

Vacuum decay and its observation in collisions of heavy nuclei

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Outline of the talk

- Introduction
- QED at supercritical Coulomb field
- Low-energy heavy-ion collisions
- How to observe the vacuum decay
- Conclusion

Introduction: Theory of superheavy atoms

Relativistic calculations of electronic structure of superheavy elements
(today talk by Ilya Tupitsyn)

Chemical behavior of superheavy elements in gas-phase experiments:
calculation and prediction *(today talk by Valeria Pershina)*

Relativistic calculations of superheavy elements with quantum
computers *(I. Maltsev, V. Zaytsev, A. Durova, M. Groshev)*

Introduction: 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.

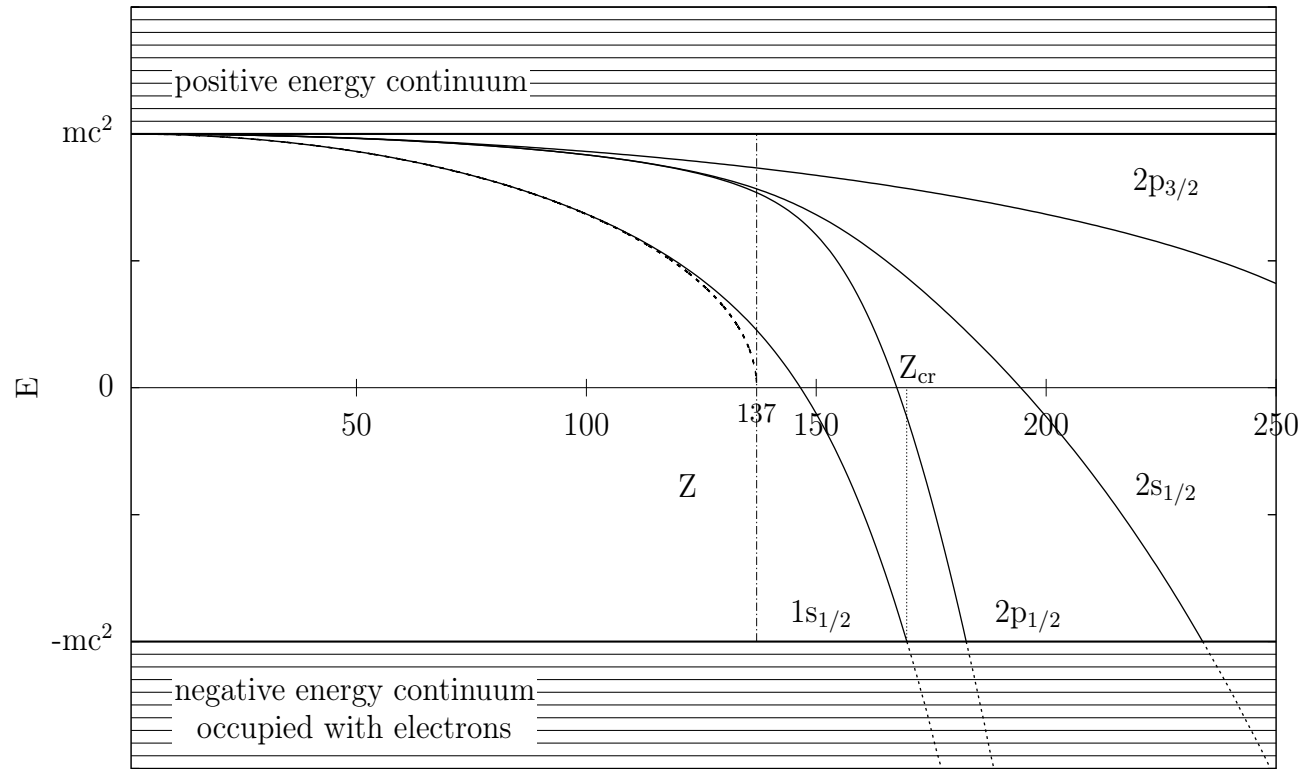
Low-energy heavy-ion collisions at $Z_1 + Z_2 > 173$ (supercritical fields):

Tests of QED in supercritical regime.

