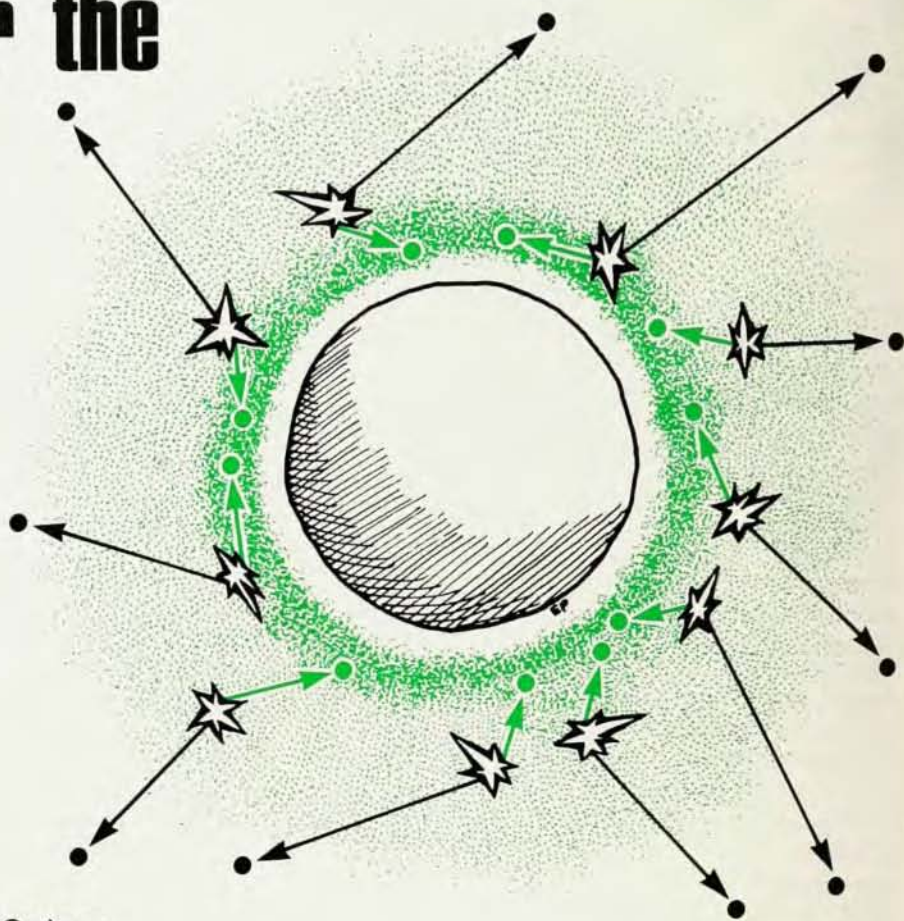


Search for the sparking of the vacuum

The static electric field near a superheavy atomic nucleus may be strong enough to pull electrons and positrons out of the vacuum.



Jack S. Greenberg and Walter Greiner

Our concept of the nature of the vacuum has been evolving for the last 25 centuries. Indeed, some aspects of today's perception of the vacuum, established by modern experimental probes, date back to ancient Greek philosophers.

Quantum mechanics and quantum field theory form the basis of the most recent concepts. In modern terms, the vacuum consists of a polarizable aggregate of virtual particles, fluctuating randomly. The notion of virtual particles is not only a theoretical construct, but directly implies observable effects. Among these are some well-known electrodynamic phenomena:

► One can attribute the spontaneous emission of radiation from atoms and nuclei to the action of the fluctuations of a gas of virtual photons

► Virtual particles, as manifestations of the zero-point motion of the electromagnetic field, account for phenomena such as the Casimir effect, in which two uncharged conducting plates attract each other in a vacuum with a force varying as the inverse fourth power of their separation

► The electrostatic polarizability of the fluctuations of virtual particles is measurable in the Lamb shift and in Delbrück scattering, the scattering of photons by photons

In this article, we consider another interesting aspect of the vacuum associated with quantum field theory. The theory allows for the spontaneous creation of real particles in strong static external fields. Under external fields where this novel process can occur, the normal vacuum state is unstable and decays into a new state that contains real particles (figure 1).

Interest in the theoretical questions inherent in this phenomenon and in the questions regarding the existence of conditions appropriate for its observation goes beyond academic curiosity

for many reasons. The most compelling reason is that laboratory conditions may now be available for observing the instability of the normal vacuum state in strong electric fields.

From the very beginning of relativistic quantum mechanics, there have been considerations of the effects of strong fields and strong binding. Studies of the Dirac equation for an electron bound to a Coulomb field include this problem. As we shall see, the specific relationship between the strong binding and the process responsible for the instability of the vacuum involves the behavior of the Dirac energy-level structure near the negative-energy continuum, which the bound states penetrate as the atomic number Z exceeds $1/\alpha$.

Early work¹ on this subject examined some aspects of the behavior of an electron in the field of a charge of sufficient magnitude to bind the electron by about $2m_0c^2$. In fact, Werner Heisenberg and H. Euler in 1936 predicted² quantitatively the creation of particles by strong static fields of infi-

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Vacuum decay. A bare superheavy nucleus, having created a strong static electric field, is spectator to a spontaneous change in the vacuum that surrounds it. The stable state of lowest energy in that space is no longer the neutral vacuum, but contains real charged particles. Positrons emitted (black arrows) would provide experimental evidence of this "sparking" of the vacuum. Figure 1

nite extension. Even earlier, Otto Klein noted² that the transmission coefficient was anomalously large for electrons incident on a sufficiently high electrostatic barrier.

Only recently, however, have extensive theoretical studies in Frankfurt and independent studies in the Soviet Union led to new insight and full theoretical clarification of the strong-field problem.³ The work of the Frankfurt school in particular has stimulated most of the recent inquiries into these questions—both theoretical and experimental. Of central importance is the suggestion that superheavy quasiatoms, formed in collisions between heavy atoms, can serve as a vehicle for examining superheavy atomic systems and for observing the spontaneous breakdown of the vacuum state.

Our discussion will center on some theoretical aspects of the stability and decay of the electron-positron vacuum, and on recent experimental efforts to observe its decay. We will consider how superheavy quasiatoms are used to investigate this phenomenon and, in a more general sense, how such collision systems supply information on the structure of superheavy atoms. The experimental picture is yet to be completed, but it has reached a sufficient level of development to promise interesting future results. One possibility is that the positron spectrum may provide evidence for the formation of superheavy metastable nuclear complexes with atomic numbers more than twice that of uranium. Moreover, the spectrum may be utilized to probe the properties of such systems.

