Supercritical QED and Time-Delayed Heavy Ion Collisions

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Abstract The theory of Quantum Electrodynamics predicts the "spontaneous" production of electron-positron pairs in the presence of strong electric fields. Collisions of heavy ions with a combined nuclear charge exceeding the value of 172 are expected to provide the required supercritical field at least transiently. Extensive experimental searches performed about two decades ago, mainly at GSI, have confirmed the expected strong enhancement of pair production in high-Z collisions. The short time scales involved, however, have prevented an unequivocal confirmation of the mechanism of supercritical pair production. We revisit this problem in the view of recent results from nuclear reaction theory. If reactions with a prolonged lifetime approaching 10^{-20} s can be selected using suitable coincidence conditions, it should be possible to experimentally verify the vacuum decay of QED.

1 Supercritical Fields: The charged Vacuum in QED

The study of Quantum Electrodynamics of strong fields dates back to the early days of quantum mechanics. (For extensive references we refer the reader to the book [1]). Soon after Dirac's formulation of the relativistic quantum theory of electrons, O. Klein discovered that scattering off an electrostatic potential barrier V_0 which exceeds the height of $2mc^2$ leads to anomalous behaviour of the transmission and reflection coefficients. In 1931 F. Sauter derived the transmission coefficient for

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"tunneling through the gap of the Dirac equation" for a potential barrier of finite width a as $T \simeq \exp\left[-\pi mc^2/(V_0/a)(\hbar/mc)\right] = \exp\left(-E_{\rm cr}/E\right)$. This expression displays a nonanalytic dependence on the electrical field strength E and is exponentially suppressed unless E reaches the value of the *critical field strength*

$$E_{\rm cr} = \frac{\pi m^2 c^3}{e\hbar} \simeq 1.3\ 10^{18}\,\frac{\rm V}{\rm m}\ . \tag{1}$$

It soon became clear, in particular through the work Heisenberg and his student Euler, that the vacuum of QED is a dynamical polarizable medium in which an external field can induce the production of virtual and (provided the field is strong enough) also real electron-positron pairs. An elegant formulation of this vacuum instability was given in 1951 by Schwinger using his eigentime formalism.

Although the existence of the "Schwinger" pair production mechanism is generally accepted, it has eluded experimental verification. Extended ultrastrong electrostatic fields $E \simeq E_{\rm cr}$ are unattainable in the laboratory. On an atomic scale, however, this is not true: The electrical field strength at the surface of a nucleus exceeds $E_{\rm cr}$ by about three orders of magnitude. Nevertheless in ordinary atoms pair creation does not occur because the created electron would not fit into the narrow well of the Coulomb potential. This changes when atomic structure is extrapolated from the known region of chemical elements by about a factor of two. When Z approaches the value of the inverse fine structure constant $1/\alpha \simeq 137$ the inner-shell electrons gain tremendously in binding energy. The lowest state $1s_{1/2}$—and also the next higher $2p_{1/2}$ state—traverses the gap between the positive and negative energy continuum solutions of the Dirac equation. The total energy E_{1s} becomes negative at $Z = 150$ and is predicted to reach the value $-m$ (i.e., a binding energy of $2m$=1.022 MeV) at the *critical nuclear charge* $Z_{\rm cr} \simeq 172$.

What happens at and beyond this critical charge was clarified in the early 1970s by our group at Frankfurt [2] and by another group in Moscow [3]. For a detailed overview of vacuum properties in the presence of supercritical fields see [1]. If the strength of the Coulomb potential exceeds the critical value, i.e., $Z > Z_{\rm cr}$, the spectrum of the stationary Dirac equation undergoes a qualitative change. The $1s$ state leaves the discrete spectrum and merges with the lower continuum of the Dirac equation which it enters as a narrow *resonance*. In Dirac's hole picture (which can be corroborated by arguments based on second-quantized field theory) the lower continuum (the Dirac sea) is occupied with electrons. If an empty bound state enters the continuum it will get filled by a sea electron which can *tunnel* through the classically forbidden gap of the Dirac equation, leaving behind a hole, i.e., a positively charged positron, which escapes to infinity. The process has been termed "spontaneous pair creation" of "decay of the vacuum" of QED. Obviously this process is closely related to the well-known Klein paradox and to the "Schwinger formula" for pair creation in a constant electric field. The difference is that in supercritical atoms the strong field is confined to a small region in space which can harbour only a small number of created electrons.

