Observation of the supercritical QED regime in slow collisions of heavy ions

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Outline of the talk

- Introduction
- The work of the SPSU group on SHE
- QED at supercritical Coulomb field
- How to observe the vacuum decay
- Conclusion

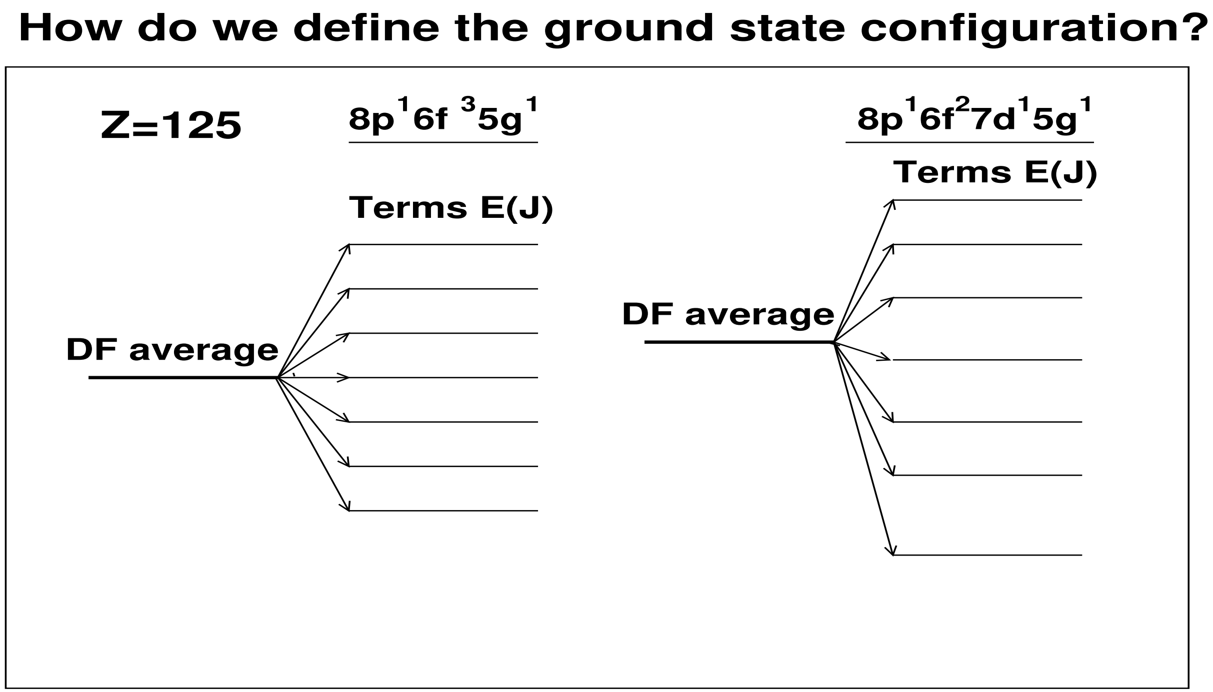
Electronic structure of superheavy elements

Periodic Table of the Elements

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	1 H																	2 He
	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 br	36 kr
	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
	55 Cs	56 Ba	57 La →	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
	87 Fr	88 Ra	89 Ac →	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
	(119)	(120)	(121) →															
Lanthanides →				58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
Actinides →				90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	
Superactinides →				(122–155)														

V. Pershina, Radiochim. Acta 107, 833 (2019).

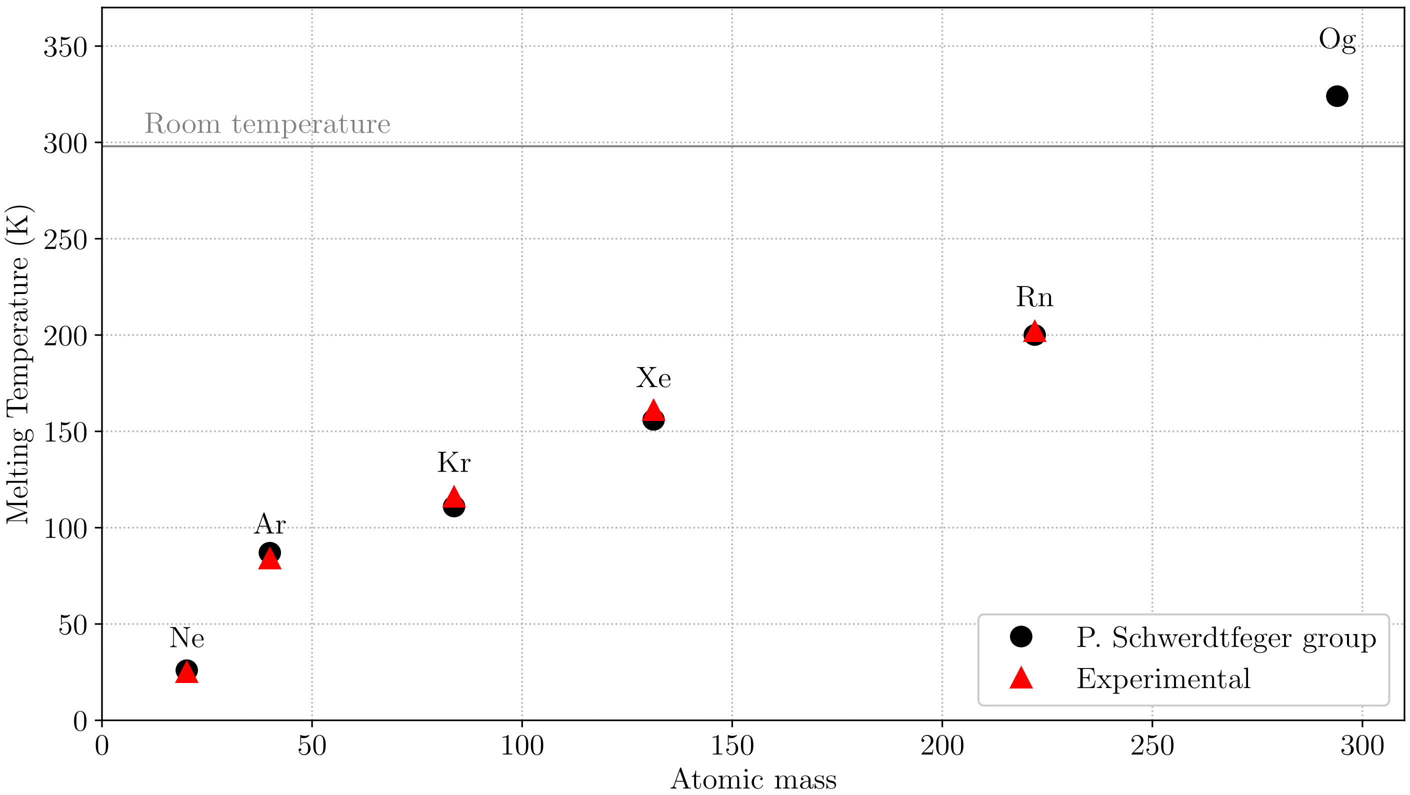
Electronic structure of superheavy elements



