Formation of quasimolecules in heavy-ion collisions

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The present state of experimental investigations of quasimolecules formed transiently in collisions between accelerated heavy ions and atoms is reviewed: the properties of the quasimolecular x-ray emission of these systems, the spectral distribution and structure of the observed x-ray continua, and their angular anisotropy. Consideration is given to the possibility of using systems formed in heavy-ion collisions to study the electron states of superheavy molecules with effective atomic number $Z \gg 100$, in particular the possibility of spontaneous creating of electron-positron pairs and decay of the neutral vacuum in a supercritical field when $Z \gtrsim 172$.

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INTRODUCTION

Two models have been proposed to explain some of the characteristic features in the ionization of the inner electron shells when heavy ions collide with atoms: direct ionization as a result of Coulomb excitation, and the model of quasimolecular orbitals. The former mechanism is predominant in the ionization process if the nuclear charge Z_1 of the ions is much less than the charge Z_2 of the target nuclei and if the velocity v_1 of the ions is appreciably greater than the orbital velocity $u \approx (2E_B/m_e)^{1/2}$ of the electrons in the shells of the target atoms. However, if the so-called adiabatic condition for the velocities is satisfied, $(v_1/u)^2 \ll 1$, and the nuclear charges of the ions and the target atoms are not too different ($Z_1 \approx Z_2$), then the ionization cross sections of the atoms and their dependence on Z_1 and Z_2 are described by the quasimolecule model.[1,2] In this model, it is assumed that during the collision the electrons can change their states adiabatically and for each sufficiently short distance $R(t)$ between the interacting nuclei can form quasimolecular orbitals in the two-center Coulomb field of the two charges Z_1 and Z_2 of the nuclei. In the limit $R \to 0$, these states go over into states of a quasiatom with effective atomic number $Z = Z_1 + Z_2$.

Only a few years ago, the concept of quasimolecules was used merely to explain the excitation of the electron shells of the atoms after the collision. However, the existence of vacancies in the quasimolecular states or quasiatoms and the radiative transitions which take place between them during the collisions make it possible to investigate such systems directly by measuring the quasimolecular x-ray emission in heavy-ion collisions. The detection and investigation of these x rays presents a severe experimental problem because the lifetime of a quasimolecule (which corresponds to the collision time, i.e., about 10^{-19} sec for the inner atomic shells) is short compared with the lifetime of the electron states against x-ray transitions (10^{-16} sec). Therefore, the yield of quasimolecular x rays is comparatively small. In addition, one must observe a continuum because x rays of different energies can be emitted during the collision process. This necessitates a careful analysis of the experiments to eliminate background effects, which also give rise to continuous spectra of x rays. In 1972, Saris *et al.*[3] observed for the first time a spectrum of noncharacteristic x rays, which they identified as the quasimolecular emission of the L shell of the Ar + Ar system. Since then, quasimolecules in heavy-ion collisions have stimulated great interest. In the first place, these investigations are attractive because one can obtain through them information on the electron structure of superheavy quasimolecules and quasiatoms with effective atomic number $Z \gg 100$ (Ref. 4), and when $Z \approx 172$ one can make a new fundamental test of quantum electrodynamics under conditions of very strong electric fields.[5,6] This last gives particular importance to investigations with very heavy ions and involving the most strongly bound electrons of the K and L shells of the quasiatoms in symmetric collisions. In the present review, we therefore analyze in the first place the high energy components of the quasimolecular x-ray emission of very heavy and symmetric quasimolecules studied in recent years by the present authors in experiments with the U-300 accelerator of multiply charged ions at the Nuclear Reactions Laboratory at Dubna.

1. SUPERHEAVY QUASIMOLECULES AND THE QUANTUM ELECTRODYNAMICS OF SUPERSTRONG FIELDS

The electron structure of an atom when $Z\alpha > 1$ and especially for the supercritical charge $Z \gtrsim 172$ is of considerable fundamental interest. In practice, the synthesis and study of atoms with such large atomic numbers in modern accelerators of multiply charged ions are not to be expected. So far, it has proved possible to synthesize in nuclear reactions artificial elements only up to $Z = 107$ inclusive,[7] and the boldest assumptions about possible islands of enhanced nuclear stability[8] do not go beyond the magic numbers 114 and 126. However, if one could produce even transiently superheavy quasimolecules and quasiatoms in heavy-ion collisions (at very short distances between the interacting nuclei) it would be possible to investigate questions relating to the electron structure when $Z\alpha > 1$. In particular, the spontaneous quasistatic creation of positrons when $Z \geqslant 172$ predicted by theory could be observed when two uranium atoms collide.