Spontaneous pair creation occurs already at the tree level of QED and it survives when higher-order processes of quantum field theory are taken into account. It was shown that the level shifts caused by vacuum polarization and electron self energy amount to less than 10^{-3} of the total K-shell binding energy (see [1]).

2 Dynamics of the Electron-Positron Field

In close collisions of two very heavy nuclei, the supercritical electric field of a combined nucleus with charge $Z = Z_1 + Z_2$ is generated transiently. To study this problem, the Dirac equation with two Coulomb centers was solved ([4, 5], see also [6] and references therein). It was found that the lowest molecular electron level ($1s\sigma$) can be traced down to the lower continuum of the Dirac equation and reaches a binding energy of $2m$ at a critical two-center distance R_{cr}. Example in U+U collisions the critical distance is approximately $R_{\text{cr}} \approx 30$ fm. However, in a heavy-ion collision the nuclei move on their Rutherford trajectories $\mathbf{R}(t)$ which causes the wave functions and binding energies to vary rapidly with time and also leads to strong dynamically induced transitions. This makes it necessary to solve the *time dependent two-center Dirac equation*.

A considerable number of approaches has been developed to attack this problem. The brute-force way is to solve the time-dependent two-center Dirac equation numerically as a system of coupled partial differential equations, either in coordinate space or in momentum space. Calculations of this kind are very demanding, in particular in view of the long range of the Coulomb potential and of the small size of pair production amplitudes. A physically inspired way to proceed is by expanding the time-dependent wave function into a complete set of basis states. The time dependent Dirac equation is thus converted to a set (in principle infinite, but truncated in practical calculations) of coupled ordinary differential equations.

At high energies (see, e.g., [7]) an expansion in terms of atomic basis states is adequate. At bombarding energies not much above the nuclear Coulomb barrier (i.e. $E/A \simeq 6$ MeV) the ion velocity is comparatively slow, $v \simeq 0.1c$, so that the relativistic inner-shell electrons have time to adjust to the nuclear Coulomb field. This gives justification for an adiabatic description of the collision in terms of *superheavy quasimolecules*. Then it is useful to expand the time-dependent wave function

$$\Psi_i(\mathbf{r}, t) \;=\; \sum_j a_{ij}(t)\varphi_j(\mathbf{R}(t), \mathbf{r})\, \mathrm{e}^{-\mathrm{i}\chi_j(t)} \quad \text{where} \quad \chi_j(t) \;=\; \int_{t_0}^{t} dt \langle\varphi_j|H|\varphi_j\rangle \;. \tag{2}$$

in the *adiabatic basis* of molecular states φ_j, i.e., eigenstates of the stationary two-center Dirac Hamiltonian H at a given internuclear distance $\mathbf{R}$

$$\Big(H(\mathbf{R}, \mathbf{r}) - E_j(\mathbf{R})\Big)\varphi_j(\mathbf{R}, \mathbf{r}) \;=\; 0 \;, \tag{3}$$

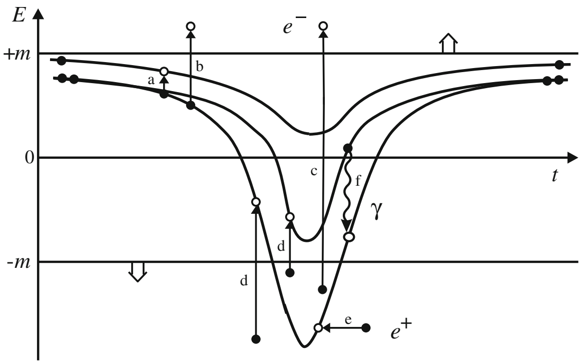

Fig. 1 The time-dependent energy levels in a supercritical heavy ion collision. The *arrows* symbolize various electron excitation mechanisms. **a** bound-bound electron excitation; **b** ionization; **c** direct (free-free) electron-positron pair production; **d** induced (bound-free) pair production; **e** spontaneous pair production; **f** quasimolecular X-ray emission