QED at supercritical Coulomb field

Supercritical Coulomb field

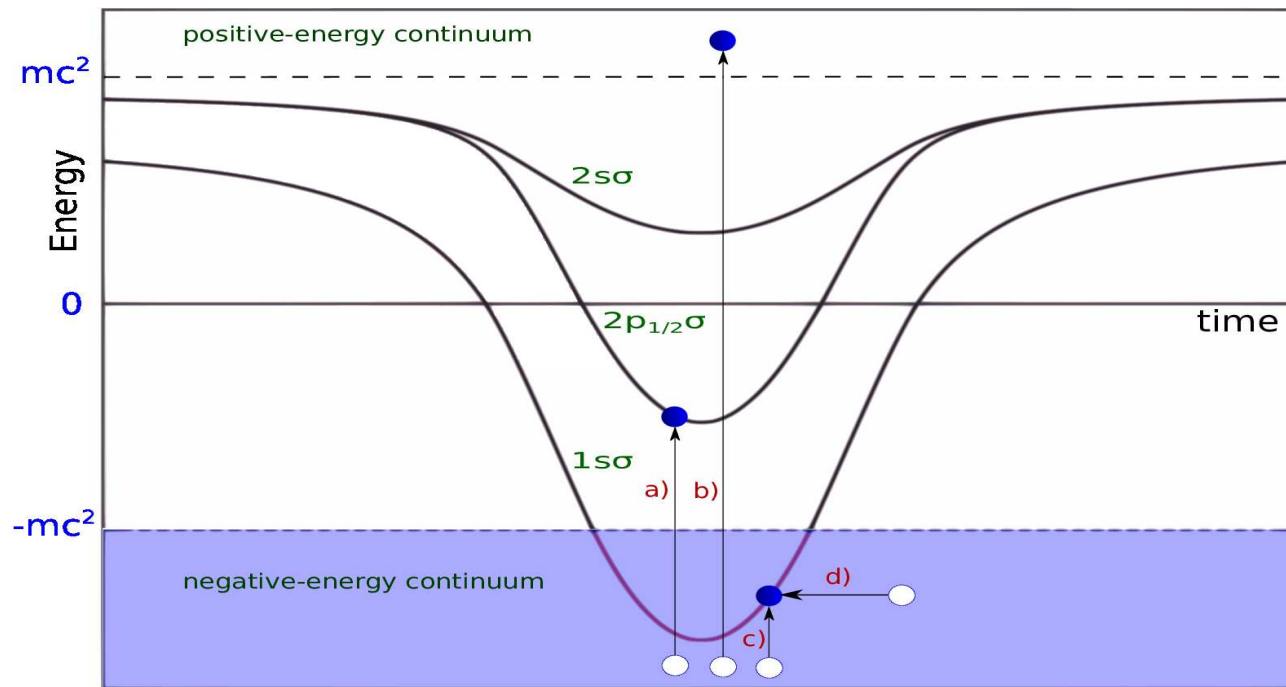
S.S. Gershtein, Ya.B. Zel'dovich, 1969; W. Pieper, W. Greiner, 1969



