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Microscopic study of the ^{238}U-^{238}U system and anomalous pair production

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Constrained Hartree-Fock-Bogolyubov calculations have been performed to simulate the collision of two ^{238}U nuclei at low energies (≈ 5.5 MeV/nucleon). These *ab initio* calculations indicate that electromagnetic transitions of energies between 1.5 and 1.8 MeV can be expected in the center of mass system of the colliding nuclei. These calculations are also consistent with the observed laboratory energy dependence and Z dependence of the anomalous pair production.

Several experiments performed at the Gesellschaft für Schwerionenforschung in Darmstadt have revealed the existence of narrow peaks in the spectrum of the positrons emitted in the collision of two heavy nuclei at a few MeV per nucleon.[1] Coincidence experiments have shown that the positrons associated with these peaks are correlated with electrons whose spectrum also contains peaks at the same energy.[2] The analysis of these experiments indicates that these peaks correspond to events where the electron and the positron are emitted back to back in the center of mass of the colliding system, with the same kinetic energy (350 keV in ^{238}U+^{238}U experiments). In addition, the peaks are observed only within narrow windows of laboratory incident energy (5.6 to 5.9 MeV in ^{238}U+^{238}U), depending on the nature of the colliding system.

Many cogent arguments have been advanced for requiring an exotic explanation to this anomalous pair production.[3] These include the lack of an identified nuclear transition that could serve as the source of the observed pairs, the experimental implication that the pairs appear to be emitted in the ion-ion center of mass, and the observed energy and Z dependence. Proposed solutions to most of these questions will emerge from predictions of new nuclear transitions from conventional microscopic Hartree-Fock calculations of the uranium-uranium system. (A brief account of this work has been presented recently.[4]) The purpose of the present Rapid Communication is to report the result of an investigation of the interaction between two ^{238}U nuclei using a completely microscopic approach based on the mean-field theory and its extensions.[5,6] Such an approach represents the most *ab initio* tool presently available for describing exotic assemblies of nucleons, since its only input is a nucleon-nucleon effective interaction.

The interaction between two ^{238}U nuclei is obtained by applying the constrained Hartree-Fock-Bogolyubov (HFB) method to an axially and left-right symmetric system composed of 184 protons and 292 neutrons. Due to these spatial symmetries, only configurations composed of two coaxial ^{238}U are envisaged here. This restriction has been made, partly in order to limit the size of the extremely large-scale self-consistent calculation, and partly because ^{238}U nuclei being prolate axial in their ground state, they are most likely to interact coaxially at low bombarding energies, both because of Coulomb polarization and low angular momentum. The total mass quadrupole moment $Q_{20}=(16\pi/5)^{1/2}\sum_{i=1}^{A} r_i^2 Y_2^0(\Omega_i)$ is used as one of the constraining operators. It allows us to specify either the distance between the centers of mass of the two U nuclei when they are separated, or the elongation of the composite system when the two nuclei overlap. A second constraint is also employed in the present study as explained subsequently. The HFB equations are solved by expanding the one quasiparticle states on two-center bases composed of 2 times twelve shells of harmonic-oscillator states. The matrix of the constrained HFB Hamiltonian is then diagonalized iteratively. No inert core is assumed. Because of the variational nature of the HFB theory, this procedure yields, for each given mean value of the constraining operators, the optimal configuration of the composite system, i.e., the one giving a local minimum in the total energy. In this study, the finite range effective force $D1S$ constructed by Gogny has been employed.[5,7] It can be used to reconstruct not only the average nuclear field, but also nucleon pairing correlations in the framework of the full HFB theory. This latter feature is important, since no empirical information exists about the magnitude of pairing in massive systems such as ^{238}U+^{238}U. On the other hand, pairing is known to play a crucial role in the collective dynamics of heavy systems at low energies. Let us mention that the $D1S$ interaction has been extensively used in the last fifteen years for describing nuclear properties and phenomena, with excellent results over all the periodic table.[5,7,8]