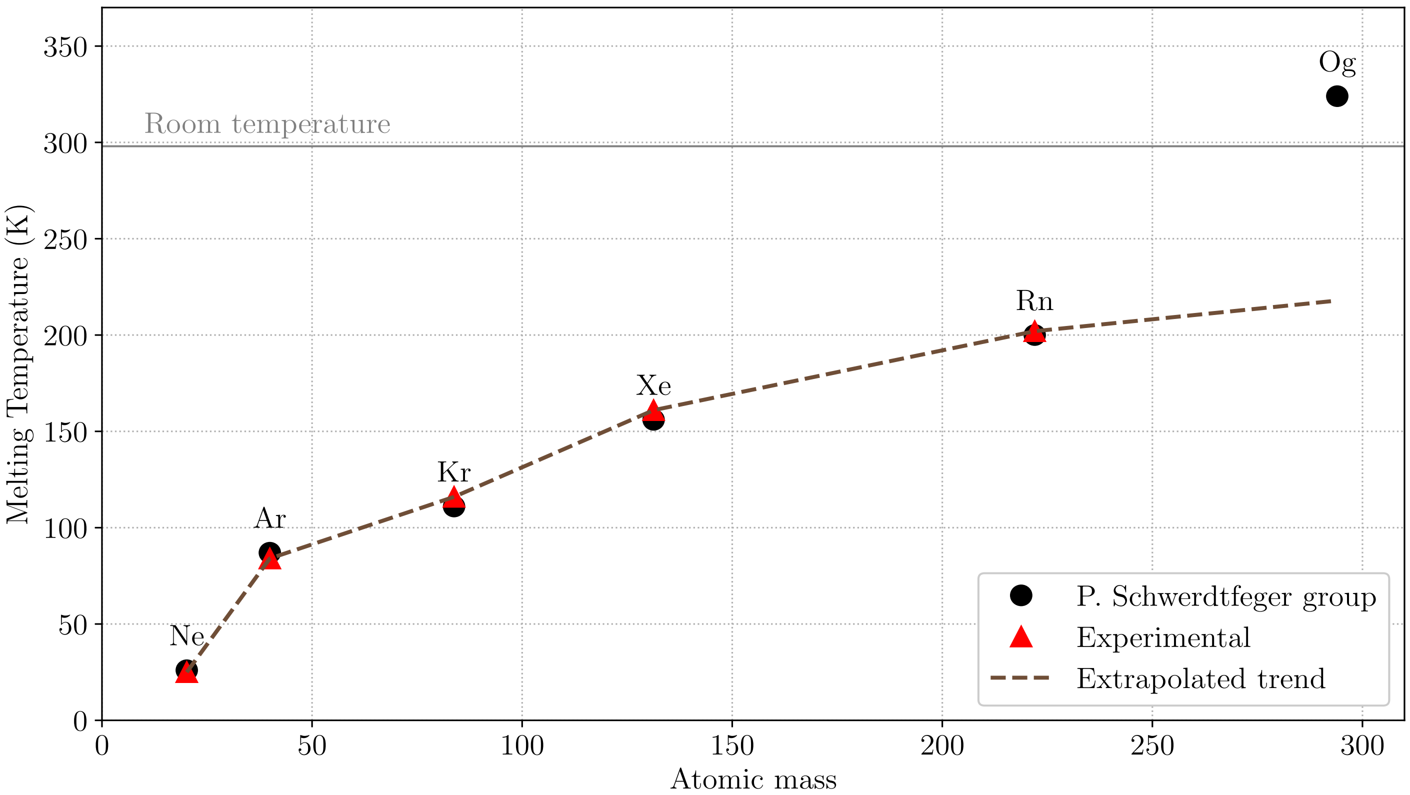
The ground state configuration is the configuration with the lowest energy E^{av}. The ground state level is the level with the lowest $E(J)$.

Ground state of superheavy elements with Z=120-170: systematic study, including electron-correlation, Breit, and QED effects: *I.M. Savelyev et al, Phys. Rev. A 107, 042803 (2023)*
(see also: *O.R. Smits et al., Nature Reviews Physics 6, 86 (2024)*).

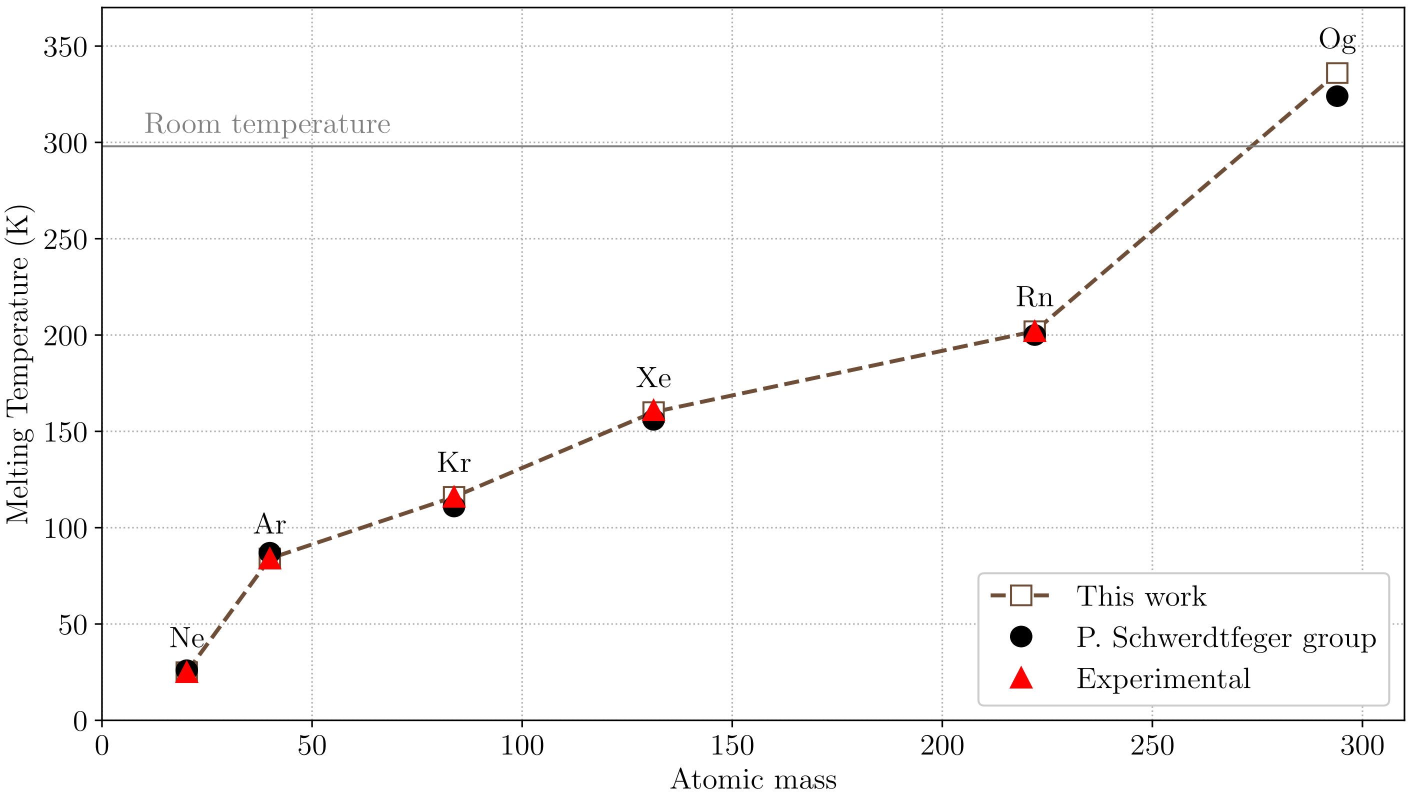
Melting temperature of Og and its homologues