The unstable vacuum

A good starting point for a discussion of the instability of the vacuum to positron emission is to consider the binding energy of atomic electrons as the nuclear charge is increased. For a point nucleus of charge Ze , the spectrum of solutions of the Dirac equation is given by the well-known Sommerfeld fine-structure expression

$$E(n, j) = m_0 c^2 \left[1 + \left(\frac{Z\alpha}{n - |K| + [K^2 - Z^2 \alpha^2]^{1/2}} \right)^2 \right]^{-1/2} \quad (1)$$

where α is the fine-structure con-

stant $e^2/\hbar c$, and n and K take on integer values: $n = 1, 2, \dots$; $K = j + 1/2 = \pm 1, \pm 2, \dots$. The dashed lines in figure 2 show as a function of Z the corresponding energy-level spectrum for some states of lowest total angular momentum j . Equation 1 and figure 2 display several interesting features as we move into the region of high Z .

On the scale of the $2m_0 c^2$ energy gap in which the bound-state solutions are allowed, the energy levels vary slowly with increasing Z ; the deviation from the upper continuum becomes appreciable only as Z approaches $1/\alpha$, or about 137. Thus, even in the heaviest man-made element to date, with $Z = 107$, the binding energy of the K-shell electron is only a small fraction of the rest mass.

We also see that a problem arises with equation 1 when the value of Z approaches $1/\alpha$. Because of the term $[K^2 - Z^2 \alpha^2]^{1/2}$, the equation breaks down when $Z\alpha > |K|$. No solutions with $j = 1/2$ are found beyond $Z = 137$. When Z is 137, the binding energy for the $1s_{1/2}$ states is equal to the rest mass of the electron. This so-called " $Z = 137$ catastrophe" has for some time been well-known to be associated with the assumption that the nucleus is point-like, and some aspects of this problem were solved by taking into account the fact that the nucleus has an extended charge distribution.¹ The solid lines in figure 2 show solutions of the Dirac equation for a nucleus of finite size. For $Z > 1/\alpha$, and nuclei of finite size, the energy-level structure fills the full energy gap.

But merely taking into account the finite size of the nucleus does not resolve the basic questions posed by the "catastrophe" at $Z = 137$; it only postpones them to reappear at a higher Z_{critical} —approximately 173. There are no undue difficulties associated with tracing the energy levels $E(n, j)$ as Z increases to the value Z_{cr} , where the levels encounter the negative-energy continuum. The problem is describing what happens when the number of protons increases beyond Z_{cr} . This critical charge marks the threshold for the onset of qualitatively new, unexplored phenomena. Our calculation of its exact value, however, depends on many assumptions concerning the radius of the nucleus and the potential in its vicinity.

Theory tells us that the bound $1s$ electron state ceases to exist as it joins the negative-energy continuum, and instead develops into a resonance as it is shared by the continuum states. The width of this resonance grows with deeper penetration into the negative-

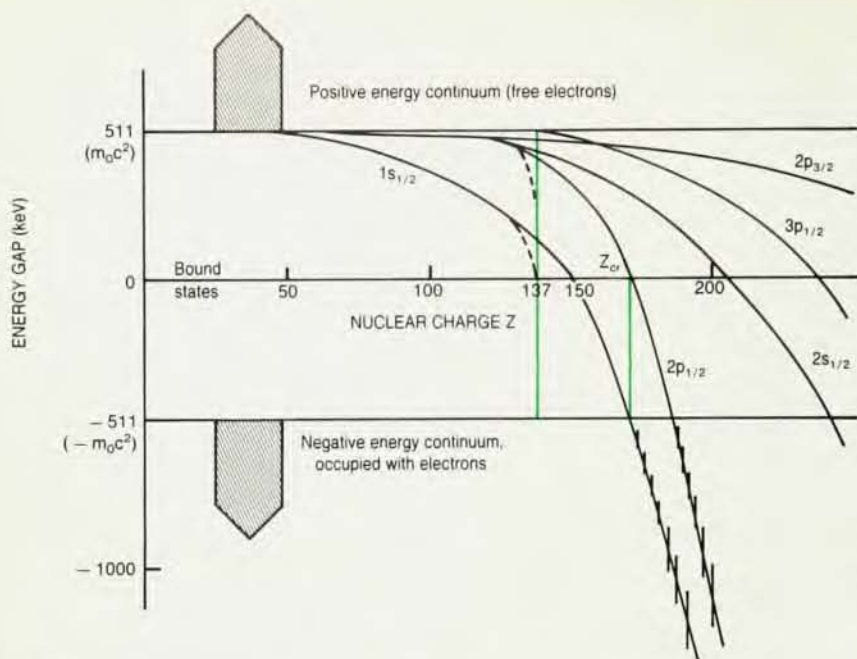
energy continuum, as Z increases beyond Z_{cr} . Although the resonance spreads in energy, the electron charge distribution remains localized. If Z is not much larger than Z_{cr} , we can visualize this charge distribution as resembling that of a bound $1s$ state in the energy gap just above $-m_0 c^2$.

The energetics when Z is greater than the critical value give us some insight into the physical consequences of overcritical binding: Figure 2 indicates that when Z exceeds about 145, the energy of the $1s_{1/2}$ state is negative. Thus the binding energy for this orbital exceeds the rest-mass energy of the electron. If this orbital is not occupied, it would be energetically advantageous to create spontaneously an electron in the $1s_{1/2}$ state, thereby reducing the total energy of the electron-nucleus system. Of course, this process is forbidden because it would violate both charge and lepton conservation. However these restrictions are absent when K-shell electrons are bound by more than $2m_0 c^2$. Then electron-positron pair creation is favored energetically and, with a hole in the K-shell, the spontaneous appearance of such a pair is not forbidden by any conservation law. The electron would bind in the $1s_{1/2}$ hole and the positron would escape.

Because of the spontaneous filling of the K-shell, the lowest energy state for overcritical potentials is qualitatively different from that existing when $Z < Z_{\text{cr}}$. The space surrounding the nucleus can never be free of charges. Thus, the vacuum—the lowest-energy stable state—is charged for the overcritical field. (In considering the "vacuum" here, the nucleus plays the role of a spectator.)