Figure 1 shows the total HFB energy of the ^{238}U+^{238}U system as a function of the constrained total mass quadrupole moment $\langle Q_{20}\rangle$ (upper scale) or, equivalently, of the distance d between the centers of mass of the two nuclei (lower scale). The most remarkable feature is that two distinct curves are obtained, corresponding to two distinct classes of solutions of the constrained HFB equations. Along the rightmost curve (19.5 fm $< d <$ 25 fm) the HFB states are composed of two well-separated ^{238}U, whose multipole deformations differ from their ground-state ones, due to the polarizing effect of their mutual Coulomb interaction. Along the other curve (16 fm $< d < 21$ fm), the HFB states describe a unique system constituted of two overlapping uranium nuclei. For d smaller than 19.5 fm, HFB solutions in the form of two separated nuclei cannot be obtained. For such distances, the nuclear short-range attraction dominates the mutual Coulomb repulsion of the two nuclei and the ^{238}U+^{238}U system be-

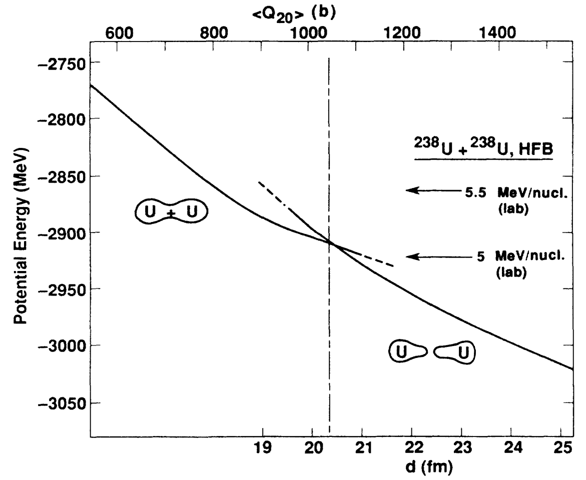

FIG. 1. Total HFB energy of the $^{238}U+^{238}U$ system as a function of the constrained mass quadrupole moment $\langle Q_{20}\rangle$ of the combined system. The lower scale gives the distance d between the centers of mass of the two nuclei when they are separated. The two horizontal arrows on the right indicate the total energy put into the U+U system in the case of collisions at 5.0 and 5.5 MeV/nucleon (laboratory), respectively.

comes unstable against fusion. Similarly, for $d > 21$ fm, the composite system is found unstable against fission. The dashes at the end of each curve indicate the regions where these instabilities begin to appear and HFB solutions of lower energy are obtained. Between 19.5 and 21 fm, the $^{238}U+^{238}U$ system may exist under two configurations having very different degrees of necking, but relatively close total energies. Note that this region would be reached in a uranium-on-uranium collision at incident laboratory energies between 5 and 5.5 MeV per nucleon if there were no internal excitation. As can be also seen in this figure, there is no pocket in the potential energy as a function of the separation distance, in contrast to earlier works.[9,10] As we use the most sophisticated microscopic approach, we believe that the pockets found in previous calculations are a result of an *ad hoc* choice of parameters.

The coexistence of two different stable configurations around 20.5 fm indicates that the interaction energy of the two ^{238}U depends not only on the distance between the two nuclei but also on other degrees of freedom. One of them clearly is the necking of the overall system shape. In fact, the transition from one curve of Fig. 1 to the other can be made without changing the distance between the two nuclei, by simply varying the necking in of the system. In order to take into account this additional degree of freedom, a second constraint has been introduced into the microscopic description. The associated constraining operator has been chosen as $Q_N = \exp(-z^2/a^2)$ in configuration space, with $a = 2$ fm. The mean value of this operator measures the average number of nucleons in a region of extension a around the $z=0$ plane (the origin $z=0$ is assumed to coincide with the center of mass of the two uranium nuclei). It therefore controls the thickness of the neck connecting the two nuclei. This constraining operator has been found more appropriate than the hexadecapole Q_{40} used in previous studies.[6,7] Indeed, preliminary tests showed that, while Q_N permits controlling very precisely the amount of matter in the neck region, Q_{40} had little effect on it and essentially changed the quadrupole and octupole deformations of each ^{238}U nucleus.

