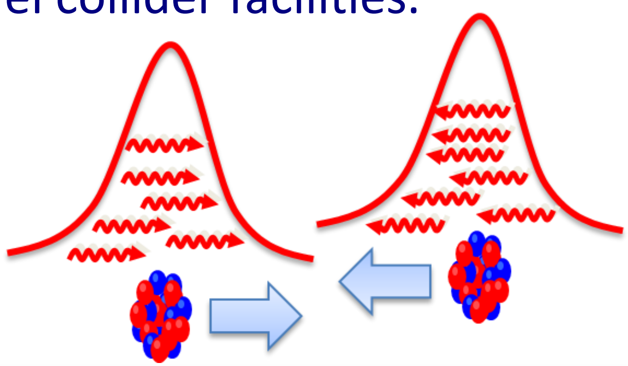
$$\frac{d\sigma_{\gamma Z}^{SA}}{d\Omega_+} = \frac{Z^5\alpha^6}{m^2} \frac{v_+ \sin^2\vartheta_+}{(\gamma_L+1)^4(1-v_+\cos\vartheta_+)^4} \times \left[v_+^2(\gamma_L+2)(1-v_+\cos\vartheta_+) - 2\frac{\gamma_L-1}{\gamma_L^3} \right]$$

more rigorous approaches are under discussion currently.

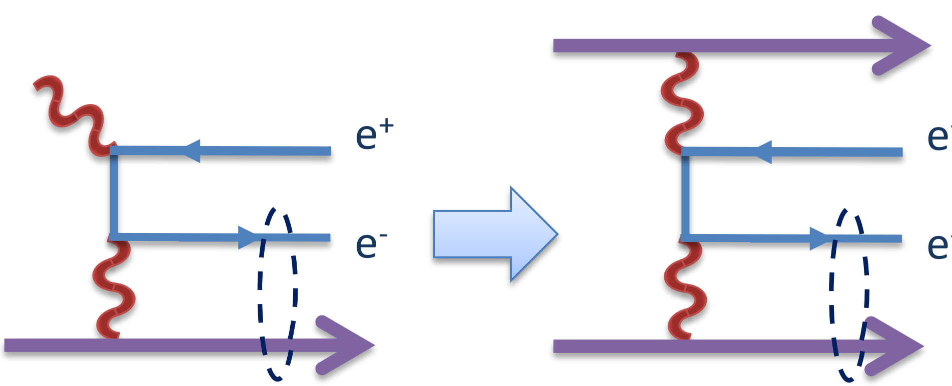
A.Artemyev, U. D. Jenschura, V. G. Serbo, and A. Surzhykov, Eur. Phys. J. C **72** (2012) 1935



- Dynamically induced strong fields may lead to electron-positron pair production.
- Apart from its fundamental importance, bound-free pair production attracts currently much attention for the development of novel collider facilities.



- For high energies, the pair production can be treated within the equivalent-photon method.



$$d\sigma^{SA}_{ZZ} = 16\frac{(Z\alpha)^7}{m^2}\frac{m}{\omega_L}\, g\left(\frac{\omega_L R}{\gamma_L}\right)\frac{d\omega_L}{\omega_L}\frac{m^2 dp_{+\perp}}{(p_{+\perp})^3}$$

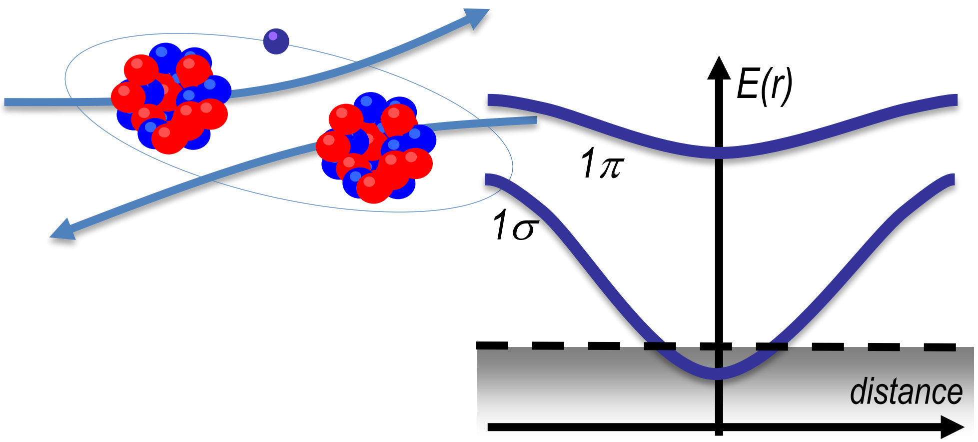
$$g(x) = \int_{x^2}^{\infty}\frac{dy}{y}\left(1-\frac{x^2}{y}\right)F^2(y/R^2)$$

A.Artemyev, U. D. Jenschura, V. G. Serbo, and A. Surzhykov, Eur. Phys. J. C **72** (2012) 1935

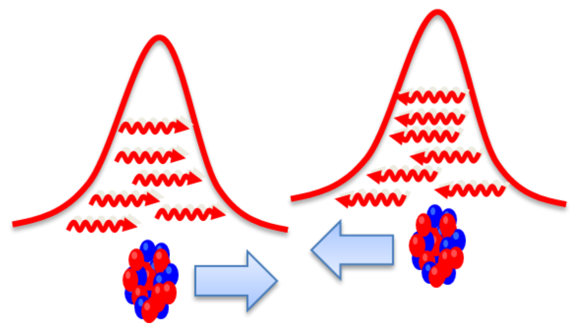
Overcritical field studies

- Currently, much attention in experiment and theory is paid to (relatively) slow heavy-ion collisions.