The summation extends over bound states and the two sets of continuum states. The time-dependent expansion coefficients $a_{ij}(t)$, which satisfy the boundary condition $a_{ij}(-\infty) = \delta_{ij}$, are determined by solving a truncated set of ordinary differential equations, the coupled channel equations

$$\dot{a}_{ik} = -\sum_{j \neq k} a_{ij} \langle \varphi_k | \frac{\partial}{\partial t} | \varphi_j \rangle \, \mathrm{e}^{\mathrm{i}(\chi_k - \chi_j)} \tag{4}$$

where $\partial/\partial t$ acts on the parametric time dependence of the basis wave functions.

To account for the nature of the Dirac vacuum, a Fermi level F has to be specified up to which all states are occupied initially. Neglecting electron correlations all the necessary information to describe the physical observables is contained in the set of single-particle transition amplitudes $a_{ij}(t \to \infty)$. The number of produced electrons N_i or holes (positrons) $\overline{N}_j$, resp., is given by the summation

$$N_i = \sum_{k<F} |a_{ki}(+\infty)|^2 \quad (i > F) \qquad \text{and} \qquad \overline{N}_j = \sum_{k>F} |a_{kj}(+\infty)|^2 \quad (j < F) \tag{5}$$

while correlated electron-hole pairs are described by [8]

$$N_{ij} = N_i \, \overline{N}_j + \left| \sum_{k>F} a^*_{ki}(+\infty) a_{kj}(+\infty) \right|^2 \quad (i > F \ , \ j < F) \tag{6}$$

For the description of inner-shell excitation and pair production in very heavy systems it was found sufficient to include only states with angular momentum $j = 1/2$ ($s_{1/2}$ and $p_{1/2}$) which are most strongly affected by the relativistic "collapse of the wavefunction". An inspection of the exact solutions of the two-center Dirac equation

[4, 5] has shown that the problem can be greatly simplified if the full two-center potential is approximated its lowest-order term in the multipole expansion (the monopole approximation). This framework has been employed with considerable success to calculate *K-hole production*, *δ-electron* and *positron emission*, and *quasimolecular X-ray radiation*, for a review see [9].

3 Supercritical Heavy-Ion Collisions

In supercritical collisions, the combined nuclear charge is sufficiently large to let the quasimolecular 1s-state enter the Dirac sea at a critical distance $R_{\rm cr}$. Then in the adiabatic picture the 1s state vanishes from the bound spectrum, becoming admixed to the lower continuum. To treat the dynamics in this case, method was developed [10] which introduces a normalizable wavefunction $\tilde{\varphi}_r$ for the supercritical 1s-state by artificially cutting off the "oscillating tail" of the resonance wave function.[1] With the help of a projection technique then a matching set of modified continuum states $\tilde{\varphi}_E$ can be constructed by solving the equation

$$(H - E)\tilde{\varphi}_E = \langle\tilde{\varphi}_r|H|\tilde{\varphi}_E\rangle\,\tilde{\varphi}_r \qquad \text{for} \quad (E < -m)\ . \tag{7}$$

Since $\tilde{\varphi}_r$ and $\tilde{\varphi}_E$ do not diagonalize the two-center Hamiltonian, there exists a non-vanishing static coupling between the truncated 1s-resonance state and the modified negative energy continuum which describes the spontaneous decay of a vacancy in the supercritical 1s-state. The decay width is $\Gamma = 2\pi|\langle\tilde{\varphi}_r|H|\tilde{\varphi}_E\rangle|^2$. The coupled channel Eq. (4) then contain the coherent superposition of an "induced" and a "spontaneous" coupling matrix element

$$\langle\varphi_{1s}|\partial/\partial t|\varphi_E\rangle \longrightarrow \langle\tilde{\varphi}_r|\partial/\partial t|\tilde{\varphi}_E\rangle + i\,\langle\tilde{\varphi}_r|H|\tilde{\varphi}_E\rangle\ . \tag{8}$$