Melting temperature of Og and its homologues



Melting temperature of Og and its homologues

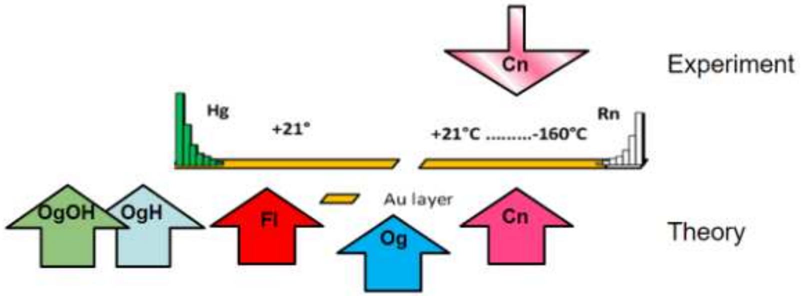


This work: *N.K. Dulaev, talk at this workshop.*

Adsorption of SHEs on Au(111) Surface

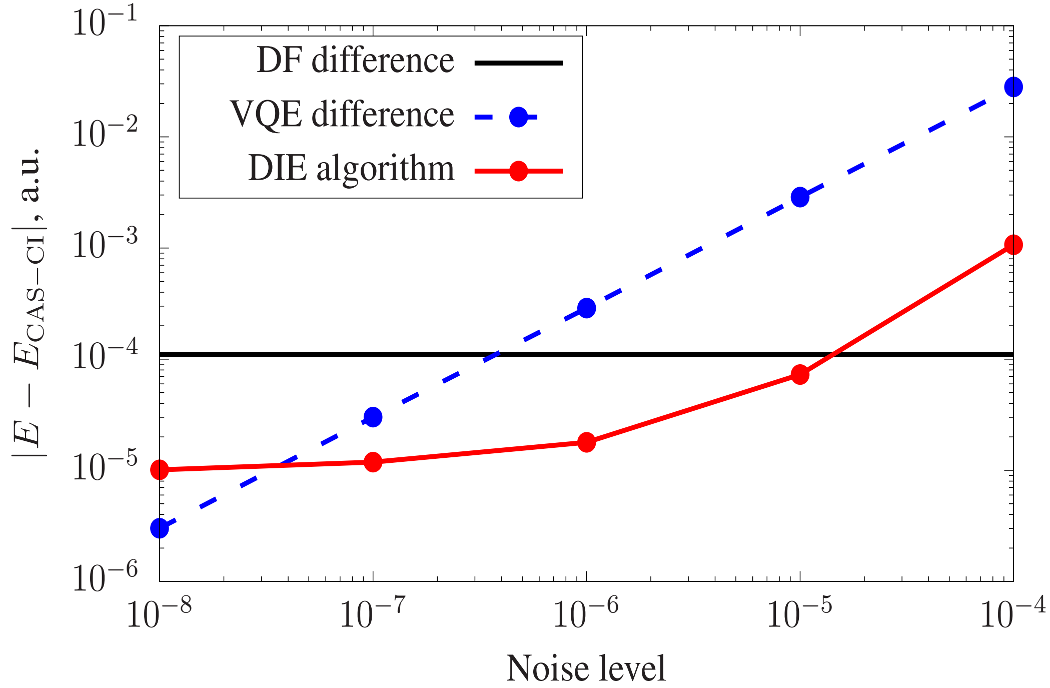
Investigated species

- Atoms
  – Hg/Cn, Tl/Nh, Pb/Fl, Bi/Mc, Po/Lv, At/Ts, Rn/Og
- Compounds
  – hydrides BiH/McH, PoH/LvH, AtH/TsH, RnH/OgH, PoH_2/LvH_2, BiH_3/McH_3
  – oxides PoO/LvO, AtO/TsO, PoO_2/LvO_2, AtO_2/TsO_2, AtOO/TsOO
  – oxyhydrides AtOH/TsOH, RnOH/OgOH, AtO(OH)/TsO(OH), BiO(OH)/McO(OH)



A. Ryzhkov, V. Pershina, M. Iliaš and V. Shabaev, *Phys. Chem. Chem. Phys.*, **25** (2023).
A. Ryzhkov, V. Pershina, M. Iliaš and V. Shabaev, *Phys. Chem. Chem. Phys.*, **26** (2024).
A. Ryzhkov, V. Pershina, N. Dulaev, M. Iliaš and V. Shabaev, *Phys. Chem. Chem. Phys.*, submitted.

A Quantum Algorithm for Calculating Ionization Energy



The difference between ionization energies E of Mc atom calculated with quantum algorithms and the corresponding values $E_{\mathrm{CAS-CI}}$ estimated using the CAS-CI method *(A.V. Durova, talk at this workshop)*.

The results of the IE algorithm are more robust to noise than the differences of two separate VQE runs.

Tests of QED with atomic systems

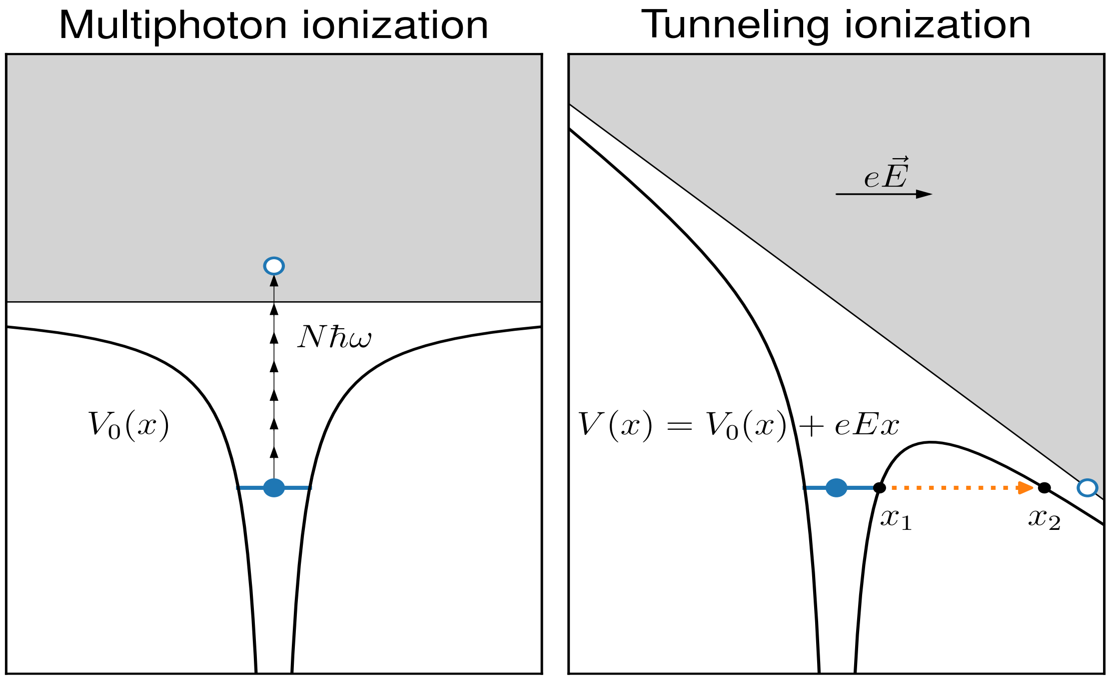
Light atoms ($\alpha Z \ll 1$, weak fields):
Tests of QED to lowest orders in α and αZ.