Low-energy collisions



Ultra-relativistic collisions



T_p ~ MeV/u

T_p ~ TeV/u

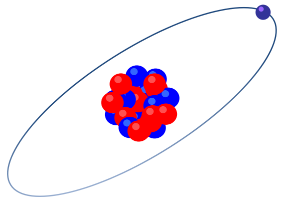
- Development of the reliable non–perturbative approaches for the description of such collisions is a great challenge for theory!

HELMHOLTZ | GEMEINSCHAFT

Helmholtz-Institut Jena

Critical electromagnetic fields

- Dirac energy of a *single* hydrogen-like ion (for the point-like nucleus):

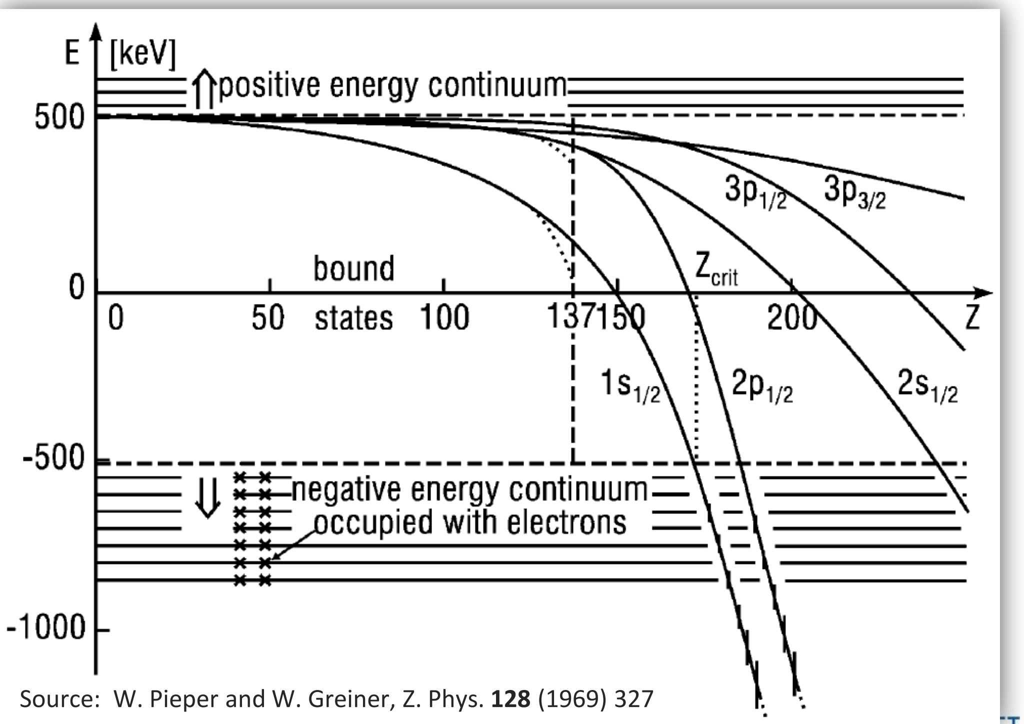


$$E_{nj} = mc^2 \Bigg/ \sqrt{1 + \left(\frac{Z\alpha}{n - |j+1/2| + \sqrt{(j+1/2)^2 - (Z\alpha)^2}} \right)^2}$$

- What happens if we increase the nuclear charge Z?

- If nuclear charge of the ion is greater than Z_{crit} the ionic levels can “dive” into Dirac’s negative continuum.

- Physical vacuum becomes unstable: creation of pairs may take place!

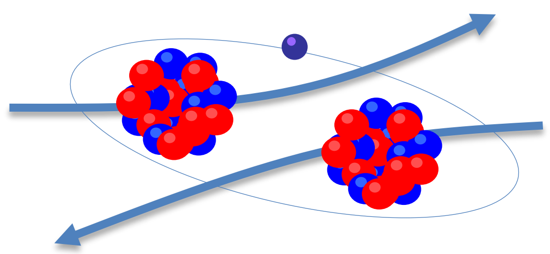


Source: W. Pieper and W. Greiner, Z. Phys. **128** (1969) 327

Super-heavy quasi-molecules

- Alternatively, we may form strong electromagnetic fields in (rather) slow collisions of two heavy ions.

- Since velocity of an electron is much higher comparing to collision velocity may think of formation of (quasi) molecule!