For elastic collisions without nuclear contact the contribution from the "spontaneous" coupling constitutes only a small fraction of the produced positrons. Furthermore, the time-energy uncertainty relation leads to a large collisional broadening. Accordingly, the calculations do not yield any perceptible change in the shape of the predicted positron spectra for such collisions when going from subcritical to supercritical systems. However, the positron cross section for $Z > 137$ will to grow at a very rapid rate that can be roughly parametrized by an effective power law

$$\sigma_{e^+}(Z) \propto Z^n, \qquad n \approx 20\ . \tag{9}$$

[1] Other definitions of the resonance wave function are possible. Example it can be defined as a state with complex energy $E_{\rm res} = E_r + i\Gamma/2$ using a complex rescaling of the coordinate $\mathbf{r} \to \mathbf{r}\,e^{i\theta}$ [11, 12].

The large value of the exponent demonstrates the nonperturbative nature of pair production in collisions of high-Z ions. The fact that this prediction has been verified in the experiments at GSI (see below) is a major confirmation of our understanding of quantum electrodynamics in strong Coulomb fields.

4 Positron Production Experiments

For nearly two decades the study of atomic excitation processes and in particular of positron creation in heavy-ion collisions had been a major research topic at GSI (Darmstadt) [13–18]. To summarize, the measured positron production rates and their dependence on nuclear charge, collision energy, and impact parameter are in quantitative agreement with parameter-free theoretical predictions based on the formalism sketched above. Figure 2 showing measurements of the EPOS group demonstrates that excellent agreement was achieved when the calculated spectra of QED positrons and the background positrons from the pair conversion caused by nuclear excitation were added up. In particular the strong rise of the QED positron yield (dotted lines in Fig. 2) as a function of the combined nuclear charge $Z = Z_1 + Z_2$ is in accordance with the expected behaviour (9) and clearly demonstrates the nonperturbative action of the strong Coulomb field.

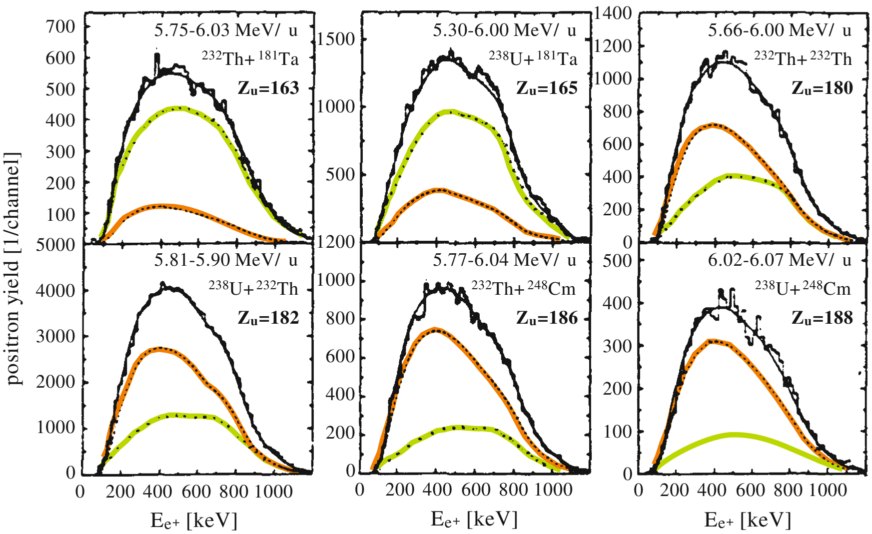

Fig. 2 Total positron spectra for various collision systems measured by the EPOS collaboration; *dotted lines*: predicted QED pair production; *dashed lines*: nuclear pair conversion; *solid lines*: sum of both. With increasing nuclear charge Z a strong rise of the QED process (dynamical plus induced positron production) is observed