Heavy few-electron ions ($\alpha Z \sim 1$, strong fields):
Tests of QED in nonperturbative in αZ regime.

Low-energy heavy-ion collisions at $Z_1 + Z_2 > 173$ (supercritical fields):
Tests of QED in supercritical regime.

QED at supercritical fields

Ionization in quantum mechanics



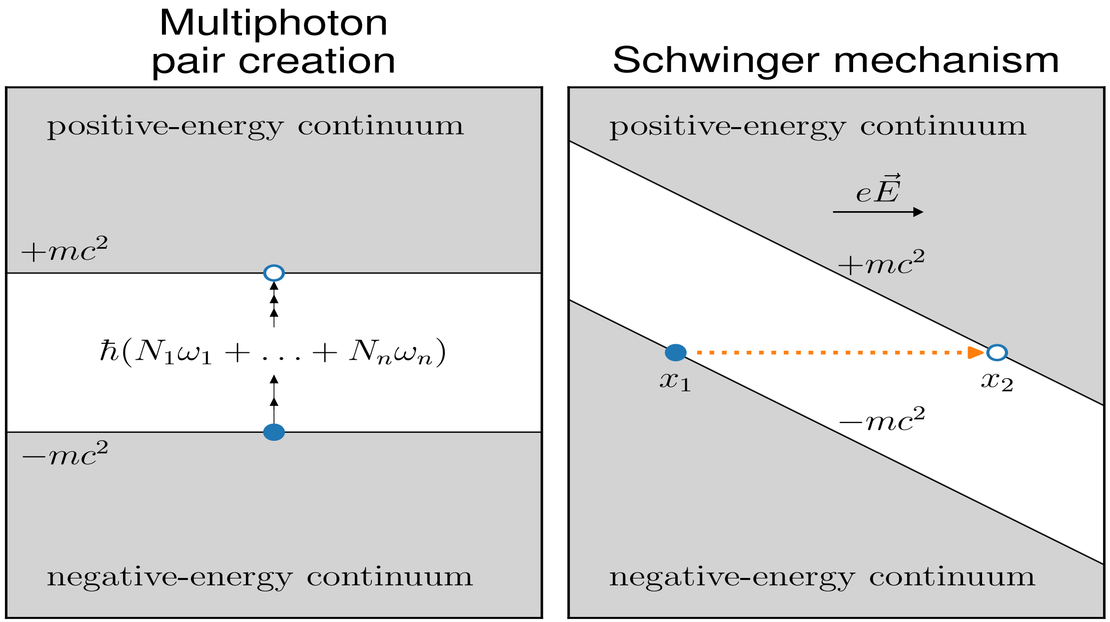
The tunneling probability for a static uniform electric field E:

$$W \sim \exp\left\{-\frac{2}{\hbar}\int_{x_1}^{x_2} dx\sqrt{2m(V(x)-\mathcal{E})}\right\}$$

where $V(x) = V_0(x) + eEx$ and $\mathcal{E}$ is the electron energy.

QED at supercritical fields

Electron-positron pair creation



The rate of pair production for a static uniform electric field E:

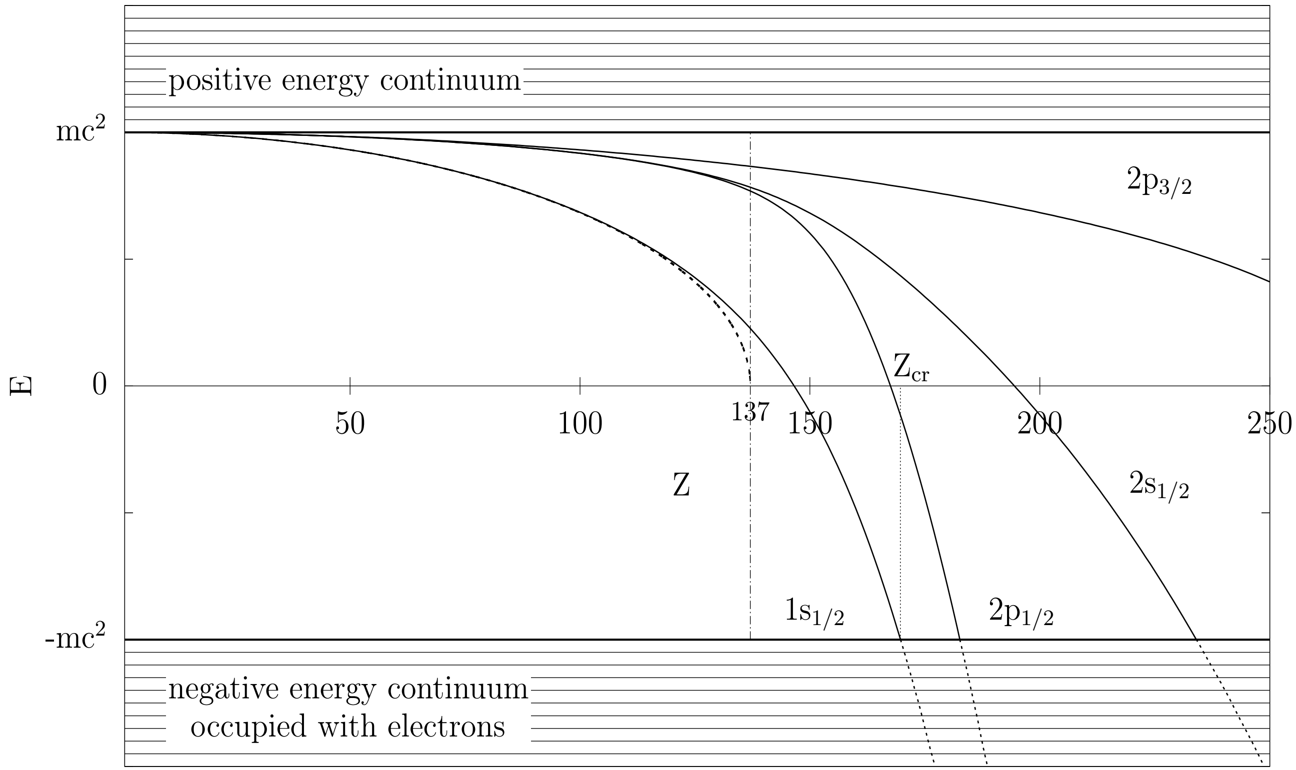
$$\frac{d^4 n_{e^+e^-}}{d^3x\,dt} \sim \frac{c}{4\pi^3 {\lambda_C}^4} \exp\left(-\pi \frac{E_c}{E}\right)$$

where $\lambda_C = \hbar/(mc)$ and $E_c = m^2c^3/(e\hbar) \approx 1.3 \times 10^{16}\mathrm{V/cm}$.