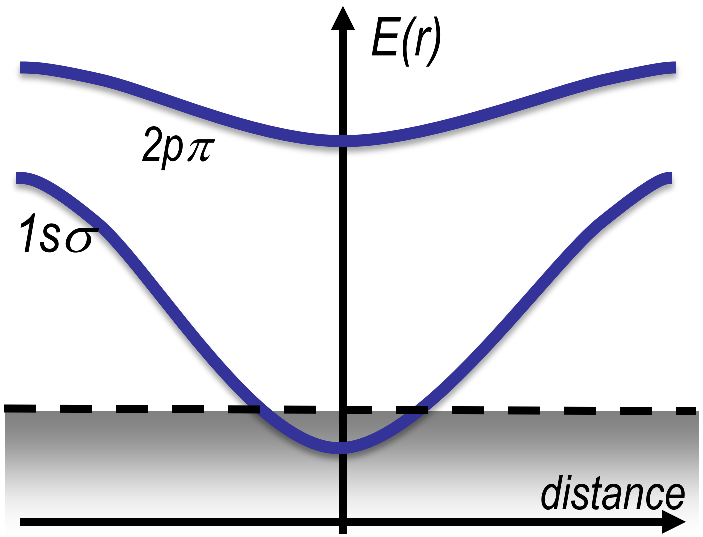


- In heavy ions velocity of electron being in ground state of U^{91+} is:

$$v_e = (\alpha Z)c \approx 0.7c$$

- At the same time velocity of colliding ions is about:

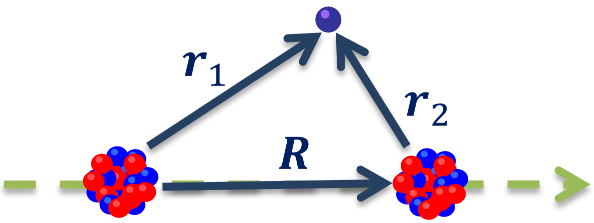
$$v_{ion} \approx 0.07c$$



- In 80's, efforts have been done to observe the 'break' of the vacuum in ion-ion collision.

Two-center Dirac problem: Non-perturbative analysis

$$\hat{H} = \hat{\boldsymbol{\alpha}} \cdot \hat{\boldsymbol{p}} + \beta - \frac{\alpha Z_1}{|\boldsymbol{r}_1|} - \frac{\alpha Z_2}{|\boldsymbol{r}_2|}$$



- To deal with the two-center Dirac problem novel approach, based on the application of B-spline (finite) basis sets, is developed.

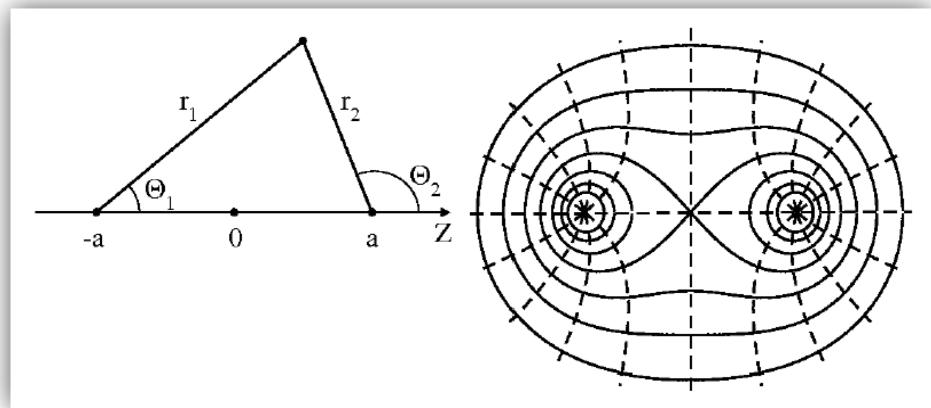
Expansion coefficients
(obtained from generalized eigenvalue problem)

Basis functions
(constructed from B-splines)

$$\Psi_k(\boldsymbol{r}) = \begin{pmatrix} \psi_{k,1}(\boldsymbol{r}) \\ \psi_{k,2}(\boldsymbol{r}) \\ \psi_{k,3}(\boldsymbol{r}) \\ \psi_{k,4}(\boldsymbol{r}) \end{pmatrix} \Rightarrow \psi_{k,i}(\boldsymbol{r}) = \sum_{n=1}^{N} \boxed{C_{k,i}(n)}\,\boxed{B_n(\boldsymbol{r})}$$

- B-spline basis set are constructed in both, the spherical and the so-called Cassini coordinates.

$$w = \frac{\sqrt{r_1 r_2}}{a}, \delta = \frac{\theta_1 + \theta_2}{2},$$
$$\phi = \phi$$