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

Low-energy heavy-ion collisions

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

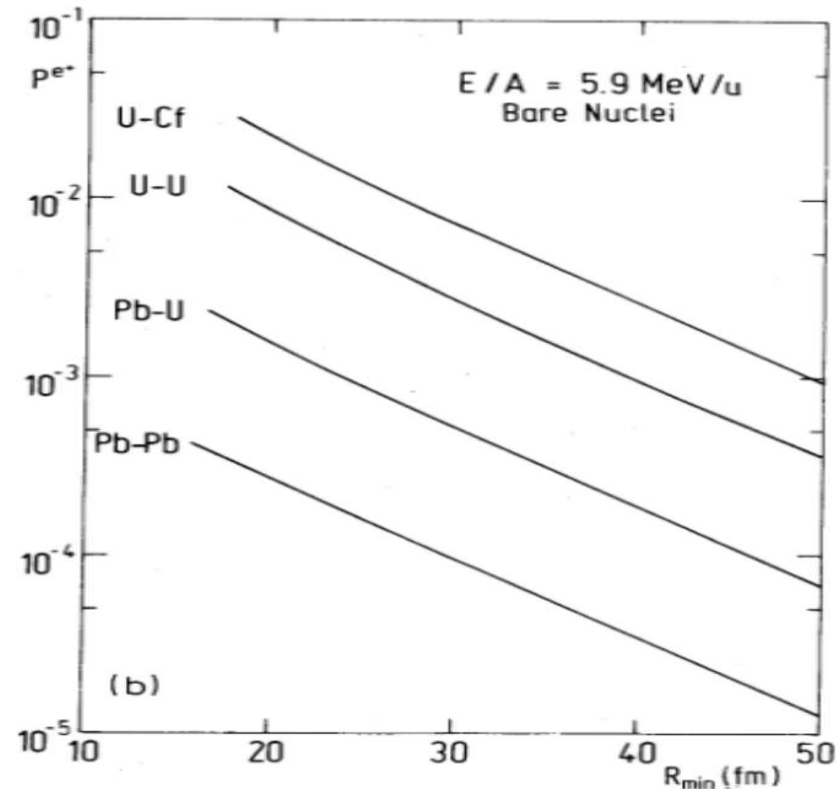


Dynamical mechanism: a), b), c). Spontaneous mechanism (vacuum decay): d). The $1s$ state dives into the negative-energy continuum for about 10^{-21} sec.

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

Pair creation beyond the monopole approximation

$$\text{U-U, } E_{\text{cm}} = 740 \text{ MeV}$$

Expected number of created pairs as a function of the impact parameter b

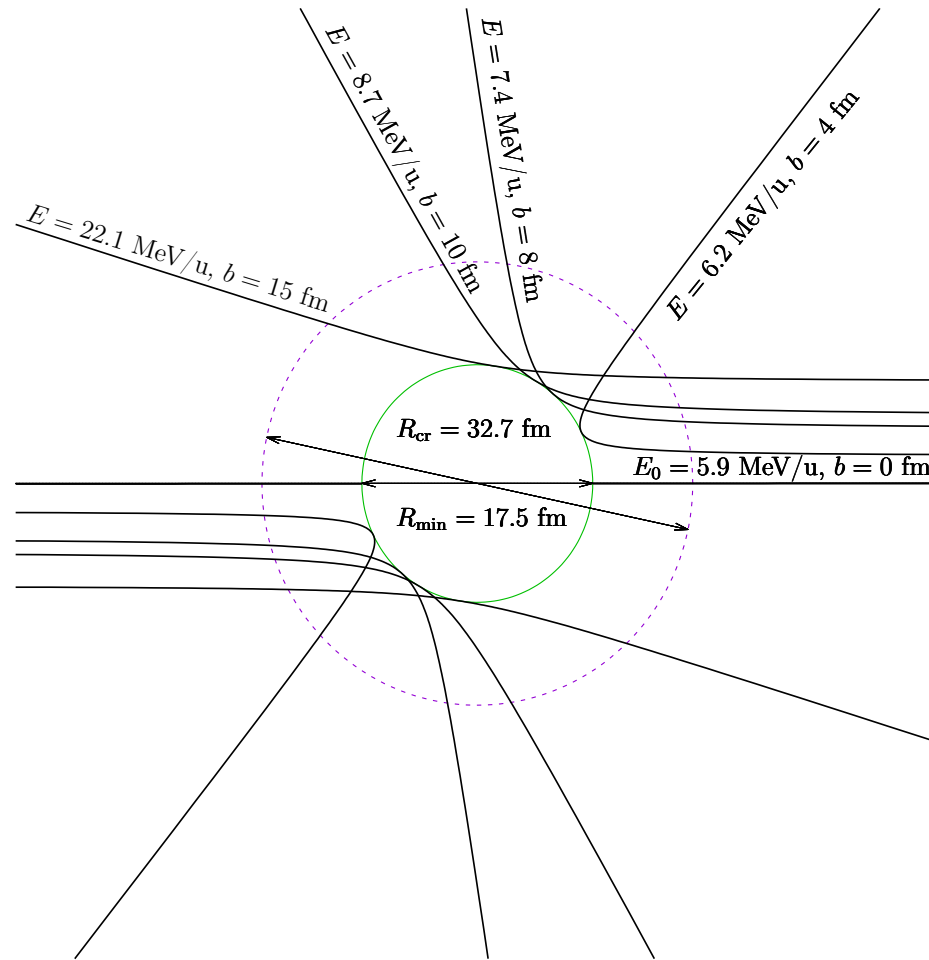
(I.A. Maltsev, V.M. Shabaev, R.V. Popov et al., PRA, 2018) .

b (fm)	Monopole approximation	Two-center approach
0	1.29×10^{-2}	1.38×10^{-2}
10	7.26×10^{-3}	8.01×10^{-3}
20	2.75×10^{-3}	3.46×10^{-3}
30	1.04×10^{-3}	1.42×10^{-3}
40	4.12×10^{-4}	7.04×10^{-4}