An unexpected feature, however, had perplexed experimentalists and theorists alike for more than a decade: Narrow line structures of unexplained origin were discovered on top of the well understood continuous spectra by the ORANGE and EPOS groups at GSI. These lines first were associated with the spontaneous positron emission line that had been predicted by theory for supercritical collision systems with long nuclear time delay [19, 20]. However, this explanation had to be ruled out because the structures did not show the expected strong Z-dependence. More exotic speculations were put forward, e.g., the creation and subsequent two-body decay of some unidentified neutral object $X^0 \to e^+ + e^-$, supported by the reported observation of line structures in the coincident electron-positron pair spectra, but no convincing model did emerge. Interest in the "positron puzzle" largely evaporated when attempts at an independent verification by the APEX collaboration at Argonne National Laboratory [21–23] as well as further experiments at GSI with improved detectors [24, 25] failed to reproduce the former results. The prevalent opinion now is that the earlier observations were caused in part by statistical fluctuations and in part also by lines from nuclear pair conversion.

It should be added that all positron experiments so far were performed by colliding partly stripped projectile ions with solid state targets. Under these conditions bound-free pair productions ("electron capture from the vacuum") is suppressed by *Pauli blocking*: The K shell initially is occupied and can contribute to pair creation only after being emptied through ionization, which at best takes place in a few percent of the collisions. Bound-free pair creation thus could be studied much more cleanly if the required holes were brought in right from the start, i.e., by using *fully stripped ions*. Heavy ions can be stripped bare quite easily at high beam energies. In fact, bound-free pair creation has been first observed at the Bevalac using 1 GeV/nucleon U^{92+} beams [26].

The consequences of the transition to collisions of fully stripped ions have been studied in [27]. The positron production cross section is predicted to grow by up to two orders of magnitude. Nearly all created electrons end up in bound states (mostly $1s$ and $2p_{1/2}$). Much of the advantage can be achieved already with fully ionized projectiles impinging on stationary neutral target atoms since here half of the projectile K-holes are transferred to the $1s\sigma$ state. It is expected that collisions of fully stripped ions at energies in the region of the Coulomb barrier will be possible in the future using new experimental possibilities at the GSI-FAIR facility.

5 Collisions with Nuclear Time Delay

When in the course of a heavy-ion collision the two nuclei come into contact, a nuclear reaction can occur that entails a certain *delay time*. For light and medium-heavy nuclei the nuclear attraction can overcome the repulsive Coulomb force, thus allowing for rather long reaction times (up to infinity, if fusion occurs). For very heavy nuclei, however, the Coulomb interaction is the dominant force between the nuclei, so that delay times are typically much shorter, of the order $1 - 2$ zs. (The zeptosecond, $1 \text{ zs} = 10^{-21}$ s, is the appropriate unit for the following discussion.)

A delay in the collision due to a nuclear reaction can lead to interesting modifications in atomic excitation processes. Two main observable effects in such collisions are: (a) interference patterns in the spectrum of δ-electrons, and (b) a change in the number of K-vacancies formed. These phenomena have become known as the *atomic clock effect*, for an overview see [9]

In a simple schematic model for the atomic clock effect, a classical trajectory $R(t)$ for the relative motion of two nuclei is used and the only effect of the nuclear reaction is to introduce a time delay T between the incoming and outgoing branches of the trajectory, most simply described by setting $\dot{R}(t) = 0$ for $0 \leq t \leq T$. It is easy to show that in first-order perturbation theory the resulting excitation amplitude with time delay then reads (assuming elastic scattering)

$$a_{ik}^T(\infty) = a_{ik}(0) - a_{ik}^*(0)\, \mathrm{e}^{\mathrm{i}(E_k - E_i)T} \;, \tag{10}$$

where the energies have to be taken at the distance of nuclear contact. The excitation probability, obtained by squaring this amplitude, is obviously an oscillating function. There are effects smearing out these oscillations and what remains is a partially destructive interference between the incoming and outgoing branches of the trajectory, observable as a decrease in the K-vacancy yield or a steepening of the slope of the low-energy part of the δ-electron spectrum. There have been several experimental studies [28–33] of the effect of nuclear reactions on delta electron emission; evidence for rather short nuclear delay times of the order 1 zs was found.