The spark

As figure 3 indicates, after K-shell ionization, an atom of atomic number greater than 173 will always shield itself spontaneously with two K-electrons (real vacuum polarization charge) while emitting positrons of rather well-defined energy. This two-electron state becomes the lowest energetically stable state for an atom with a supercritically bound $1s_{1/2}$ state; calculations show that it forms on a time scale of 10^{-19} seconds, corresponding to the width of the resonance state referred to above. As the central nuclear charge is increased arbitrarily, so that successive bound states $1s_{1/2}$, $2p_{1/2}$, $2s_{1/2}$, ... join the negative-energy continuum, successive phase transitions occur in which the vacuum increases its negative charge. Thus the vacuum "sparks" in overcritical fields, and the resulting charged vacuum is a new ground state.



Lowest bound-state energy solutions of the Dirac equation, as a function of the nuclear charge Z . Sommerfeld energy levels (dashed curves) for $j = 1/2$ terminate with $Z = 137$. But for nuclei of finite size (solid curves) the solutions enter the negative-energy continuum, which they first join at a critical charge Z_{cr} . In the negative-energy continuum the bound states become resonances; these are shown magnified in the schematic diagram. Figure 2

Some theoretical work has addressed questions regarding the possibility that there are effects that may prevent the states from diving into the negative-energy continuum, so that there would be no spontaneous decay. These considerations include³ the effects of vacuum polarization, electron self energy, non-linear electrodynamics and even non-linearities in the Dirac field itself. To date, these studies have found that although the various effects modify Z_{cr} by a few percent, there is no way to prevent the monotonic increase of the binding energy to $2m_0c^2$ without simultaneously contradicting the existing precise experimental data on stable atoms.

With this knowledge of the conditions for overcritical fields, we can revisit the point nucleus to obtain a consistent understanding of what we previously referred to as the "catastrophe" at $Z = 137$. We begin with an extended nucleus and examine the atomic structure as the nuclear radius shrinks. With decreasing radius, all the $1s_{1/2}$ and $p_{1/2}$ states meet the negative-energy continuum at lower values of Z . As each level dives, the vacuum assumes a successively higher charge. In the limit of $Z = 137$ for a point nucleus, the vacuum charge becomes infinite and has to be treated self-consistently. But because of the electron-electron interaction, there is a self-screening of the vacuum, stabilizing the vacuum at a finite charge. The Frankfurt group has found⁴ that the

charge of a point particle cannot exceed 137 because any surplus charge initially present is screened by the overcritical vacuum. Thus in nature there cannot be point-like charged objects with effective coupling constants $Z\alpha > 1$. The divergences given initially by the potential outside, $V(r) \propto 1/r$, disappear through a change in the vacuum such that the singularities are smeared out and thereby removed.

The decisive experiments to probe all these new aspects of quantum electrodynamics associated with overcritical binding involve the observation of the spontaneously emitted positrons. It is clear that such experiments require atoms with $Z > 173$ and inner shells that are unoccupied. Although the effort continues, attempts to synthesize superheavy nuclei in nuclear reactions have not been successful or even very promising, and the possibility of forming stable superheavy nuclei with as many as 173 protons appears to be very remote. But as we noted above, the new essential idea in this field was that one might use heavy-ion collisions to form transient superheavy "quasimolecules."

Fields in quasimolecules

The basis of quasimolecule formation in heavy-ion collisions is the disparity between the nuclear collision velocities and those of the orbiting electron. For a uranium ion colliding with a uranium atom, the relative velocity required to bring the nuclei into contact is approxi-

mately $0.1c$. Thus, for the fast-moving inner-shell electrons, whose velocities are close to c , the Coulomb potential of the colliding nuclei varies sufficiently slowly for the electrons to adjust adiabatically. At small internuclear separations, well within the electrons' orbiting radii, the electrons cannot distinguish between the two nuclear centers, so they act as if they were bound by all 184 protons of the two nuclear charges. Thus, we expect the electrons to evolve through a series of well defined quasimolecular states in the two-center field as the internuclear separation decreases and then increases again.

Some aspects of the solutions of the two-center Dirac equation are especially relevant to the process of spontaneous positron emission. Clearly, a critical parameter is the internuclear separation R_{cr} at which the electron binding energy exceeds $2m_0c^2$. Calculations show that for the Pb-Pb and Pb-U collision systems, overcritical binding is not allowed for any internuclear separation. For the U-U collision system, the predicted critical separation is about 30 fm; this increases to about 45 fm for the U-Cf system. Confining ourselves to Rutherford trajectories, these values for R_{cr} imply that the necessary conditions for the study of overcritical phenomena are fulfilled for ion bombarding energies of about 4 to 6 MeV/nucleon.

Therefore, we can readily visualize how the formation of superheavy quasimolecules can be a vehicle for observing the spontaneous emission of positrons. Figure 4 shows a schematic representation of the time evolution of an ion-atom collision, the associated energy-level structure and the atomic excitation and deexcitation processes. Focusing on the deepest lying $1s\sigma$ molecular orbital, we see that during the collision the potential binding changes from the undercritical value, due to the nuclear charge Z , to the overcritical value, due to the charge $2Z$. Just as we would expect spontaneous positron emission from a stable superheavy atom, we expect spontaneous positron emission to occur in the collision system during the brief time when the binding is overcritical. The collision itself supplies the necessary $1s\sigma$ vacancy by ionizing $1s\sigma$ electrons in the time-dependent electric fields produced by the nuclear motion. We expect a positron yield of about 1% of the $1s\sigma$ vacancy production.

Thus, it would seem that if this were the only process involved, demonstrating spontaneous positron emission should not be too difficult a task. One would select various collision energies or various values of the total Z of the collision system, and proceed systematically from undercritical to overcritical.

cal binding. However, there is a very basic difference between a static superheavy atom and a dynamic simulation of a superheavy atom. The same nuclear motion that provides the crucial $1s\sigma$ vacancies engenders additional electron-positron pair production processes, which also operate by way of the time-dependence of the electromagnetic potentials in the collision. In fact, the dynamic effects play an essential role in all quasimolecular phenomena, and understanding them in detail is a critical aspect of the use of heavy-ion collisions to study overcritical binding phenomena. Such effects enter in the ionization processes that are the precondition for the spontaneous emission of positrons, but they are also a prominent feature of the deexcitation modes, such as molecular orbital x-ray emission and positron emission.