The total energy of the $^{238}U+^{238}U$ system as a function of the $\langle Q_N\rangle$ variable for different values of the total mass quadrupole moment $\langle Q_{20}\rangle$ (or of the distance d between the two uranium nuclei) is displayed in Fig. 2. With the definition of Q_N given above, the thickness of the neck increases when going from left to right on the bottom horizontal scale. As could be expected from Fig. 1, the curves obtained between $\langle Q_{20}\rangle = 975b$ and $1075b$, where two U-U configurations coexist, have two minima, one for two well-separated nuclei ($\langle Q_N\rangle < 5$ nucleons) and the other for a one-nucleus system ($\langle Q_N\rangle > 15$ nucleons). For the other values of $\langle Q_{20}\rangle$, only one true minimum exists and an inflexion point replaces the missing second minimum. The two curves drawn in Fig. 1 appear in Fig. 2 as the two almost vertical lines connecting the locations of the left and right minima on each $\langle Q_{20}\rangle$ = constant energy curve. Figure 2, in fact, is a representation of the two-dimensional potential-energy surface (PES) $V(\langle Q_{20}\rangle\langle Q_N\rangle)$ of the $^{238}U+^{238}U$ system. This PES is composed of two valleys separated by a barrier whose maximum height is about 3 MeV. Note that no barrier appears in the PES calculated in Ref. 11 using other collective variables in a non-self-consistent method.

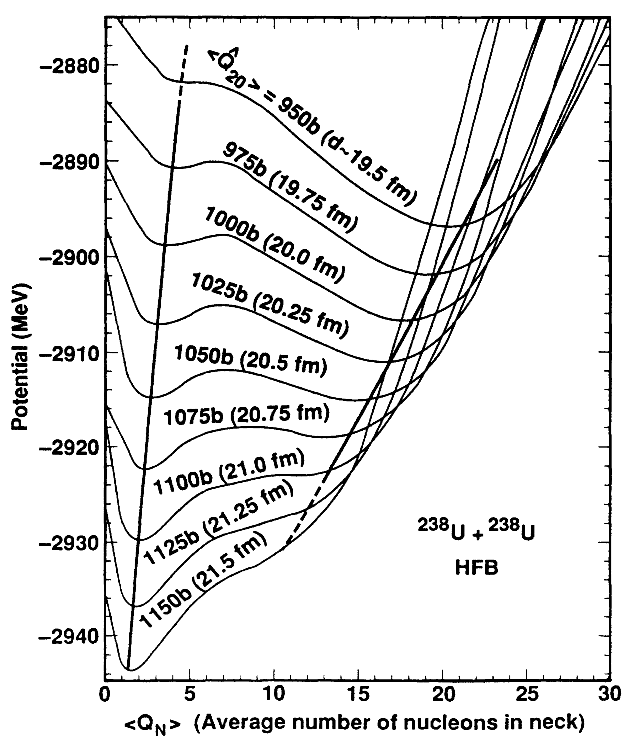

FIG. 2. Total HFB energy of the $^{238}U+^{238}U$ system as a function of the constrained necking parameter $\langle Q_N\rangle$ defined in the text, for nine values of the mass quadrupole moment $\langle Q_{20}\rangle$.