The two-center result for $b = 0$ has been confirmed by a different method *(R.V. Popov, A.I. Bondarev, Y.S. Kozhedub et al., EPJD, 2018) .*

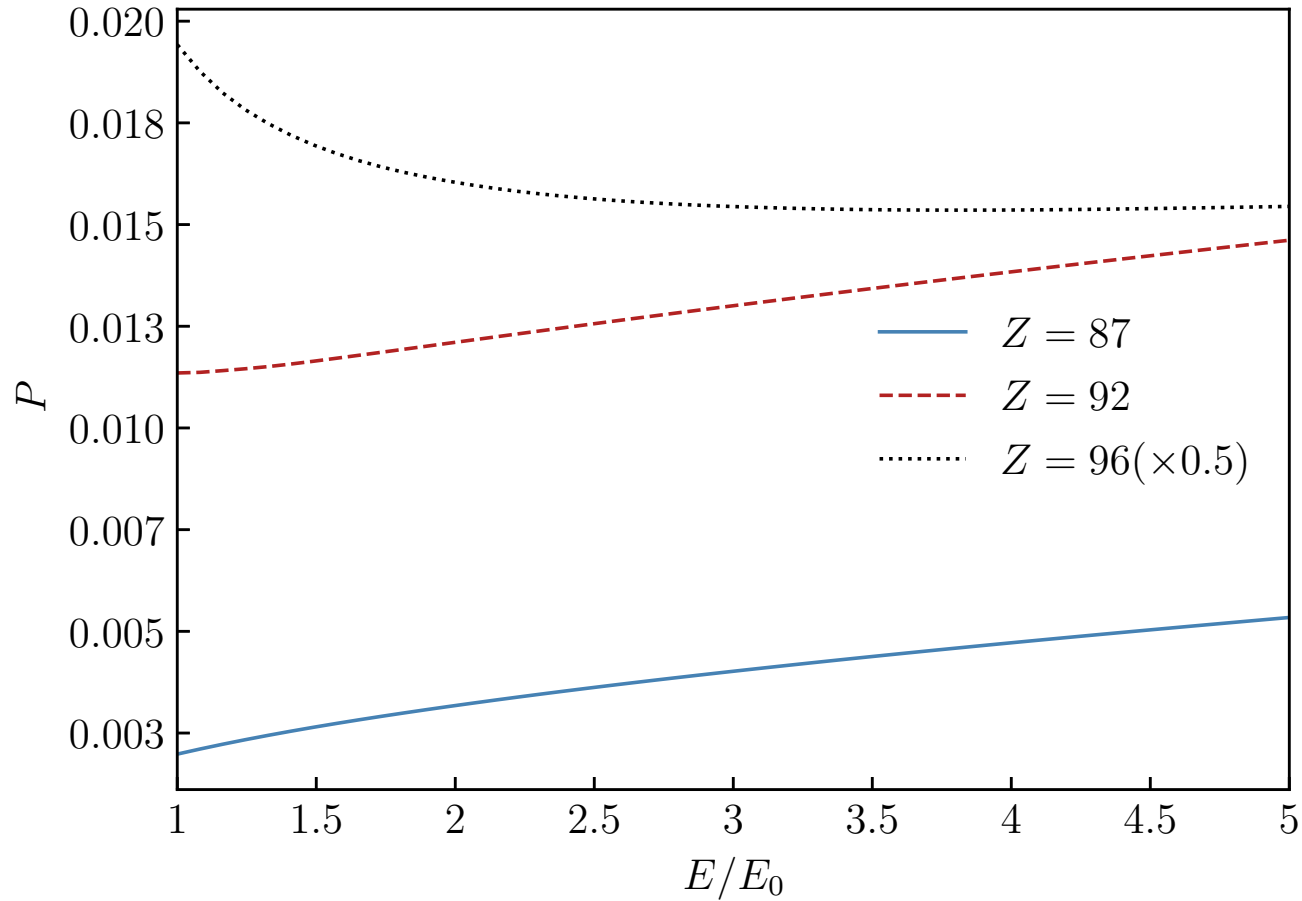
How to observe the vacuum decay