Dynamical processes

Our access to information on the effects of strong binding in quasimolecules begins with the ionization processes involving the inner shells. While the excitation process leads to delta electron emission—the ejection of inner-shell electrons—the deexcitation of the vacancy can occur through the emission of characteristic x rays, Auger electrons, molecular-orbital x rays and positrons, all of which we can treat as experimental probes. Figure 4 illustrates these processes schematically for a time-varying potential that becomes overcritical at small distances.

In the molecular description of the excitation processes, the time variation of the initial quasimolecular states induces the ionization and excitation of the electrons. Both a radial variation and a rotation of the internuclear axis are involved, so that the transitions are induced by a radial as well as a rota-

tional coupling. The latter is the familiar Coriolis coupling. The two types of transitions display different radial dependence and different selection rules. In the last 100 fm of approach—when the levels begin to penetrate into the negative-energy continuum—radial coupling becomes the dominant term for the $s_{1/2}$ and $p_{1/2}$ states. This is the region where electrons are kicked out and positrons are produced dynamically—features of superheavy systems that are not found in collisions of light systems. Of particular relevance are the rapid increase of the two-center binding energy as the internuclear separation becomes small, and the rapid relativistic collapse of the electron distribution about the nuclear centers. These properties lead to large radial transition matrix elements, which dominate at small internuclear separations.

It bears emphasis that several dynamical processes contribute to the production of positrons in undercritical as well as in overcritical collision systems.³ Process **b** in figure 4, the spontaneous filling of a previously-produced vacancy when the level acquires a binding greater than $2m_0c^2$, is the vacuum decay that we described earlier. The time-varying electric fields introduce other sources of positron production. In fact, as the transitions represented by **c** and **d** in figure 4 indicate, the same matrix elements responsible for ionization of bound electrons lead to the creation of positrons.

Process **c**, by drawing energy from the nuclear motion, leads to the filling of a vacancy even at distances larger than R_{cr} . This effect occurs in second order and may be called "induced production." Its influence on the production of positrons is twofold: It obscures the threshold that would be associated

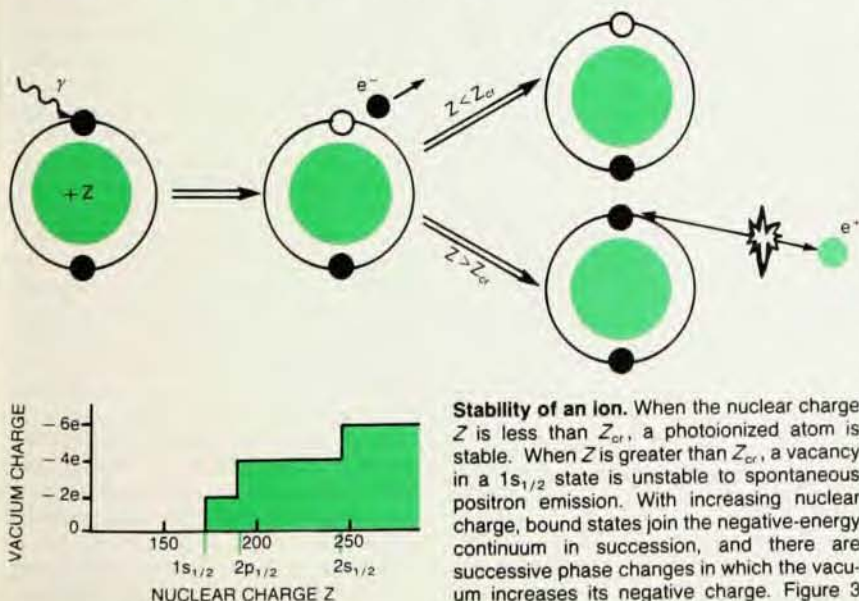
with spontaneous positron production alone, and for pure Rutherford scattering trajectories, it greatly enhances the production cross section over that expected from the spontaneous process.

Direct pair production, represented by process **d** in figure 4, is well known in the scattering of light charged particles. But in our case the very strong two-center electromagnetic field of the slowly moving nuclei distorts the continua strongly. As a result, this process is especially non-perturbative (unlike, say, proton-proton scattering), and it exhibits a cross section that scales approximately as $(Z_1 + Z_2)^n$, with $n \approx 20$. Like the mechanism of induced decay, it can overwhelm the production process for spontaneous positrons, for collisions below the Coulomb barrier.

Positron spectrum. We can study the induced and direct processes in isolation because they both occur in undercritically bound states. Calculations show that the spectrum from the total of direct and induced emissions, taken alone, reflects the considerable spread in Fourier frequencies characteristic of the collision velocity. This spectrum differs considerably from the nearly monoenergetic spectrum we would expect from spontaneous positron emission alone, in a quasistatic situation. Unfortunately, the collision dynamics also broaden the spontaneous spectrum, so we expect that in general the coherent sum of all three processes will produce a broad spectral distribution that differs by only 5–10% of the subcritical case.

Therefore, these calculations indicate that the only way we can identify a contribution from spontaneous emission to the positron spectrum is by way of detailed quantitative comparison with theory; spontaneous emission has no clear quantitative signature for collisions involving only Rutherford trajectories. In fact, for such scattering we expect any of the other measurable features of positron emission, such as the probability of emission as a function of the distance R_{min} of closest approach between the nuclei, to make the transition from subcritical and overcritical systems without showing any prominent signature to identify the change.

The subordinate role played by the spontaneous component in the sub-Coulomb collisions is clearly an outgrowth of the short collision time, which does not allow the spontaneous amplitude to develop. For this reason Johann Rafelski, Berndt Müller and Greiner suggested⁵ that one could enhance the effect of the spontaneous amplitude by taking advantage of time delays that may be associated with nuclear reactions. Figure 5 illustrates the idea. If two colliding ions stick



together for an extended period Δt before separating again, the time spent by the quasimolecular levels in overcritical binding is correspondingly prolonged. During the sticking time, the energies of the electronic states do not change, in the limit that a static nuclear shape is maintained. Two important consequences follow.⁶

► If vacant overcritically bound states are present, a clear peak should develop for spontaneous positron emission as the spontaneous amplitude grows with time (figure 5b).