QED at supercritical Coulomb field

Supercritical Coulomb field

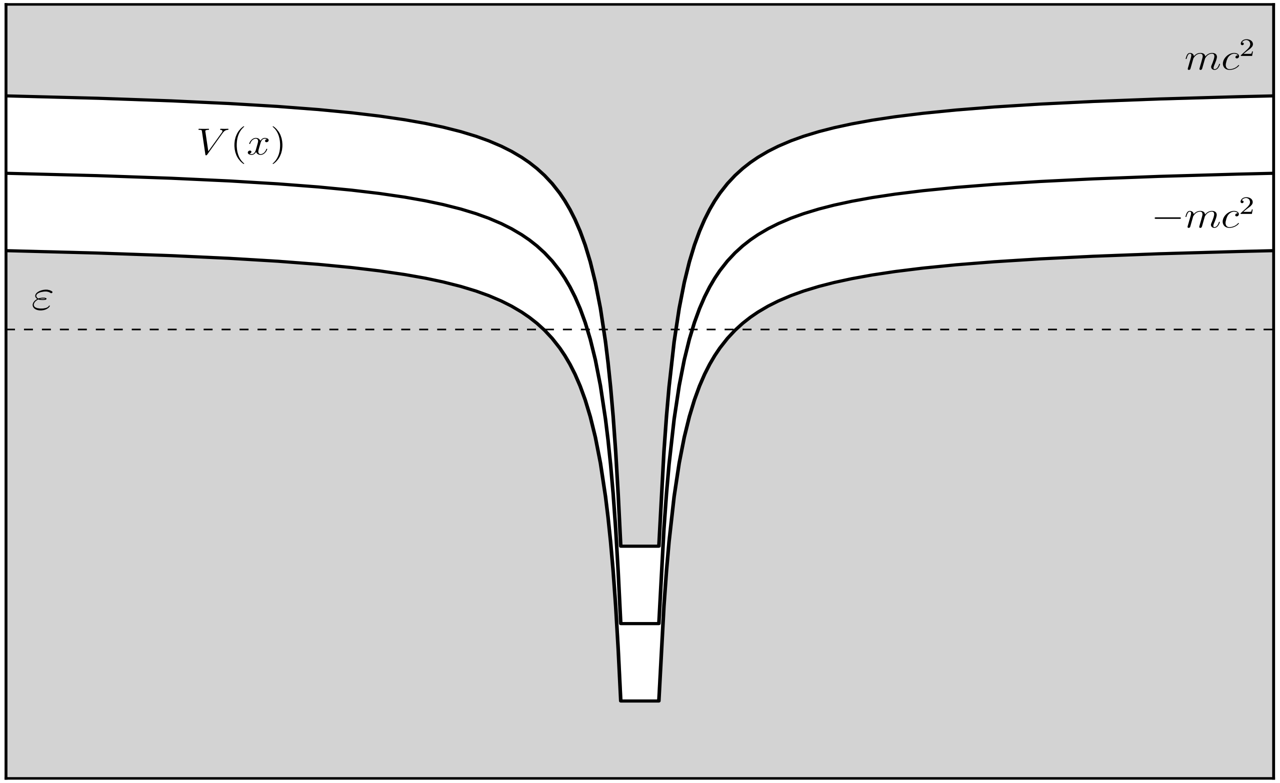
S.S. Gershtein, Ya.B. Zel'dovich, 1969; W. Pieper, W. Greiner, 1969



The $1s$ level dives into the negative-energy continuum at $Z_{\rm crit} \approx 173$.

QED at supercritical Coulomb field

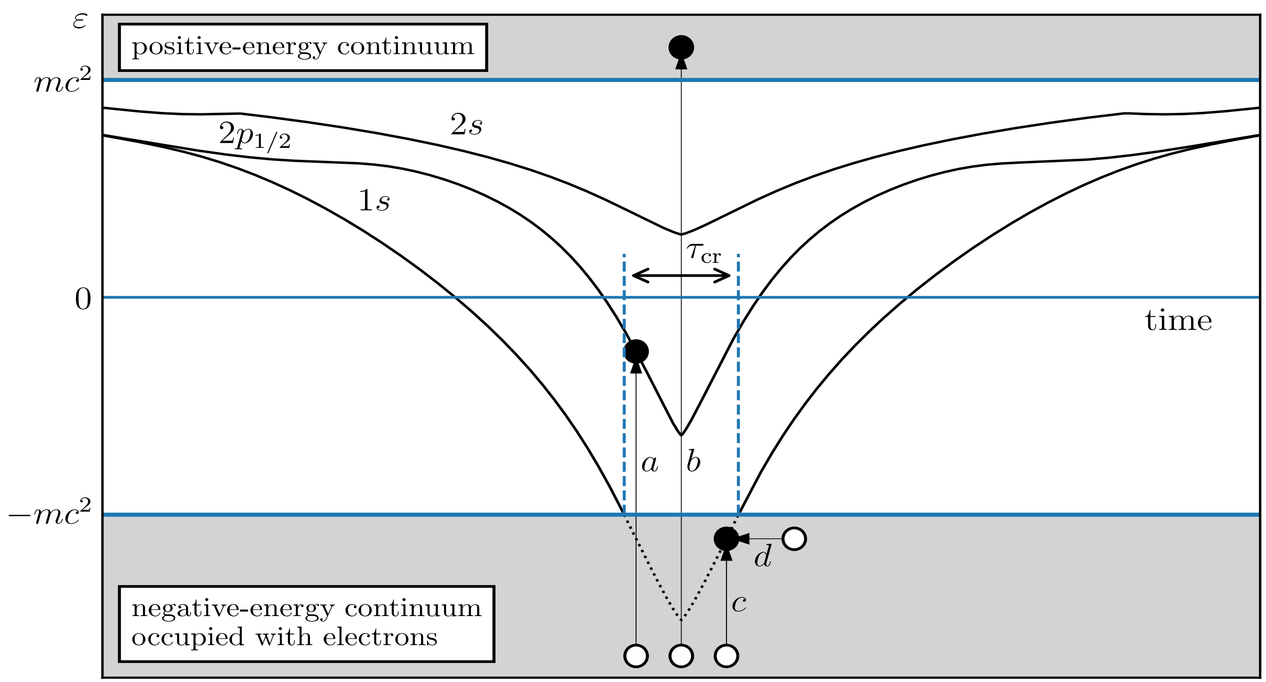
Supercritical Coulomb field



The level with the energy $\varepsilon < -mc^2$ belongs to both the positive and negative energy continua if $Z > Z_{\rm crit} \approx 173$.