Nuclear time-delays are of particular interest for supercritical collisions since they have the potential to shift the balance between induced and spontaneous positron production. In a supercritical system an additional coupling between the resonant bound state and the positron continuum states arises, cf. Eq. (8). In the schematic model this leads to (again invoking perturbation theory for simplicity)

$$a_E^T(\infty) = a_E(0) - a_E^*(0)\, \mathrm{e}^{\mathrm{i}(E - E_r)T} - \langle \tilde{\varphi}_r | H | \tilde{\varphi}_E \rangle \, \frac{\mathrm{e}^{\mathrm{i}(E - E_r)T} - 1}{E - E_r} \;, \tag{11}$$

where E_r is the energy of the supercritical state when the nuclei are in contact. The extra term vanishes for $T = 0$, but grows rapidly with increasing T. For delay times considerably greater than 10^{-21} s the additional term in Eq. (11) begins to dominate over the first two terms, causing the emergence of a *peak in the positron spectrum* at the energy of the supercritical bound state. This is illustrated in Fig. 3 which compares the spectra of positrons produced in subcritical ($Z = 164$) and supercritical ($Z = 184$) collisions assuming delay times from 0 to 10 zs. Our coupled channel results [19, 20] recently were confirmed by an independent calculation solving the time dependent Dirac equation using a mapped Fourier grid matrix method [34].

In supercritical systems the positron yield is predicted to increase strongly when the delay time exceeds about 3 zs. Even a small admixture of collisions with very long reaction times might become visible in the positron spectrum and serve as a

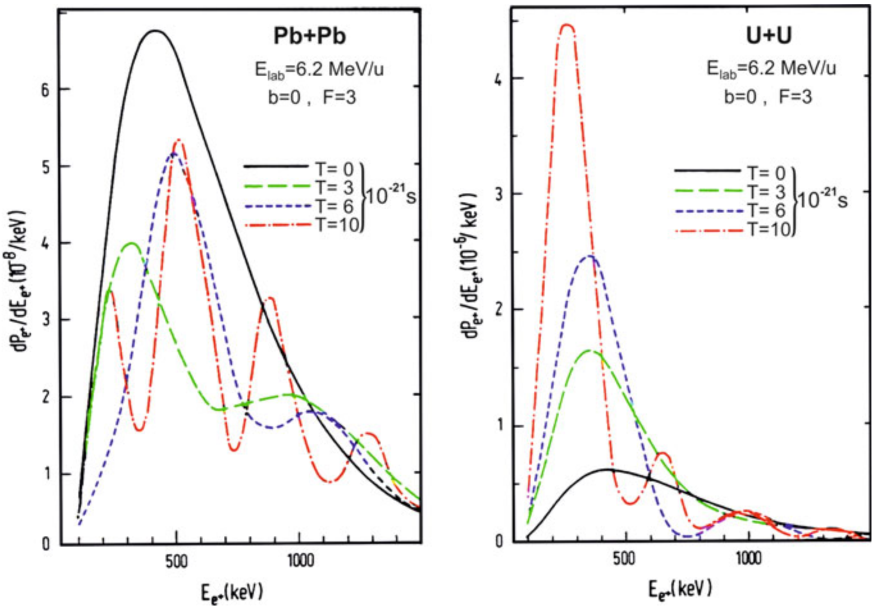

Fig. 3 Positron spectra in central Pb+Pb and U+U collisions at $E_{\mathrm{lab}}/A = 6.2$ MeV assuming various nuclear delay times. The subcritical system displays destructive interference while in the supercritical system spontaneous positron production leads to the build-up of a *peak* in the spectrum [19, 20]

proof for spontaneous positron creation, since this mechanism acts as a "magnifying glass" for long delay times [19, 20, 35].

The most obvious mechanism for obtaining long reaction times would be the presence of an attractive pocket in the internuclear potential in which the dinuclear system could be trapped. In lighter nuclear systems this phenomenon is known to lead to the formation of nuclear molecules which can undergo several revolutions. For heavy systems like U+U it appears that the conditions for a potential pocket are not met because of the strong Coulomb repulsion.