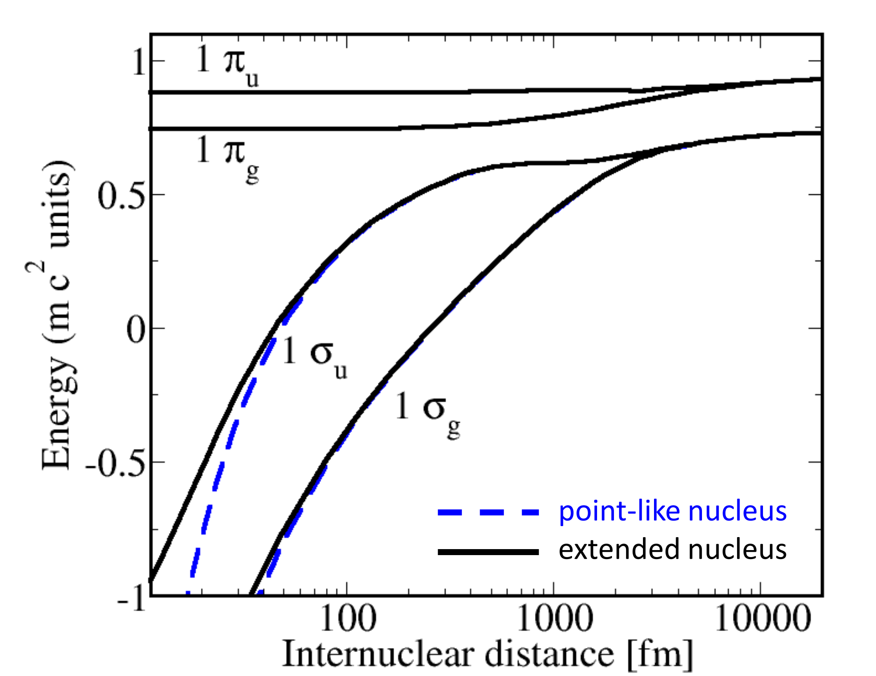


A. Artemyev *et al.*, J. Phys. B **43** (2010) 235201
S. McConnell, A. Artemyev, and A. Surzhykov, Phys. Rev. A **86** (2012) 052705

Quasi-molecules: Structure and dynamics

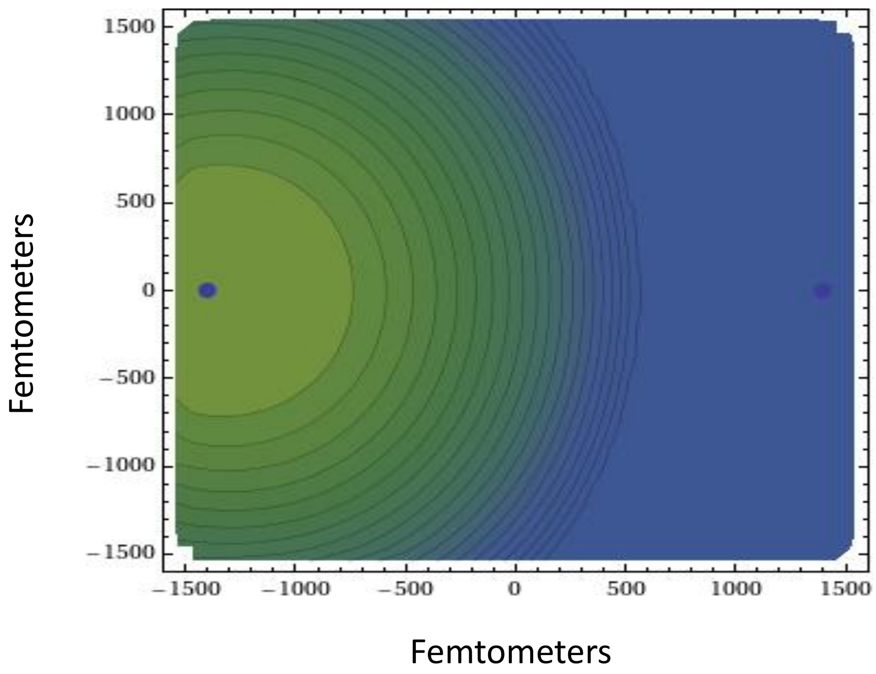
- Application of the final basis-set approach allows one an accurate study of both structure properties and dynamical behaviour of quasi-molecules.

Energy spectrum of U^{92+} - U^{91+} quasi-molecule



- Currently analysis is underway to understand the role of many-electron and QED effects

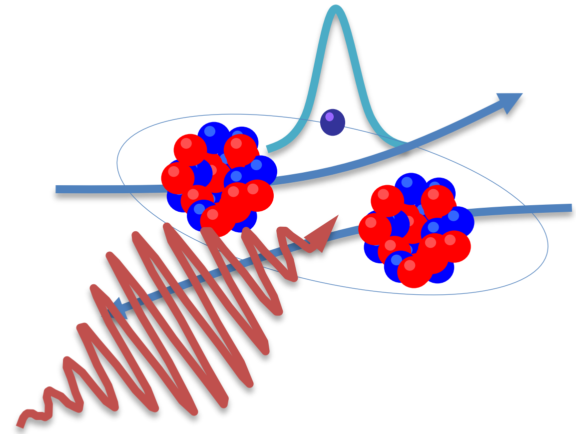
Pb^{82+} - Pb^{81+} collision at energy 3 MeV/u