► Even without the occurrence of overcritical binding, the positron spectrum should exhibit an oscillating structure as a function of positron energy (figure 5c). This reflects the delayed interference between incoming and outgoing induced-positron-production amplitudes along the trajectory of the colliding ions.

The longer the sticking time, the more relevant is the static approximation we discussed earlier, so that for Δt sufficiently long, the positron spectrum develops a sharp line structure reflecting the natural lifetime of the resonant positron-emitting state (about 3 keV for the U-U system). It bears emphasis that in addition to providing the qualitative signature for the spontaneous decay of the vacuum, the observation of a sharp line would also be a strong

indication that we are forming superheavy nuclear systems with $Z > 180$. Moreover, we might be able to exploit the oscillating structure as a fast atomic clock that gives information on the sticking time. The exciting possibility then presents itself that the positron spectrum may be a sensitive probe of the nuclear properties of the short-lived exotic nuclei.

Experimental search

The search for spontaneous positron emission in heavy-ion collisions began in 1976 with the first acceleration of uranium beams at Gesellschaft für Schwerionenforschung (GSI) in Darmstadt, West Germany. Experiments at this laboratory have utilized three detection systems, which have pursued complementary aspects of the problem.^{7,8,9} We should note that in connection with these experiments it was necessary to establish that the conditions for forming quasimolecules could be met for the nuclear velocities required to achieve internuclear separations sufficiently small to produce overcritical binding. It was also critically important to demonstrate that the production probability for $1s\sigma$ vacancies was both large in magnitude and concentrated at small internuclear separations.

Now let us consider briefly some of

the experimental investigations bearing on the two latter questions about the production of $1s\sigma$ vacancies.

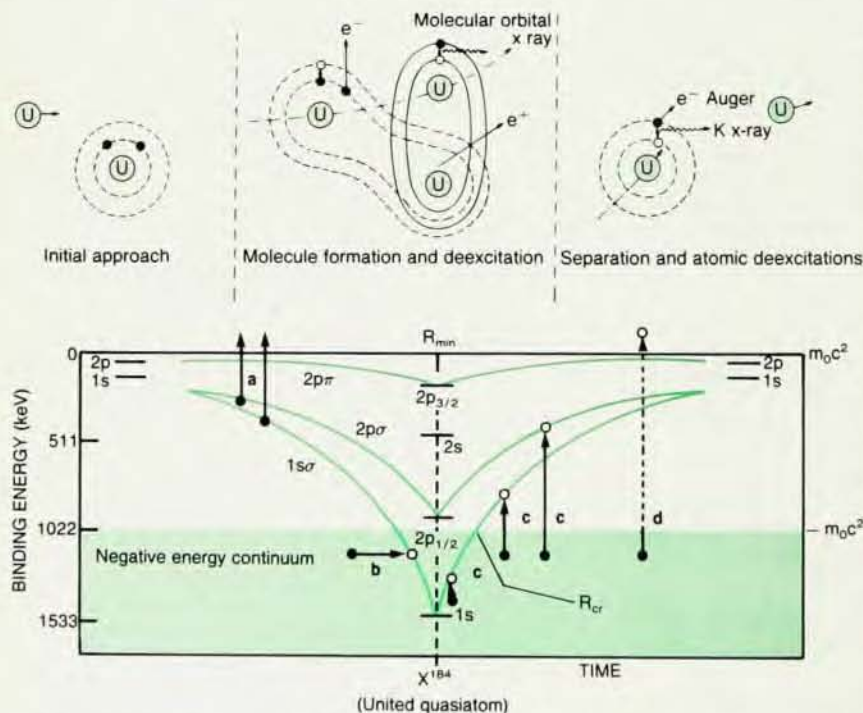
Delta electrons. Measurements of the emission of electrons in the ionizing process have long been a source of information on atomic wavefunctions. In particular, the energy distribution of the so-called delta electrons ejected from the inner shells provides a measure of the momentum of the ionized state. For superheavy collision systems the quasimolecular picture of the collision anticipates that the delta-electron spectrum will contain high-energy components, with appreciable intensity. This reflects both the relativistic shrinkage of the atomic space by the deep binding potentials and the focusing of the ionization near R_{min} . In general, if there are significant electronic structures within about 100 fm of the nuclear centers (as is expected for quasiatoms with $Z_1 + Z_2 > 150$), then we expect delta electrons with energies greater than 1 MeV to appear with a measureable probability.

In fact, experiments¹⁰ show this characteristic in delta-electron emission from Pb^{208} - Pb^{208} collisions. Studies of other collision systems also indicate that we are dealing with the bound states of the quasimolecule and not atomic states of the individual collision partners, at least for the inner shells.