Low-energy heavy-ion collisions

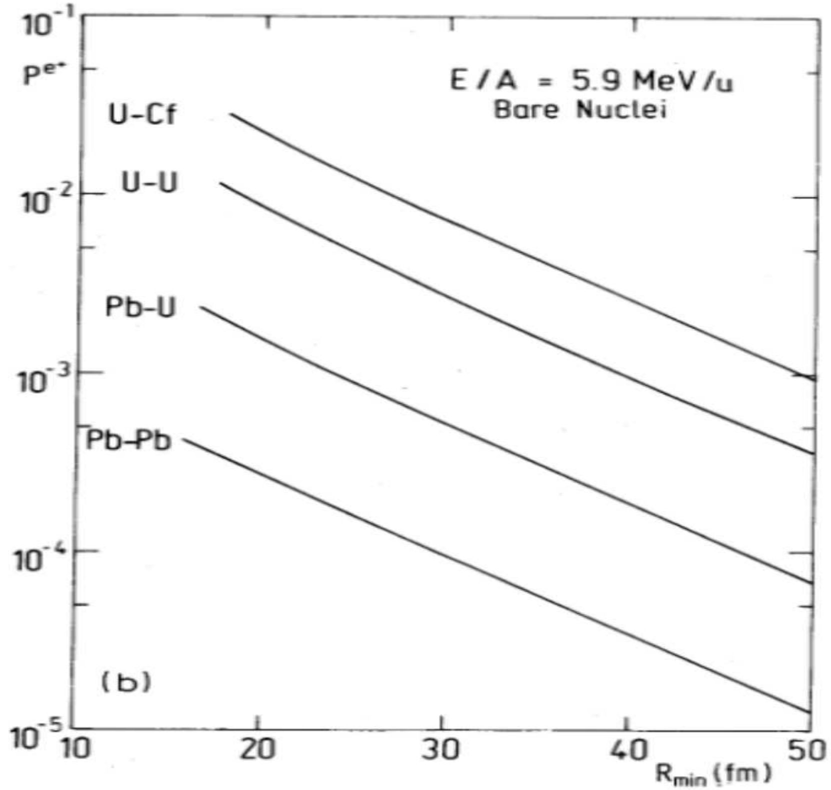
Creation of electron-positron pairs in low-energy heavy-ion collisions, with $Z_1 + Z_2 > 173$



Dynamical mechanism: a),b),c). Spontaneous mechanism (vacuum decay): d). The $1s$ state dives into the negative-energy continuum for about 10^{-21} sec.

Low-energy heavy-ion collisions

Positron production probability in 5.9 MeV/u collisions of bare nuclei as a function of distance of closest approach $R_{\min}$
(J. Reinhardt, B. Müller, and W. Greiner, Phys. Rev. A, 1981).



Conclusion by Frankfurt's group (2005):The vacuum decay could only be observed in collisions with nuclear sticking, in which the nuclei are bound to each other for some period of time by nuclear forces.

Low-energy heavy-ion collisions

New methods for calculations of quantum dynamics of electron-positron field in low-energy heavy-ion collisions at subcritical and supercritical regimes have been developed:

- *I.I. Tupitsyn, Y.S. Kozhedub, V.M. Shabaev et al., Phys. Rev. A 82, 042701 (2010).*
- *I. I. Tupitsyn, Y. S. Kozhedub, V. M. Shabaev et al., Phys. Rev. A 85, 032712 (2012).*
- *G. B. Deyneka, I. A. Maltsev, I. I. Tupitsyn et al., Russ. J. of Phys. Chem. B 6, 224 (2012).*
- *G. B. Deyneka, I. A. Maltsev, I. I. Tupitsyn et al., Eur. Phys. J. D 67, 258 (2013).*
- *Y.S. Kozhedub, V.M. Shabaev, I.I. Tupitsyn et al., Phys. Rev. A 90, 042709 (2014).*
- *I.A. Maltsev, V.M. Shabaev, I.I. Tupitsyn et al., NIMB, 408, 97 (2017).*
- *R.V. Popov, A.I. Bondarev, Y.S. Kozhedub et al., Eur. Phys. J. D 72, 115 (2018).*
- *I.A. Maltsev, V.M. Shabaev, R.V. Popov et al., Phys. Rev. A 98, 062709 (2018).*

Low-energy heavy-ion collisions

Time-dependent Dirac equation

$$i\frac{\partial}{\partial t}\psi(\mathbf{r},t) = (\boldsymbol{\alpha}\cdot\mathbf{p} + \beta m_e + V(\mathbf{r},t))\psi(\mathbf{r},t)$$

with

$$V(\mathbf{r},t) = V_{\rm A}(|\mathbf{r}-\mathbf{R}_{\rm A}(t)|) + V_{\rm B}(|\mathbf{r}-\mathbf{R}_{\rm B}(t)|)\,.$$

We introduce two sets of the solutions *(see book: E.S. Fradkin, D.M. Gitman, S.M. Shvartsman, Quantum Electrodynamics with Unstable Vacuum, 1991):*

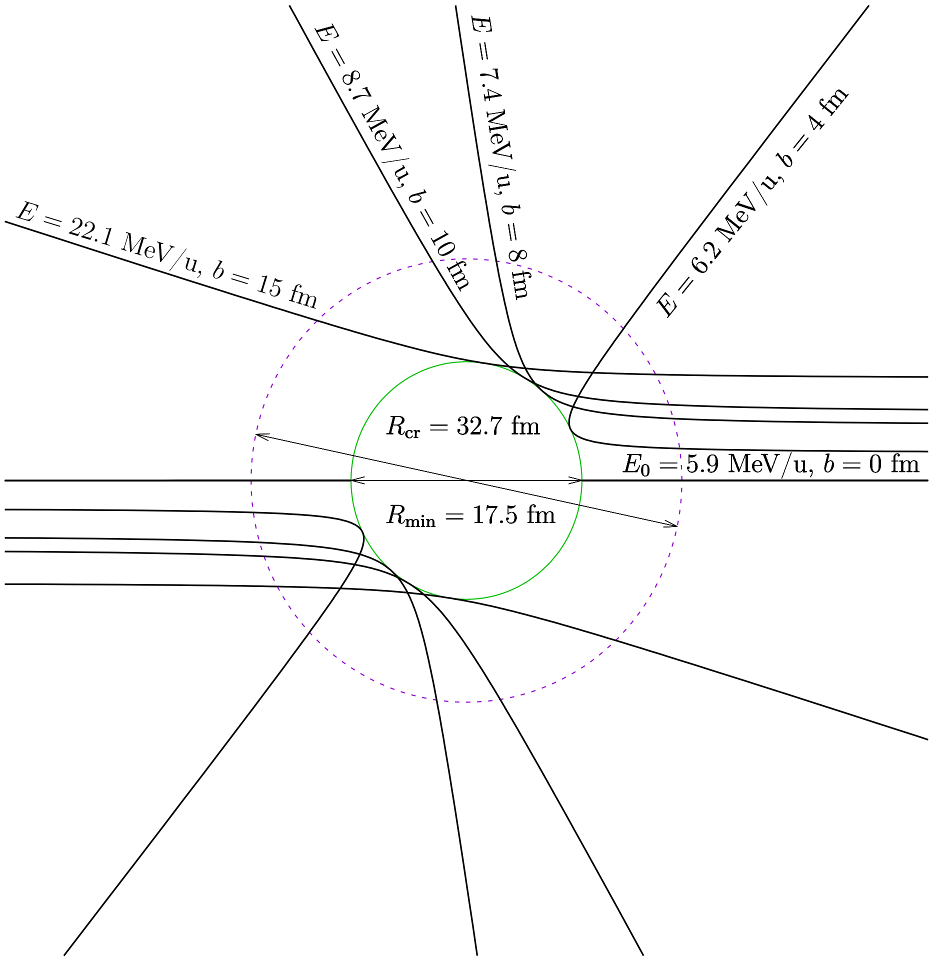
$$\psi_i^{(+)}(\mathbf{r},t_{\rm in}) = \phi_i^{\rm in}(\mathbf{r})\,, \qquad \psi_i^{(-)}(\mathbf{r},t_{\rm out}) = \phi_i^{\rm out}(\mathbf{r})\,,$$

where $\phi_i^{\rm in}(\mathbf{r})$ and $\phi_i^{\rm out}(\mathbf{r})$ are the eigenfunctions of the Dirac Hamiltonian at the corresponding time moments. The number of created positrons in a state “p” is given by

$$\overline{n}_p = \sum_{i>F}\left|\int d\mathbf{r}\,\psi_p^{(-)\dagger}(\mathbf{r},t)\psi_i^{(+)}(\mathbf{r},t)\right|^2 .$$