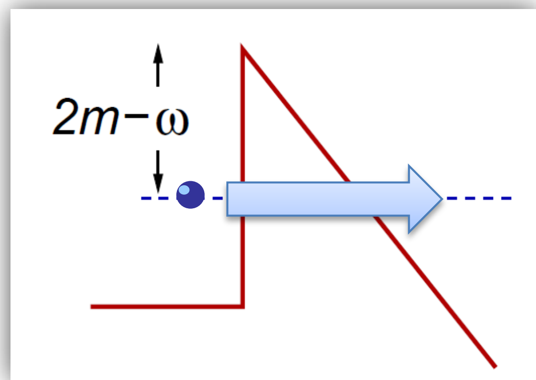


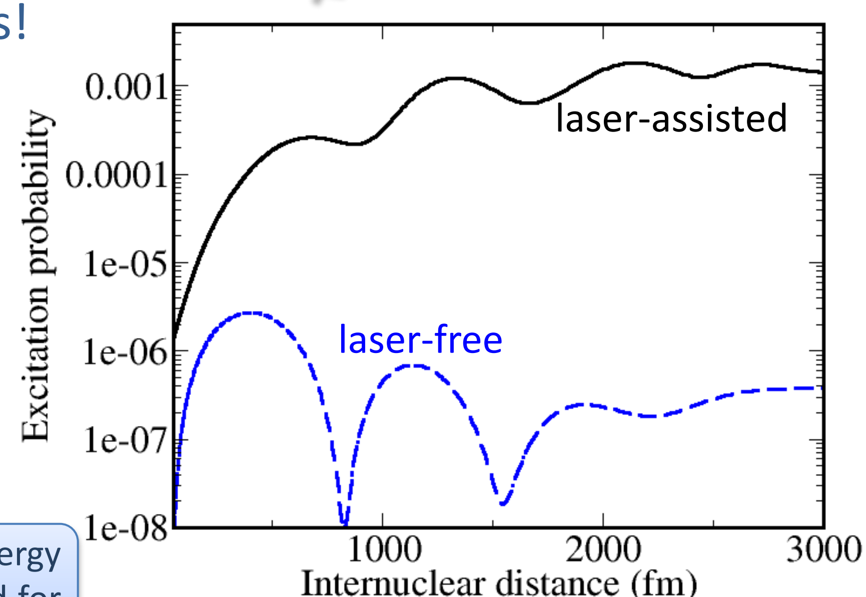
- Towards the treatment of charge-transfer, excitation, ionization and even pair production processes!

Laser-assisted ion collisions

- Of special interest is the study of fundamental processes accompanying laser-assisted ion collisions.
- Can one catalyze lepton pair production by applying intense laser?
- Dynamically assisted Schwinger mechanism attracts now attention in strong laser field physics!







Excitation probability in laser-assisted U^{92+} - U^{91+} collision at energy 3 MeV/u and zero impact parameter. Calculations are perfumed for laser intensity $I = 10^{17}\frac{W}{cm^2}$ and energy $\hbar\omega$=50 eV.

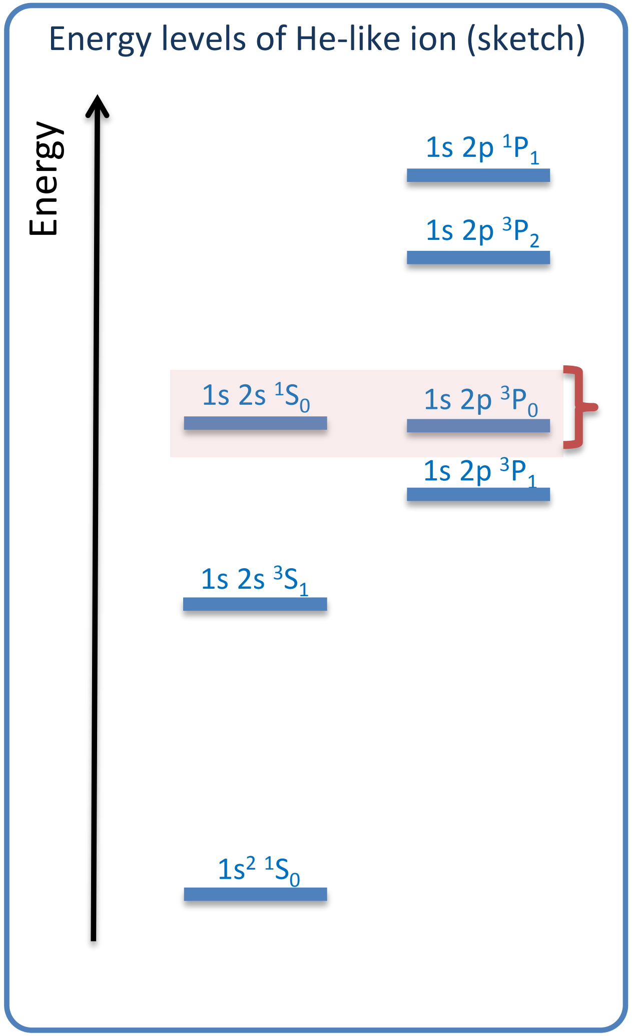
Preliminary results!

Physics of strong fields: Lasers and Ions

We will briefly recall two case studies in the strong-field physics:

- Pair production in strong electromagnetic fields
- Atomic structure studies and fundamental symmetries

Helium-like ions: Energy spectrum



- Helium-like ions, the simplest many-electron systems, attract currently considerable interest:
  - Many-body relativistic effects
  - QED and nuclear phenomena

TABLE I. Contributions to the energies of the $1s2s\,^1S_0$ and $1s2p\,^3P_0$ states in He-like ^{238}U ions, relative to the ionization threshold. All energies are in eV.