Up to now no conclusive theoretical or experimental evidence exists for long nuclear delay times in very heavy collision systems. However, based on widely different methods, several recent works from nuclear reaction theory, which we will briefly review in the following, hint at the possibility of prolonged reaction times.

Maruyama et al. [36] have performed dynamical microscopic simulations for Au + Au collisions using the method of constrained molecular dynamics (CoMD). This model is based on solving the classical equations of motions for the nucleons, described by Gaussian wave packets, complemented with a constraint which to some extent accounts for quantum effects, i.e., Pauli blocking and Fermi motion. In their CoMD simulations at low energies the authors observe a reaction type somewhat between deep-inelastic and molecular resonance scattering, where an elongated di-nuclear system persists for a considerable life-time. The available experimental information does not constrain the parameters of the model sufficiently so that no unique predictions can be made. For certain parameter sets the CoMD model predicts reaction times of more than 10 zs, being largest at $E_{\rm lab} = 10$ MeV/u.

Tian et al. [37] have performed another microscopic study based on quantum molecular dynamics. Their ImQMD model treats the mean field and collision term properly and approximates antisymmetrization using a phase space occupation constraint. Shell effects, the spin-orbit force and groundstate deformation are not included. Caused by strong dissipation and the shape of the single-particle potential, the ImQMD model predicts a prolonged lifetime of the giant dinuclear system. Example for ^{238}U+^{238}U collisions at $E_{\rm lab}/A = 9$ MeV the average lifetime of the composite nuclear system is predicted to be 4 zs.

A different kind of microscopic simulation of ^{238}U+^{238}U collisions was presented by Golabek and Simenel [38, 39]. These authors performed a fully 3D Time Dependent Hartee-Fock (TDHF) calculation using a Skyrme energy density functional. On this basis, collision times of up to 4 zs were predicted, with a maximum at $E_{\rm lab}/A = 10$ MeV. The temporal evolution was found to be quite sensitive to the relative orientation of the strongly deformed uranium nuclei, with belly-to-belly configurations showing the longest reaction time.

Zagrebaev et al. [40–42] studied the problem using a macroscopic dynamical model based on the solution of Langevin-type equations for the motion of the two interacting overlapping nuclei, including dynamical deformation and orientation. To describe the production of superheavy elements, a description of the de-excitation of the two excited primary fragments via fission or light-particle emissions was added. The method has been applied to collisions of ^{238}U+^{238}U, ^{238}U+^{248}Cm, and ^{232}Th+^{250}Cf, leading to a good description of available experimental data on the production of superheavy elements.

Analyzing the time-dependence of the reaction ^{238}U+^{248}Cm at 800 MeV c.m. energy ($E_{\rm lab} = 6.6$ MeV/u) Zagrebaev et al. [40–42] found a sizable fraction of events with nuclear contact lasting for 10 zs or longer, see Fig. 4. Although the employed internuclear potential does not exhibit a pocket, it is found that owing to nuclear viscosity the system moves through the multidimensional potential surface with almost zero kinetic energy. Bombarding energies directly at the Coulomb barrier are found to be best suited to achieve long reaction times. The predicted absolute cross section for long-lasting reactions (> 10 zs) is be about 0.5 millibarn.

Since the majority of nuclear reactions proceed on a short time-scale, a trigger for delayed collisions will be needed when searching for signs of spontaneous positron production. Zagebaev et al. [40–42] suggest looking for the most strongly damped collisions (highest loss of total kinetic energy), (Fig. 4c) in conjunction with small deflection angles (Fig. 4d). A further promising trigger is the selection of large mass transfer (Fig. 4b). The emerging fragment will be highly excited and in most cases will undergo fission. However, there is a chance that fragments in the region of the doubly magic lead nucleus ^{208}Pb (30 nucleons transferred from uranium) will cool down by nucleon evaporation and survive. Zagrebaev et al. suggest searching for outcoming Pb-like nuclei at c.m. angles less than 60° as the most promising trigger to select for reactions with long delay times.