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



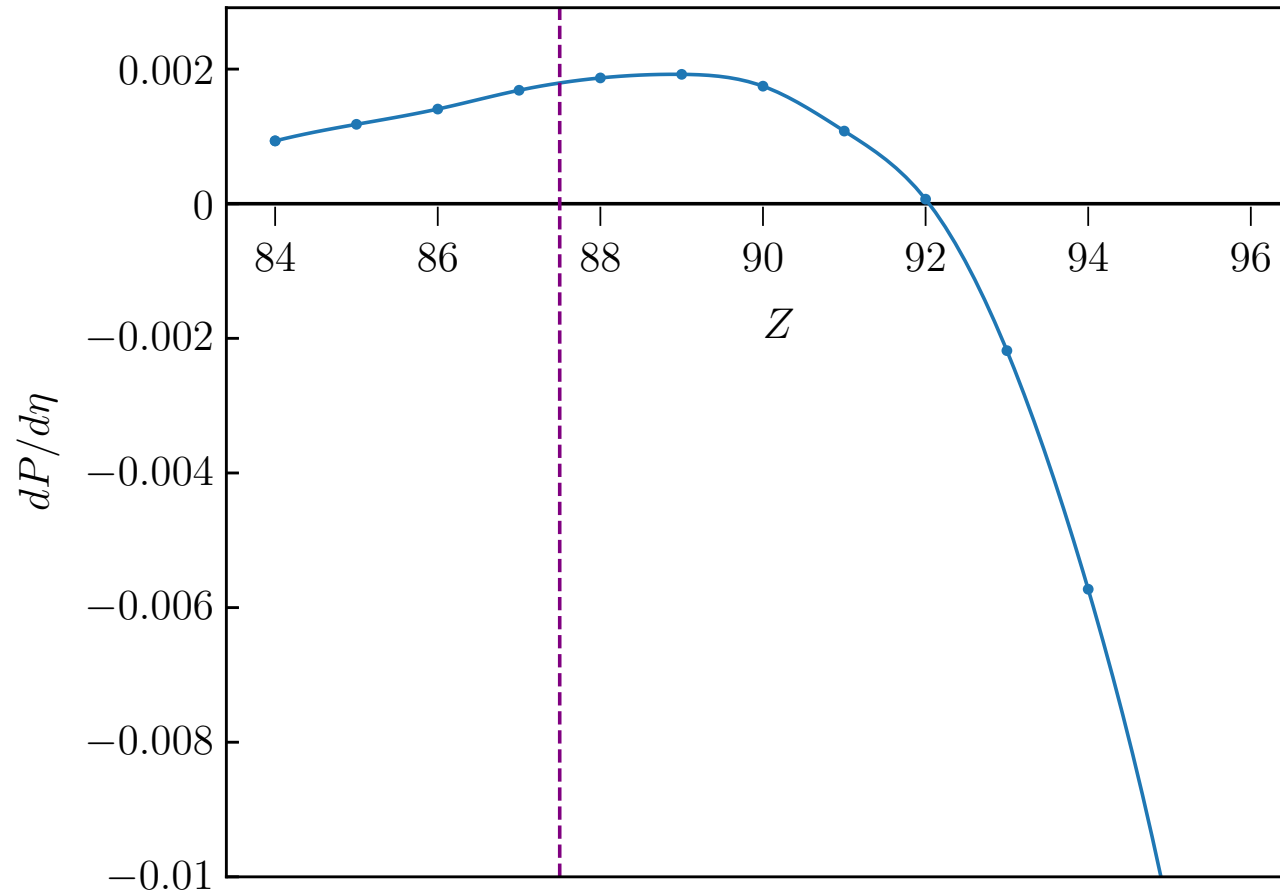
We consider only the trajectories for which the minimal internuclear distance is the same: $R_{min} = 17.5$ fm. We introduce $\eta = E/E_0 \geq 1$.