	$1s2s\,^1S_0$	$1s2p\,^3P_0$
Dirac energy (pointlike nucleus)	−34 215.481	−34 215.4811
Nuclear size effects[a]	37.738	4.4133
Total zeroth-order energy	−34 177.743(27)	−34 211.0678(56)
First-order correlation [30]	850.135	923.198
Second-order correlation	−6.5368	−5.6726
Higher-order correlation	−0.0005	−0.0174
Total electron correlations	843.598(1)	917.508(4)
One-electron QED correction [26]	49.547(75)	6.846(12)
Two-electron QED correction [17]	−3.8259(4)	−4.4740(3)
Higher-order QED correction [14]	−0.009(51)	0.002(73)
Nuclear polarization and recoil correction [27]	0.0890	0.0491
Total energy	−33 288.344(94)	−33 291.137(74)

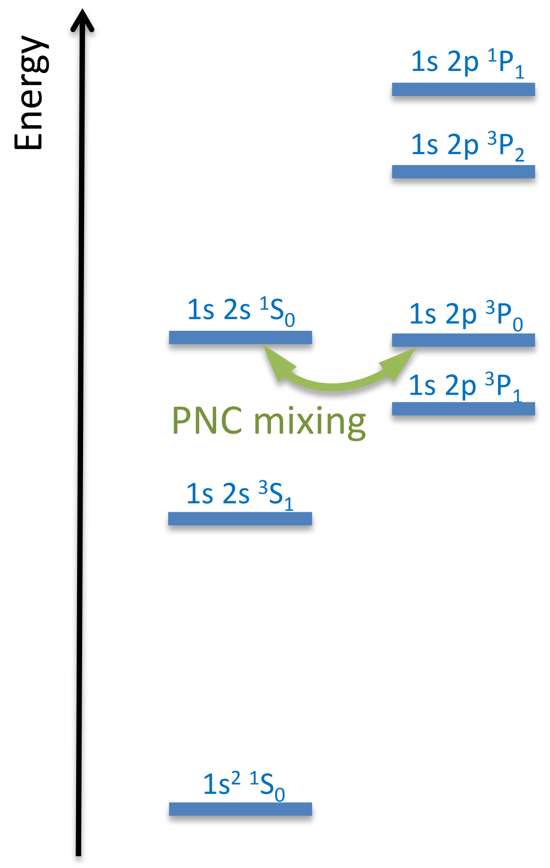
[a]A Fermi distribution for the nuclear charge with rms radius $\langle r^2\rangle^{1/2} = 5.8569(33)$ fm [28] was adopted.

Table from: F. Ferro *et al.*, Phys. Rev. A **81** (2010) 062503

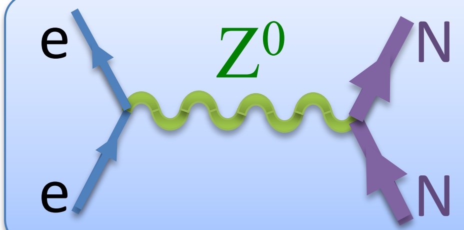
- Theoretical prediction for the 2^3P_0-2^1S_0 energy splitting in U^{90+} is $\Delta E = -2.793(131)$ eV.

Helium-like ions: PNC effects

Energy levels of He-like ion (sketch)



- Helium-like ions, the simplest many-electron systems, attract currently considerable interest:
  - Atomic parity non-conservation effects



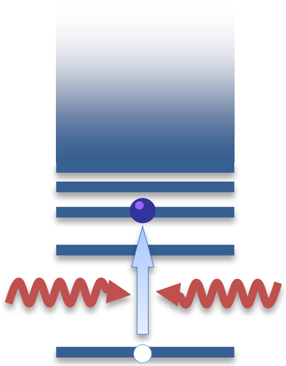
$$H_{PV} = -\frac{G_F}{2\sqrt{2}} Q_W \gamma_5 \rho(\boldsymbol{r})$$

- Weak interaction between nucleus and electrons leads to a mixing between 2^1S_0 and 2^3P_0 states:

$$\tilde{\Psi}_{2^1S_0} = \Psi_{2^1S_0} + i\eta\Psi_{2^3P_0}$$

Mixing parameter: $$\eta = \frac{\left\langle \Psi_S \middle| -\frac{G_F}{\sqrt{2}}\frac{Q_W}{2}\gamma_5\rho(\boldsymbol{r}) \middle| \Psi_P \right\rangle}{E_S - E_P - i\,\Gamma/2}$$