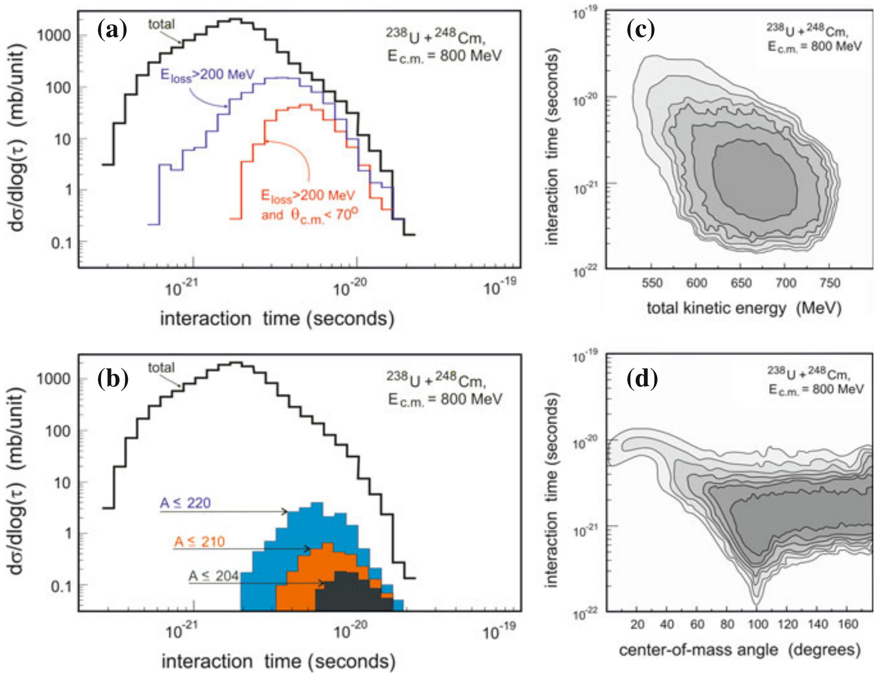

Fig. 4 *Left:* **a** Calculated distribution of reaction times in $^{238}U+^{248}Cm$ collisions at 800 MeV c.m. energy. The two *lower curves* refer to a selection collisions with large total kinetic energy loss $E_{\rm loss} > 200$ MeV and in addition a selection in *scattering angle* $\theta_{\rm cm} < 70^0$. **b** As *above*, but with cuts in the mass number A of the emitted fragment. *Right*: Contour plots of reaction times versus **c** total kinetic energy or **d** c.m. angle. The lines are drawn on a logarithmic scale over one order of magnitude, the quasi-elastic peak is removed. Results taken from Zagrebaev et al. [40–42]

Because of the small cross sections and large backgrounds involved, performing positron spectroscopy under these conditions requires a dedicated experimental effort. From the theoretical side, one should perform calculations of positron production using realistic time-dependent nuclear charge distributions predicted by nuclear reaction models, including trigger conditions for long reaction times and averaging over many collisions. Whether this will produce a robust signal which stands a chance to overcome the inevitable experimental backgrounds is an open question. However, such studies may hold the key for finally identifying the decay of the vacuum of QED.

6 Summary

Quantum Electrodynamics of strong fields offers a "clean" laboratory where a fundamental quantum field theory can be studied theoretically and tested through experiment. A particularly interesting prediction is the decay of the neutral vacuum in the presence of strong external Coulomb fields. Collisions of very heavy ions provide an opportunity to realize this situation experimentally, although impeded by the short duration of these collisions. Inner-shell hole production, δ-electron emission, and positron creation all are sensitive to the strong electric fields. These processes have been studied experimentally in great detail and are well described by theory. There is clear evidence for a rapid growth in binding energy and strong localization of inner shell orbitals in high-Z systems.

The goal to detect the process of spontaneous positron creation and thus the instability of the QED vacuum in the presence of a supercritial field, however, remains elusive. To overcome the problem posed by the short time scale of supercriticality ($\tau \simeq 10^{-21}$ s) one would need to select collisions in which a nuclear reaction with sufficient time delay occurs. Recent results from nuclear reaction theory give hope that such reactions indeed do occur.

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