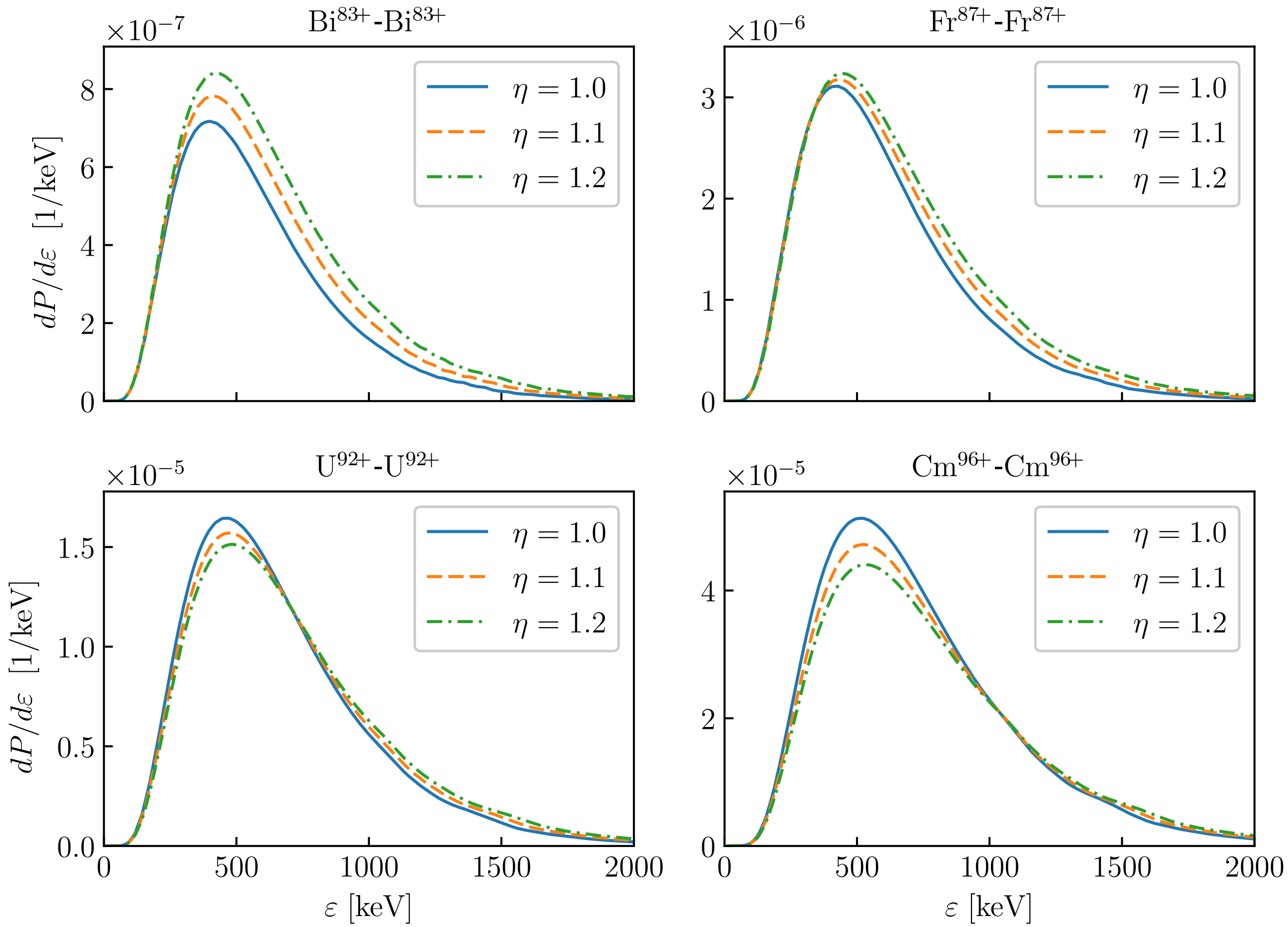
How to observe the vacuum decay

(I.A. Maltsev et al., PRL, 2019; R.V. Popov et al., PRD, 2020)



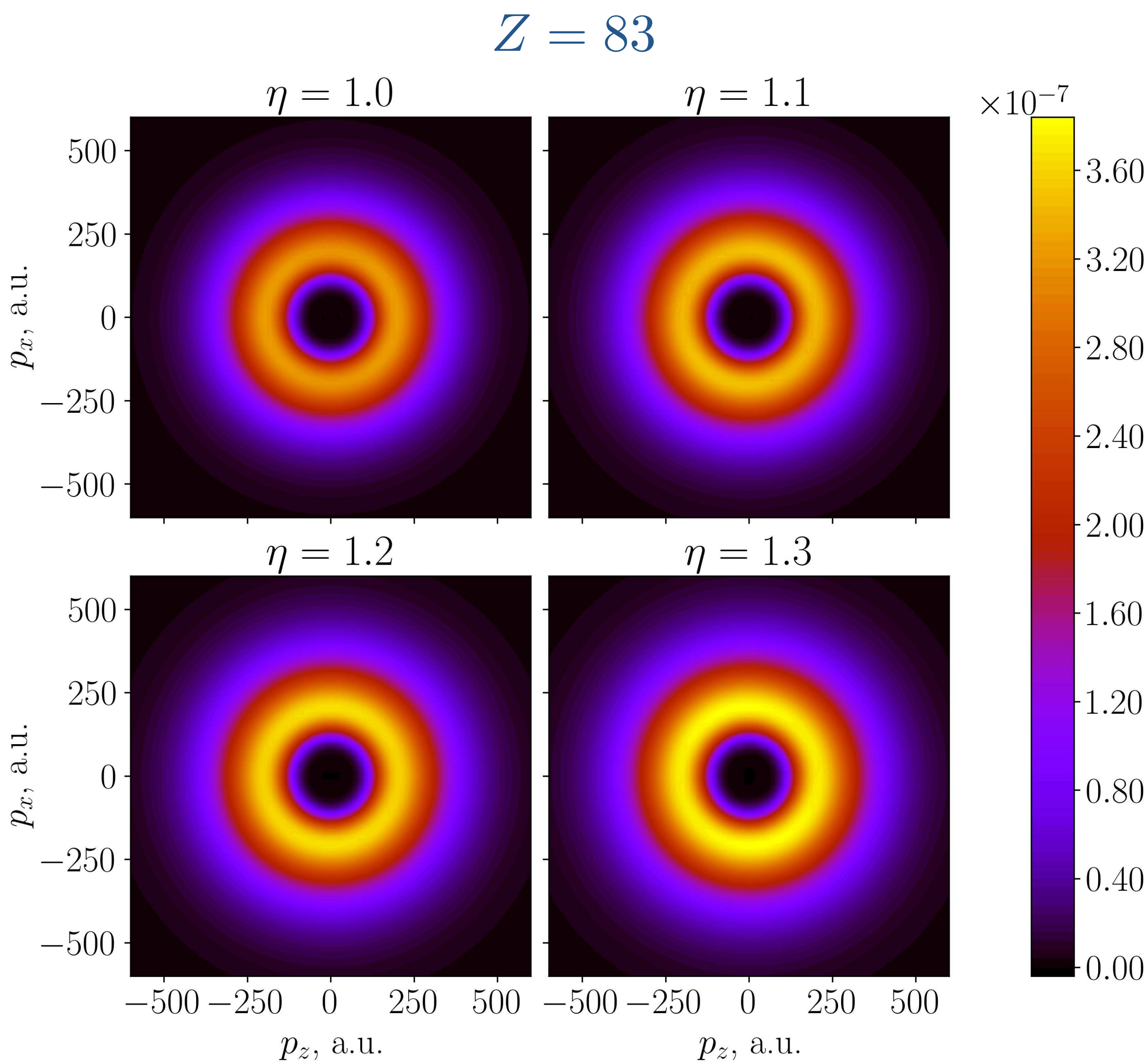
We consider only the trajectories for which the minimal internuclear distance is the same: $R_{\rm min} = 17.5$ fm. We introduce $\eta = E/E_0 \geq 1$.