In the restricted collective space spanned by the $\langle Q_{20}\rangle$ and $\langle Q_N\rangle$ variables, the $^{238}U+^{238}U$ collision can then be represented in the following way: A two-dimensional wave packet evolves initially in the lower part of the left valley of Fig. 2. The $\langle Q_{20}\rangle$ (or d) component of this wave packet describes the relative motion of the two closing nuclei, while the $\langle Q_N\rangle$ component represents particular vibrations of the individual nuclei. Let us now assume that the laboratory incident energy is around 5.5 MeV/nucleon. The incident uranium then has sufficient energy to reach the region where a "fusion"-type transition can take place (see Fig. 1). In addition, the relative motion of the nuclei is slow enough so that such a transition can occur for distances d where the two valleys have not too different relative potential energies ($d < 19.5$ fm). The composite ^{238}U-^{238}U system formed in this way will then acquire a low collective excitation energy (a few MeV), and it could deexcite by releasing a low-energy gamma ray.

In order to get a more quantitative picture of this kind of nuclear transition, we have calculated the energies and the wave functions of the quasistatic vibrational states that can develop along the $\langle Q_N\rangle$ mode for the different values of $\langle Q_{20}\rangle$ associated with the transition region. The method used consists of calculating the eigenstates of the one-dimensional collective Hamiltonian:

$$H=-\frac{\hbar^2}{2}\frac{\partial}{\partial q}\frac{1}{M(q)}\frac{\partial}{\partial q}+V(q)-V_0(q)$$

built with the fixed- $\langle Q_{20}\rangle$ potential-energy curves $V(q)$ in Fig. 2 and the cranking collective inertia $M(q)$ deduced from the corresponding HFB constrained states. The $V_0(q)$ represent the zero-point energy correction that must be extracted from the HFB potential energy in a dynamical model involving collective coordinates defined as the mean values of operators. The result of the calculation for seven values of $\langle Q_{20}\rangle$ is displayed in Fig. 3. The horizontal lines indicate the position of the first energy states. In the case of two-well potential shapes, these lines may appear as partly solid and partly dashed. The solid-line part indicates the region where the square of the cor-