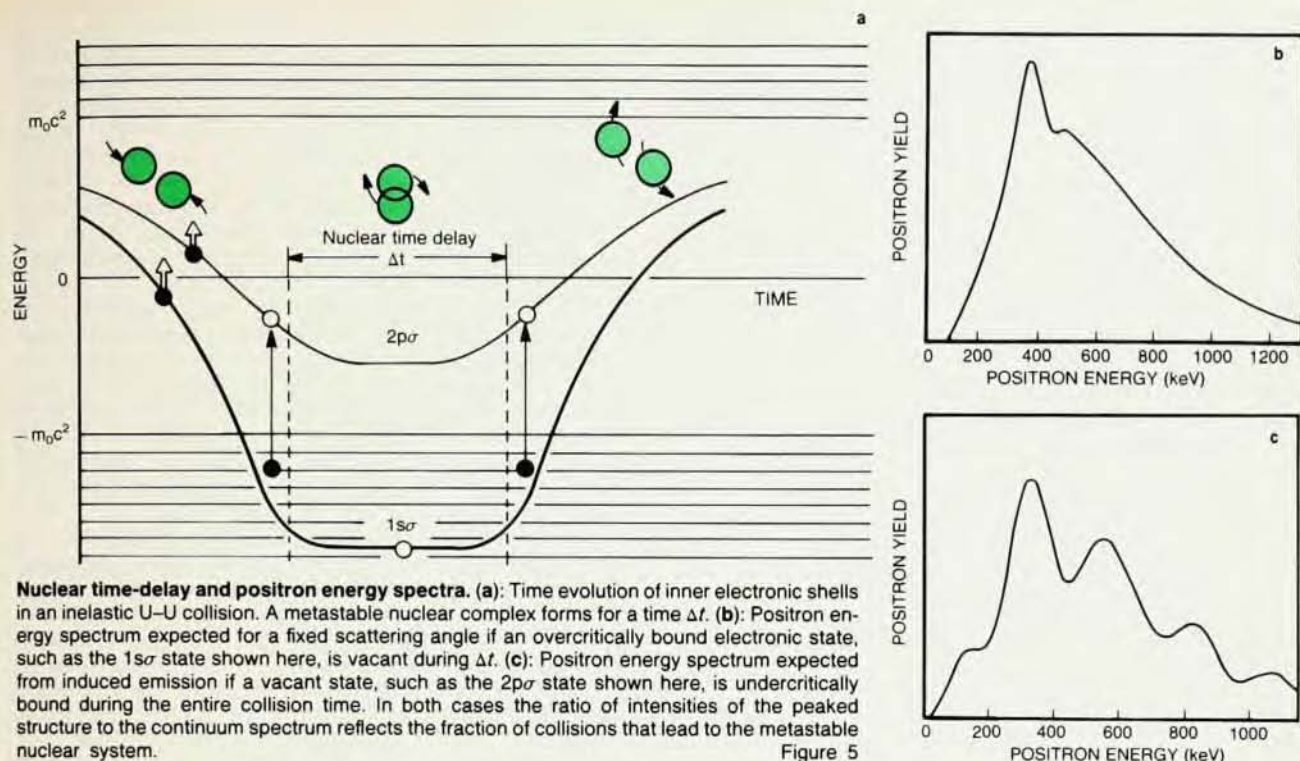
Molecular-orbital x rays. Of all the experimental approaches to investigating quasimolecular phenomena, one would expect that the direct observation of the radiative transition of electrons between molecular orbitals during the collision would perhaps provide the most straightforward demonstration of the formation of quasimolecules and the most direct information on their structure. A multitude of experiments have pursued this goal.¹¹

We expect the energy distribution of molecular-orbital spectra to form a continuum because the binding energies of the molecular orbitals vary smoothly with internuclear separation, changing from the energies associated with the separated atom to those appropriate to the united atom. In fact, such spectra are seen for projectiles and targets spread over the whole periodic table. But although the upper-energy limits of those spectra roughly scale with the K x-ray transition energies corresponding to an atom with united nuclear charge ($Z_1 + Z_2$), it is difficult to establish a quasiatom's spectroscopic signature because of the dynamic collision broadening of the spectra. For this reason, people have sought more convincing evidence that the continuum spectra seen in ion-atom collisions is properly identified with quasimolecular transitions.

One unambiguous signature came with the discovery of a unique charac-



Time evolution of the electron energy-level structure during a uranium-uranium collision. Schematic diagram shows the processes of atomic excitation and deexcitation. In the graph, time increases to the right. Energy levels of the separated atoms appear at the upper left and right. When the uranium nuclei are within R_{cr} (about 30 fm) of each other, the $1s\sigma$ level is embedded in the negative-energy continuum. In the process labeled **a**, the collision causes ionization. Processes **b**, **c**, and **d** are mechanisms of positron production: spontaneous emission, induced emission into bound states and direct induced emission into continuum states. Figure 4



Nuclear time-delay and positron energy spectra. (a): Time evolution of inner electronic shells in an inelastic U-U collision. A metastable nuclear complex forms for a time Δt . (b): Positron energy spectrum expected for a fixed scattering angle if an overcritically bound electronic state, such as the $1s$ state shown here, is vacant during Δt . (c): Positron energy spectrum expected from induced emission if a vacant state, such as the $2p$ state shown here, is undercritically bound during the entire collision time. In both cases the ratio of intensities of the peaked structure to the continuum spectrum reflects the fraction of collisions that lead to the metastable nuclear system.

Figure 5

teristic of quasimolecular radiation: an anisotropic emission that depends on the frequency of the x rays in a very clearly defined manner.^{11,12} A further important step toward identifying the molecular-orbital radiation was the verification¹³ that the velocity of the emitting system corresponds to the center-of-mass velocity of the quasimolecule. In these and other experiments, the study of molecular-orbital x rays has played a very important historical role in bringing about confidence in quasimolecular formation in heavy-ion collisions.

Inner-shell vacancies. Much of our quantitative knowledge of the properties of strongly bound quasimolecular states come from experiments on inner-shell ionization. These experiments also address specific questions concerning $1s$ excitation. They indicate that the theory based on the quasimolecular picture of the collision is correct in most aspects of its predicted inner-shell excitation cross sections.

For example, experiments demonstrate¹⁴ that the cross sections for the production of K vacancies in very heavy collision systems are indeed large compared to the millibarn cross sections predicted by extrapolating the nonrelativistic calculations that are valid for lighter collision systems. This confirms the important role of relativistic effects in the ionization process, and it implies the participation of the very strongly bound quasimolecular levels in the excitation mechanism. Moreover, we know¹⁵⁻¹⁷ that not only is the probability for $1s$ ionization large,

but that it occurs at small internuclear separations, as required for the process of spontaneous positron emission.

In general, calculations reproduce¹⁶ the measurements very well once we include electron screening and multi-step processes of excitation to bound states and to the continuum. Such success not only confirms our general understanding of the ionization process, but is obviously an important first step toward being able to predict positron emission in heavy-ion collisions.

Positron detection experiments

The experiments noted above support theoretical expectations for the formation of superheavy quasiatoms with deeply bound $1s$ states. Also, they support the predictions for the production of $1s$ vacancies with the desired properties. But we are left with the task of finding evidence for spontaneous positrons in a complex spectrum generated by the dynamic mechanisms discussed above and by other background sources.

The experimental approach to the problem is dictated by the need to detect a small cross section in an overwhelming radiation field of γ rays, delta electrons and nuclear constituents such as neutrons. To meet this challenge, the experiments⁷⁻⁹ employ detection systems very sensitive to primary positrons, and relatively insensitive to positrons from secondary processes, such as external pair creation by electrons and γ rays.

The three primary features of the detection devices are a magnetic trans-

port system that removes positrons from the area of the collision and sends them to an area of low background where they can be identified by their annihilation radiation, a system that discriminates against transporting electrons to the same area and a device to measure the positron energy spectrum. To determine parameters of the reaction kinematics— $R_{\min}$, for example—the spectrometers typically employ one or more heavy-ion detectors to monitor the scattered nuclear products. A precise definition of the kinematics of the scattered ions is an essential part of the measurements, particularly if nuclear reactions contribute to the scattering process. The various experiments carried out to date have achieved this kinematic identification with differing degrees of completeness.