How to observe the vacuum decay



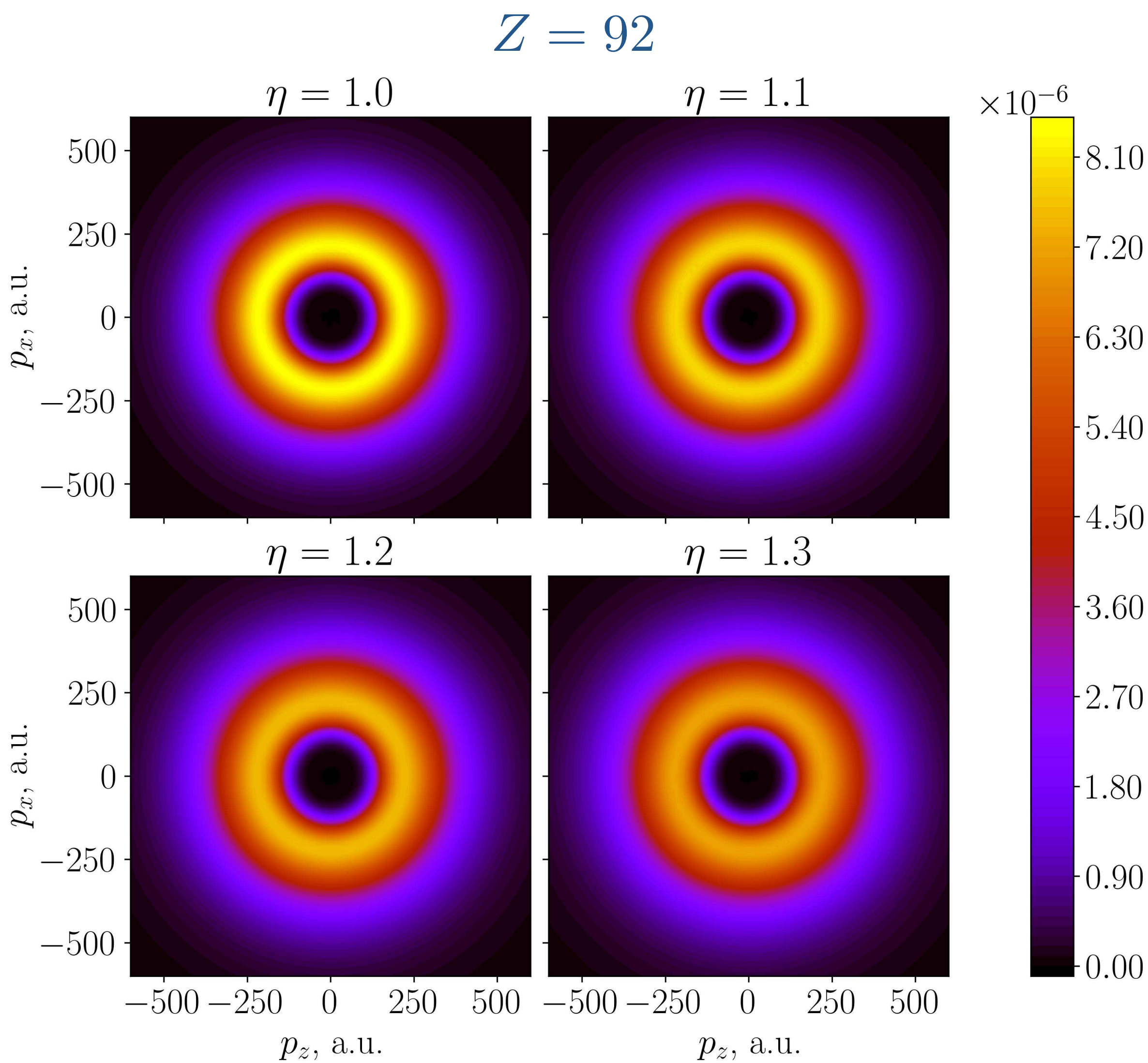
Positron spectra in symmetric ($Z = Z_1 = Z_2$) collisions for different collision energy $\eta = E/E_0$ at $R_{\text{min}} = 17.5$ fm. *(R.V. Popov, V.M. Shabaev, D.A. Telnov et al., PRD, 2020)*

How to observe the vacuum decay



N.K. Dulaev, D.A. Telnov, V.M. Shabaev et al., PRD, 2024.

How to observe the vacuum decay



N.K. Dulaev, D.A. Telnov, V.M. Shabaev et al., PRD, 2024.

How to observe the vacuum decay

Background effects creating positrons *(W. Greiner et al., 1985)*

- Internal conversion of γ-rays from nuclear states
- External conversion of γ-rays in the target
- External conversion of γ-rays in the detector
- Conversion of x-rays from nuclear or electronic bremsstrahlung

All these background effects can either be kept under control or they can be neglected.

Conclusion

The experimental study of the proposed scenarios for heavy-ion collisions would either prove the vacuum decay in the supercritical Coulomb field or lead to discovery of a new physical phenomenon, which can not be described within the presently used QED formalism.

For details:

I.A. Maltsev, V.M. Shabaev, R.V. Popov et al., Phys. Rev. Lett. 123, 113401 (2019).

R.V. Popov, V.M. Shabaev, D.A. Telnov et al., Phys. Rev. D 102, 076005 (2020).

R.V. Popov, V.M. Shabaev, I.A. Maltsev et al., Phys. Rev. D 107, 116014 (2023).

N.K. Dulaev, D.A. Telnov, V.M. Shabaev et al., Phys. Rev. D 109, 036008 (2024).

N.K. Dulaev, D.A. Telnov, V.M. Shabaev et al., Phys. Rev. D 111, 016018 (2025).