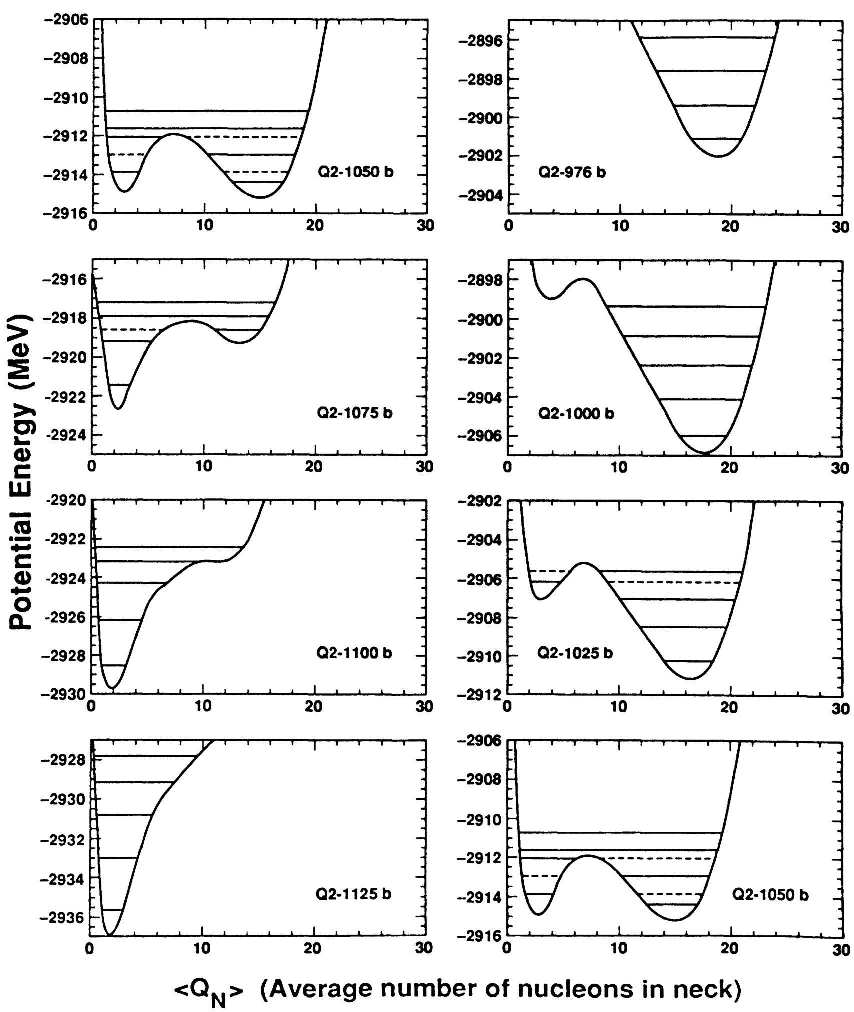

FIG. 3. Quasistatic vibrational levels along the necking-in mode $\langle Q_N\rangle$, for seven values of the mass quadrupole moment $\langle Q_{20}\rangle$. In the case of two-well potential shapes, the solid-line part of the level indicates the region where the vibrational state preferentially develops.

responding eigenfunction has its maximum, and, therefore, in which of the two wells the vibrational state preferentially develops. The two drawings on the lower-left part of Fig. 3 display vibrational states taking place in each separate uranium, while the levels represented in the four right drawings correspond to vibrations in the composite ^{238}U-^{238}U system. One observes that the energy spacing between this latter type of state is of the order of 1.5–1.7 MeV. According to the discussion of the previous paragraph, a ^{238}U-^{238}U collision at a laboratory energy around 5.5 MeV/nucleon should populate these states. More precisely, most of the relative kinetic energy should be converted into potential and rotational energy when distances of the order of 19 fm are reached, so that the system is expected to stay a rather long time in the vicinity of this distance. Let us emphasize that the energy of the predicted transition remains rather constant over a large range of relative distance. This indicates that the composite system will live long enough for the transition to occur. We are presently investigating quantitatively this problem by means of a time-dependent model of the collective dynamics on the two-dimensional PES. The deexcitation of the resulting collectively excited composite system could then release gamma rays of energy in the range 1.5–1.7 MeV. If these gamma rays were to decay into pairs of an electron and a positron they would share a combined kinetic energy between 480 and 680 keV.

The microscopic analysis of low-energy ^{238}U-^{238}U collisions given in this work therefore provides a mechanism for producing correlated electron-positron pairs, the origin of which is a fusionlike nuclear transition. Such a transition can only occur for bombarding energies in a narrow energy range and can yield an electron and a positron with kinetic energies (ignoring possible Coulomb shifts) between 240 and 340 keV. The similarity of these figures with the experimental ^{238}U-^{238}U collision data is the most striking result of the present study. Let us note that, according to the present interpretation, the energies of correlated pairs emitted in other actinide collisions should be very similar. In fact, the collective properties of very heavy nuclear systems of the type considered here are not expected to change appreciably between, say, $A=180+230$ and $A=250+250$. This observation is quite consistent with the available experimental data.[3] The present work is based on the interaction properties of two cold uranium nuclei. In real life, the two nuclei are heated by the effect of their mutual Coulomb interaction before nuclear interaction can take place. Let us stress in this respect that the collective properties of the mean field are virtually unaffected by the presence of a low nuclear "temperature," until at least $T=1$ MeV. The levels calculated above are then expected to be essentially the same in the presence of a significant amount of intrinsic excitation.

In summary, we feel we have predicted nuclear electromagnetic transitions that could be the source of the observed pair production. We are presently evaluating a coupling of this radiation to the atomic electrons which qualitatively could produce the observed pairs. We do not know if it will do so quantitatively. However, the nuclear system has a volume an order of magnitude larger than those of conventional nuclei and can be expected to have very strong atomic coupling. Independent of that, these new nuclear transitions may be observables in themselves and would serve as a test of this, the largest mean-field calculation yet performed.

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