One of the first experimental goals in the search for spontaneous positron emission was to determine the rate at which positrons are produced from the atomic processes relative to the rate at which they are produced from nuclear effects such as internal pair conversion of nuclear transitions. The first measurements⁸ on the $\text{Pb}^{208}\text{-Pb}^{208}$ collision system played a particularly important role in this respect and in confirming our theoretical understanding of the dynamic processes of positron production in heavy-ion collisions. In this particular collision system the nuclear background is especially simple to evaluate. It is associated with a well-known excitation mechanism and known energy levels, so that it can be

simulated exactly.

Figure 6 shows the results of an experiment⁸ on the Pb-Pb system. This experiment was the first convincing demonstration that positron production in heavy-ion collisions originates with the electronic quasimolecular complex and not with the nuclear structure alone. In fact, the nuclear component is only a fraction of the total positron yield, particularly at large values of R_{min} . This is in good agreement with the theory,¹⁸ as is the exponential fall-off of the cross-section with R_{min} within distances of a few nuclear diameters. These experimental results stress that the mechanisms of positron production are closely associated with the strong relativistic concentration of the electronic flux around the nuclear centers, as we would expect for the high- Z quasimolecular complex.

Measurements⁹ on Pb-U and U-U collisions have carried these investigations into heavier systems, but under different and more complex background conditions. To investigate the consequences of this nuclear background in more detail, researchers carried out a systematic investigation of the ratio of positron intensity to γ -ray intensity over a broad range in Z . Figure 7 illustrates the interesting qualitative observation that emerged from these studies.^{7,9} When Z_u , the combined nuclear charge $Z_1 + Z_2$, exceeds about 160, there is a spectacular increase in the total positron yield over that expected from nuclear internal pair conversion as it is extrapolated from the positron to γ -ray ratios measured for $Z_u < 160$. More precisely, for constant R_{min} and relative velocity, the production of positrons in superheavy collision systems is found to increase as $(Z_1 + Z_2)^{21}$. In this striking feature, which seems to have no other analog in nature, the theory¹⁸ of dynamic positron creation in heavy-ion collisions again anticipated the experimental results.

In fact, the first experiments did not reveal any surprises. Although one would expect the U-U system to produce overcritical electron binding for some of the bombarding conditions used, there were no anomalous deviations from the positron production rates predicted from the dynamic mechanisms. Nothing unusual and unexpected happened as scattering angles were reached corresponding to internuclear separations smaller than R_{cr} . Moreover, although these experiments gave us increased confidence in our understanding of the dynamic processes of positron production, they also indicated that a signature for the spontaneous emission of positrons was not going to be readily forthcoming—at least not in gross features such as the angular distribution of the total positron excitation probability. The search

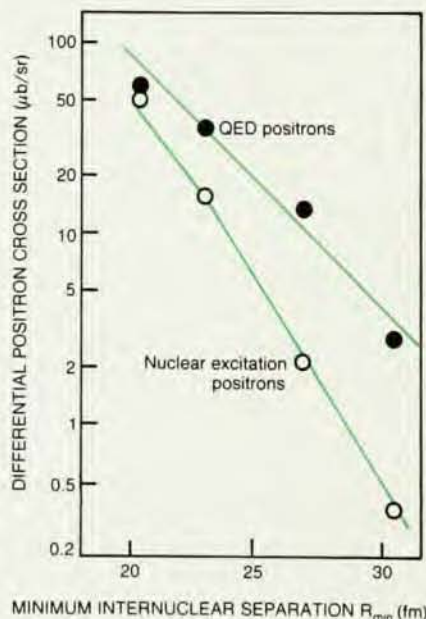
for such a signature, then, has evolved naturally into the examination of finer details of the positron emission process.

Recent experiments

The most recent experiments¹⁹⁻²² have focussed on studying positron spectra and on extending the investigations to collision systems with higher total nuclear charge. With more comprehensive data, new phenomena have appeared that may be connected with the effects being sought. Of special interest are peak-like structures in the positron energy distribution. The most compelling evidence for these comes from experiments^{19,22} where coincidences between two scattered ions are used to define clearly events with two-body final states consistent with, or bordering on, elastic scattering. We illustrate these interesting results with an example.

The uranium-curium collision system, with $Z_u = 188$, has the largest combined nuclear charge investigated to date. Figure 8 shows positron spectra from uranium-238 and curium-248 colliding at an energy close to that of the Coulomb barrier.²² Particularly striking in figure 8a is the well-defined peak centered at an energy of about 320 keV. The height of this peak above the smoother continuum is correlated with the choice of two-body final states corresponding to a selected range of scattering angles for the two heavy ions.

By comparison, figure 8b shows that



Differential positron cross sections as a function of the minimum internuclear separation in $\text{Pb}^{208}\text{-Pb}^{208}$ collisions (from reference 8). The nuclear excitation positrons contribute a fraction of the total differential cross section. Scattering angle is $45^\circ \pm 10^\circ$. Lines are from theory. Figure 6

singling out scattering angles more forward than those selected in figure 8a largely excludes this peak and leads to a spectrum that mirrors the general shape of the continuum underlying the peak in figure 8a. The continuum distributions are well represented by the spectra we expect¹⁸ from the dynamically induced processes at the corresponding scattering angles. As we will see, it is also significant to find that the measured width of the peak in figure 8a is less than 100 keV. Moreover, this width is consistent with the Doppler broadening expected for a positron line spectrum emitted from a system moving with the velocity of the quasimolecular system. Therefore, the intrinsic width of the peak is surely less than 100 keV and, indeed, it could be very much smaller than this value.