How to observe the vacuum decay



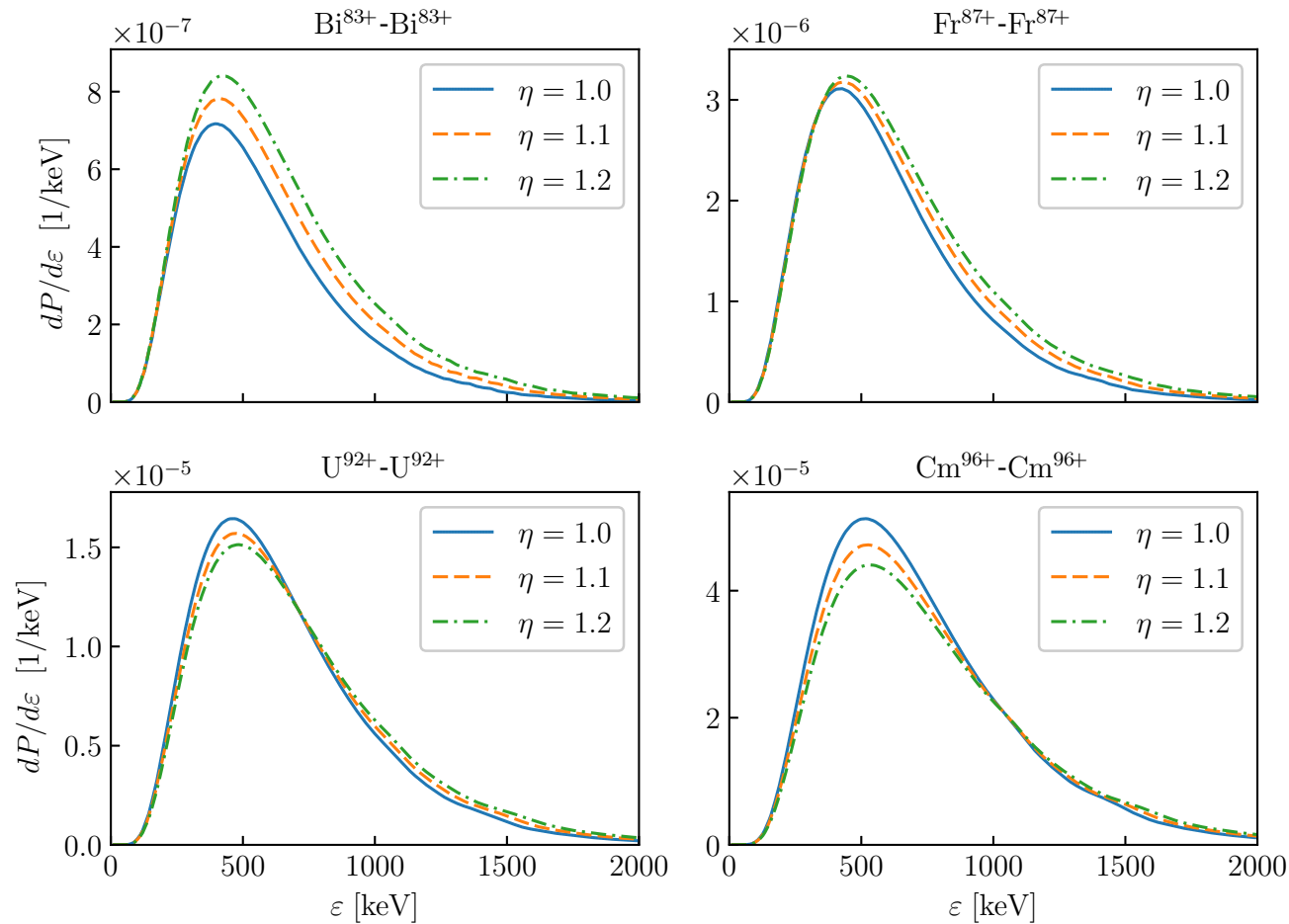
Total pair-production probability for symmetric ($Z = Z_1 = Z_2$) collisions as a function of the collision energy at $R_{\min} = 17.5$ fm.

How to observe the vacuum decay



The derivative of the pair-production probability with respect to the energy $dP/d\eta$, where $\eta = E/E_0$, at the point $\eta = 1$ as a function of the nuclear charge number $Z = Z_1 = Z_2$ at $R_{\min} = 17.5$ fm.

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 $R_{\min} = 17.5$ fm.

Conclusion

The experimental study of the proposed scenarios would either prove the vacuum decay in the supercritical Coulomb field or lead to discovery of a new physics, which is beyond the presently used QED formalism.

The same scenarios can be applied to observe the vacuum decay in collisions of bare nuclei with neutral atoms.

For details:

I.A. Maltsev, V.M. Shabaev, R.V. Popov, Y.S. Kozhedub, G. Plunien, X. Ma, Th. Stöhlker, and D.A. Tumakov, Phys. Rev. Lett. 123, 113401 (2019).

R.V. Popov, V.M. Shabaev, D.A. Telnov, I.I. Tupitsyn, I.A. Maltsev, Y.S. Kozhedub, A.I. Bondarev, N.V. Kozin, X. Ma, G. Plunien, T. Stöhlker, D.A. Tumakov, and V.A. Zaytsev, Phys. Rev. D 102, 076005 (2020).