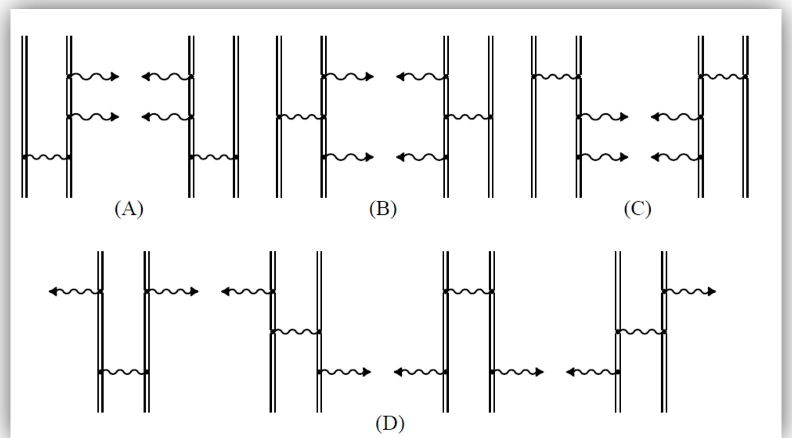
Relativistic two-photon calculations



- Analysis of two-photon transitions in many-electron systems is a rather non-trivial task.
- Generally, it requires evaluation of the second-order transition amplitudes and summation over the entire spectrum of the ion:

$$M_{2\gamma} = \sum_{\nu} \frac{\langle \tilde{\Psi}_P | \boldsymbol{\alpha}\, \boldsymbol{A}_1 | \Psi_\nu \rangle \langle \Psi_\nu | \boldsymbol{\alpha}\, \boldsymbol{A}_2 | \tilde{\Psi}_S \rangle}{E_\nu - E_S + \hbar\omega}$$

Rigorous QED treatment



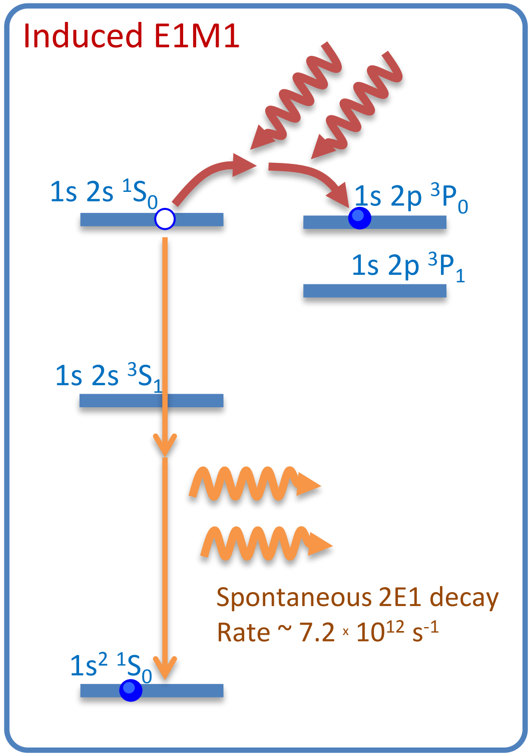
Multi-configuration Dirac-Fock approach

$$\Psi_{n\, J^\pi M} = \sum_r C_r(n)\, \underbrace{|\beta_r\, J^\pi\, M\rangle}$$

$$\langle \boldsymbol{r}_1, \boldsymbol{r}_2 | \beta_r\, J^\pi\, M \rangle = \sum_{m_1 m_2} C_{m_1 m_2 M} \begin{vmatrix} \varphi_{j_1 m_1}(\boldsymbol{r}_1) & \varphi_{j_2 m_2}(\boldsymbol{r}_1) \\ \varphi_{j_1 m_1}(\boldsymbol{r}_2) & \varphi_{j_2 m_2}(\boldsymbol{r}_2) \end{vmatrix}$$

A. Volotka, A. Surzhykov, V. Shabaev, and G. Plunien, Phys. Rev. A **83** (2011) 062508
A. Surzhykov *et al.*, Phys. Rev. A **84** (2011) 022511

Laser-induced two-photon transitions



- Induced two-photon transition rate:

$$\Gamma_{2\gamma} \propto I^2 \left| \sum_{\nu} \frac{\langle \widetilde{\Psi}_P | \boldsymbol{\alpha}\, \boldsymbol{A}_1 | \Psi_\nu \rangle \langle \Psi_\nu | \boldsymbol{\alpha}\, \boldsymbol{A}_2 | \widetilde{\Psi}_S \rangle}{E_\nu - E_S + \hbar\omega} \right|^2$$

- Based on our many-body relativistic calculations we found that for helium-like uranium ion:

$$\Gamma_{2\gamma}(E1M1) = I^2\, (\boldsymbol{\epsilon}_1 \times \boldsymbol{\epsilon}_2)^2 \times 5.31 \cdot 10^{-25}\ \text{s}^{-1}$$

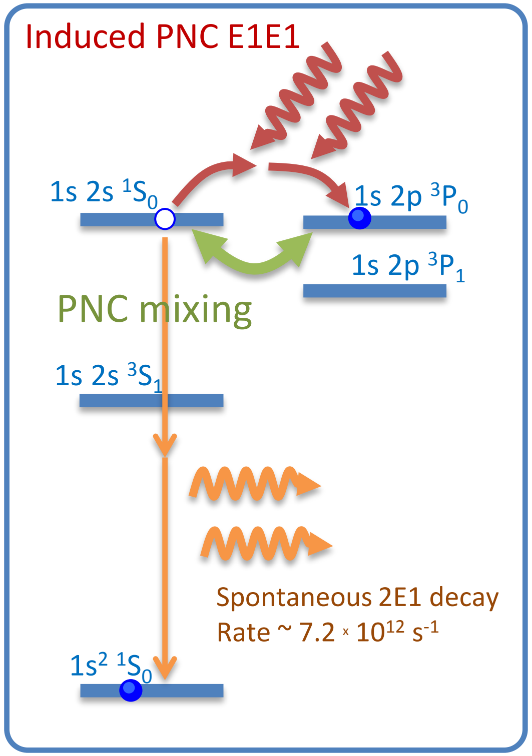
Polarization vectors should be orthogonal!