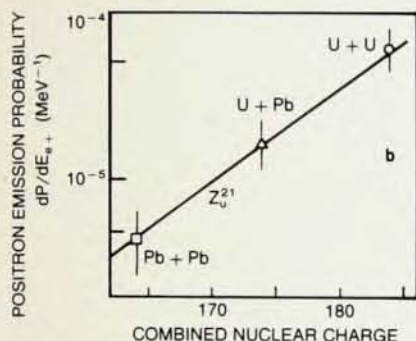
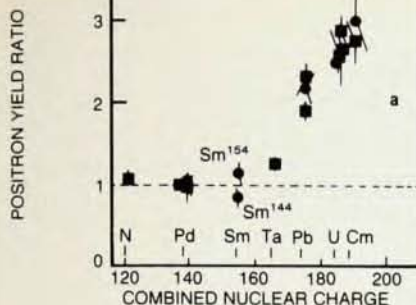
Whatever the source of the peak, it is apparent that we must seek an explanation outside the scope of the theory based on Rutherford scattering alone, because this theory of dynamic positron creation does not allow for narrow peak structures in the positron spectrum. Deviations from this theory also have been demonstrated¹⁹⁻²¹ for U-U collisions in other experiments carried out at GSI. Details of the effects seen differ from experiment to experiment because of differences in the detection schemes and conditions of measurement. But the broad conclusions are similar in the following sense: All experiments carried out to date indicate that there is a new source of positrons—a source that does not originate with the known dynamic mechanisms associated in a simple way with the time-varying electric field produced in Coulomb trajectories.

It is also difficult to attribute these deviations from smooth positron spectra to pure nuclear effects. There are two prominent candidates:

- the internal pair conversion of a nuclear transition leading to a positron energy distribution that may be peaked,
- the internal pair conversion process followed by the capture of the electron into empty atomic orbits, which leads to positron line spectra.

The relatively narrow peak shapes that appear seem to preclude the former, while intensity considerations exclude the latter by orders of magnitude. But to exclude any connections with nuclear transitions, we need additional direct studies of these and other effects, and work is in progress toward this goal.

Of course, the observation of the U-Cm system's line-like positron spectrum, and the fact that it seems to appear only under particular scattering conditions, opens up to serious consideration the possibility that we may be observing the spontaneous emission of positrons. We are encouraged by the



Positron yield and positron emission probability as a function of the total charge Z_u of the colliding nuclei.^{7,9} (a): Collisions between uranium and the nuclei indicated above the horizontal axis. Plotted is the ratio of the measured positron yield to the yield expected from internal pair conversion of nuclear γ rays. Squares and circles represent uranium incident with 5.9 MeV and 5.2 MeV per nucleon, respectively. (b): Positron emission probability increases as the 21st power of the combined nuclear charge. In each of the three collisions indicated, $R_{\min} = 30$ fm, velocity = $0.11c$ and $E_{e^+} = 478 \pm 54$ keV. Figure 7

fact that this peak happens to occur at an energy consistent with a calculation⁶ of the $1s\sigma$ resonance energy in the U-Cm quasiatom. Obviously, a systematic confirmation is required to follow up on these very suggestive data, but these new developments already raise the possibility of another important observation. For if the narrow positron peak does indeed represent spontaneous positron emission, the parent nuclear supercritical charge must exist for a long time compared to the collision times for scattering beneath the Coulomb barrier, as we pointed out earlier.

Therefore Joachim Reinhardt, Udo Müller, Berndt Müller and Greiner of the Frankfurt group suggested⁶ that the observation of spontaneous positron emission as a sharp line necessarily implies that, at bombarding energies close to that of the Coulomb barrier, a metastable superheavy nuclear composite system forms with a lifetime long enough to account for the relatively narrow peak. Widths of 100 keV or less correspond to lifetimes for



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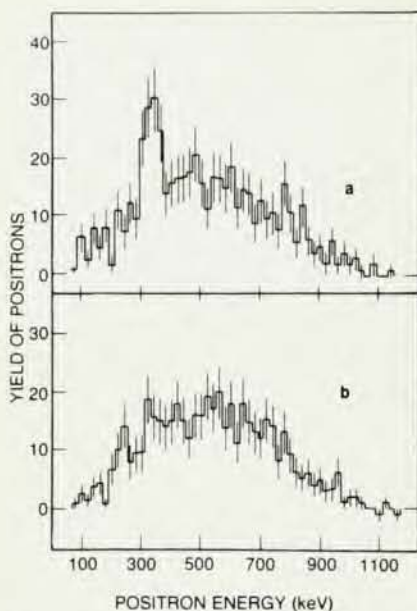
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Positron spectra from 5.8 MeV/amu uranium-curium collisions. The spectra are not corrected for spectrometer transport efficiency, which primarily affects the smallest and largest positron energies. In **a** and **b**, kinematic conditions were selected to emphasize backward and forward scattering events, respectively, in the center-of-mass frame for the collision. (From reference 22.) Figure 8

the dinuclear system longer than about 40 times the Rutherford scattering collision time, during which the $1s\sigma$ state is overcritically bound. Indeed, without introducing a time delay it is difficult to invent any mechanism associated with atomic positron emission that would explain the narrow peak width found in the U-Cm spectrum or the positron distribution emitted from the U-U collisions.¹⁹⁻²¹ Such a delay could be supplied by the formation of a rather cold intermediate superheavy nuclear complex as the nuclei barely touch in overcoming the Coulomb barrier. As a specific example of the relation between the peak structures and the time delay, recall the interaction illustrated in figure 5. In this case, without necessarily requiring overcritical binding, interference between incoming and outgoing dynamically induced positron emission amplitudes separated by a time delay leads to peaks in the positron distribution.

Thus several independent measurements confront us with evidence that there are peak structures in the positron spectra of collision systems where the quasiautom can have overcritically bound electrons. We are left with the task of identifying unambiguously the sources for these structures among the possibilities we have discussed. Research toward this goal is progressing by way of a number of approaches, including

- further studies of positron creation as a function of the nuclear charge of the collision complex
- attempts to correlate the peak structures with nuclear properties and excitation functions
- more exhaustive investigations of nuclear-related background sources.

Of course, identifying the spontaneous emission of positrons, and thereby obtaining the first observation of the spontaneous decay of the ground state in a fundamental field theory, is the primary goal of these investigations. But it would be also interesting to find that peaks in the positron spectra reflect nothing more than the interference of induced emission amplitudes, and thus, that overcritical binding does not occur in a situation where Dirac theory predicts that it should.

We have seen that nuclear time delay, such as can be produced by the formation of giant metastable nuclei, could play a central role in demonstrating the sparking of the vacuum. Conversely, from the point of view of nuclear physics, we can use the peaks in the positron spectra as an atomic clock that indicates the existence of the superheavy nuclear complex and provides a measure of its lifetime and properties. These experiments portend interesting and challenging research in the months and years to come.

* * *

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