- To "compete" with the spontaneous decay channel we have to induce two-photon E1M1 transition by unpolarized light with the intensity:

$$I \sim 10^{15} - 10^{16}\ \text{W/cm}^2$$

A. Surzhykov *et al.*, Phys. Rev. A **84** (2011) 022511

Laser-induced two-photon transitions



- Induced two-photon transition rate:

$$\Gamma_{2\gamma} \propto I^2 \left| \sum_\nu \frac{\langle \tilde{\Psi}_P | \boldsymbol{\alpha}\, \boldsymbol{A}_1 | \Psi_\nu \rangle \langle \Psi_\nu | \boldsymbol{\alpha}\, \boldsymbol{A}_2 | \tilde{\Psi}_S \rangle}{E_\nu - E_S + \hbar\omega} \right|^2$$

- Based on our many-body relativistic calculations we found that for helium-like uranium ion:

$$\Gamma_{2\gamma}(2E1) = I^2\, \eta^2 (\boldsymbol{\epsilon}_1 \cdot \boldsymbol{\epsilon}_2)^2 \times 4.35 \cdot 10^{-20}$$

$$= I^2\, (\boldsymbol{\epsilon}_1 \cdot \boldsymbol{\epsilon}_2)^2 \times 1.26 \cdot 10^{-33}\ \text{s}^{-1}$$

Polarization vectors should be parallel!

- To “compete” with the spontaneous decay channel we have to induce two-photon E1E1 transition by polarized light with the intensity:

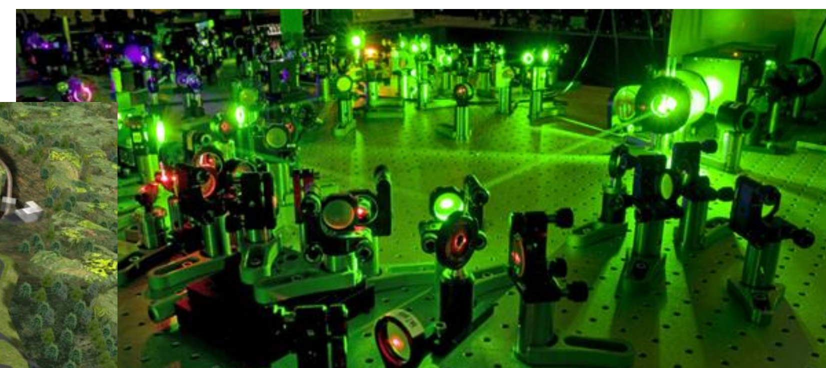
$$I \sim 10^{21} - 10^{22}\ \text{W/cm}^2$$

A. Surzhykov *et al.*, Phys. Rev. A **84** (2011) 022511

Physics of strong fields: Lasers and Ions

We recalled two case studies in the strong-field physics:

- Pair production in strong electromagnetic fields
- Atomic structure studies and fundamental symmetries



HELMHOLTZ
GEMEINSCHAFT
Helmholtz-Institut Jena

Many thanks to

Anton Artemyev
Fabrizio Ferro*
Filippo Fratini*
Jonas Gunst*
Walter Hahn*
Johan Holmberg
Thorsten Jahrsetz
Stefan Kraft*
Manuel Mai*
Oliver Matula
Sean McConnell
Robert Müller
Lalita Sharma*
Vladimir Yerokhin*

*former group members

Helmholtz Young Investigators Group
University of Heidelberg / Helmholtz Institute Jena

Financial support

HELMHOLTZ ASSOCIATION

DAAD
Deutscher Akademischer Austausch Dienst
German Academic Exchange Service

Deutsche Forschungsgemeinschaft
DFG

International Max Planck Research School
Quantum Dynamics
in Physics, Chemistry and Biology

HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

cnrs

Many thanks to

Stephan Fritzsche
Thomas Stöhlker
Helmholtz Institute Jena
and University of Jena

Stanislav Tashenov
University of Heidelberg

Alexandre Gumberidze
Yuri Litvinov
GSI Helmholtz centre

Vladimir Shabaev
St. Petersburg State University

Renate Märtin
Günter Weber
Helmholtz Institute Jena

Günter Plunien
Andrey Volotka
TU Dresden

Paul Indelicato
ENS, Paris

Financial support

HELMHOLTZ ASSOCIATION

DAAD
Deutscher Akademischer Austausch Dienst
German Academic Exchange Service

Deutsche Forschungsgemeinschaft DFG

International Max Planck Research School
Quantum Dynamics
in Physics, Chemistry and Biology

HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

cnrs