Let us begin by discussing the main results of the theory of what happens to the electron shells of atoms under

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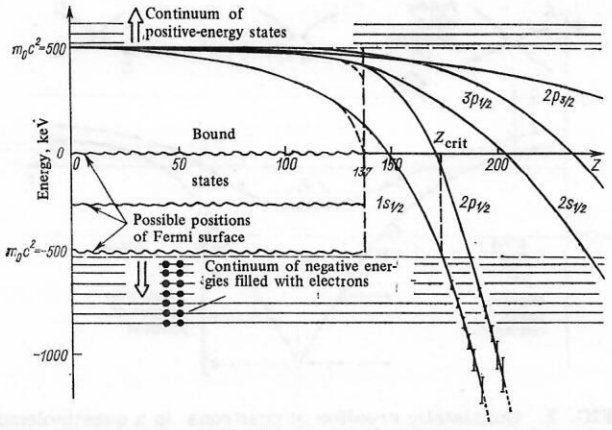

FIG. 1. Energies of the lowest electron states in the Coulomb field of superheavy nuclei with allowance for the finite size of the nuclei. At the critical $Z \approx 172$, the energy of the $1s_{1/2}$ state reaches the lower continuum of Dirac states.

the condition $Z\alpha > 1$. Details about this problem can be obtained from the reviews Refs. 9 and 10. The solution of the Dirac equation for a relativistic electron in the Coulomb field of a point charge Ze has a square-root singularity at the point $Z = 137$. For example, the energy of the lowest level $1s_{1/2}$ of the discrete spectrum decreases to zero and then stops there. This is due to the unrealistic singular behavior of the Coulomb potential at short distances. In reality, because of the finite size of the nucleus, the potential remains finite and the problem must be solved with a potential cut off at $r \leqslant 10^{-12}$ cm. It was shown in Refs. 11 and 12 that when allowance is made for the finite nucleus the electron levels have a continuation in the region $Z\alpha > 1$, and at certain critical charges Z_c of the nuclei the electron states reach the boundary $E = -m_0c^2$ of the lower continuum (Fig. 1). The values of the critical charges are $Z_c \approx 172$, 185, 245 respectively, for the electron states $1s_{1/2}$, $2p_{1/2}$, $2s_{1/2}$. What happens near $Z = Z_c \approx 172$ when the lowest $1s_{1/2}$ electron level in the atom merges with the continuum? The investigations in Refs. 13 and 14 of the solutions of the Dirac equation for Z near Z_c clarified this situation and led to the following perspicuous interpretation. At $Z = Z_c \approx 172$ the $1s_{1/2}$ discrete level reaches the edge $E = -m_0c^2$ of the continuum, and then, when $Z > Z_c$, this results in strong excitation of the wave functions of the lower continuum, after which the level disappears. The wave function of the former discrete bound state is distributed with a certain resonance width over the continuum states.

We represent the wave function $|\Psi_E\rangle$ for the supercritical system as an expansion with respect to functions in the $Z = Z_c$ basis:

$$|\Psi_E\rangle = a(E)\,|\Phi\rangle + \int b_{E'}(E)\,|\Psi_{E'}\rangle\,dE'.$$

Here, $a(E)$ and $b_{E'}(E)$ are expansion coefficients; $|\Phi\rangle$ and $|\psi_{E'}\rangle$ are wave functions of the bound state and the continuum at the point $Z = Z_c$ satisfying the equations

$$H(Z_c)\,|\Phi\rangle = -m_0c^2\,|\Phi\rangle; \quad H(Z_c)\,|\Psi_{E'}\rangle = E\,|\Psi_E\rangle.$$

Since the function $|\Psi_E\rangle$ must be a solution of the supercritical Hamiltonian $H(Z = Z_c + Z') = H(Z_c) + U(Z')$ with excess charge $Z' = Z - Z_c$, it will be an eigenfunction of the operator, $H(Z_c + Z')\,|\Psi_E\rangle = E\,|\Psi_E\rangle$ and the expansion coefficients $a(E)$ take the form of the following Breit–Wigner resonance distribution:

$$|a(E)|^2 = \frac{1}{2\pi}\,\frac{\Gamma}{(E + m_0c^2 - \Delta E_0)^2 + \Gamma^2/4},$$

where ΔE_0 is the energy by which the discrete $1s_{1/2}$ state is lowered into the continuum, and Γ is the width of this state. Both these quantities are determined by the matrix elements of the additional potential $U(Z')$ $= H(Z_c + Z') - H(Z_c) \approx Z'U(r)$:

$$\Delta E_0 = \langle \Phi\,|\,U(Z')\,|\,\Phi\rangle \approx -Z'\delta;$$
$$\Gamma(E) = 2\pi\,|\langle \psi_E\,|\,U(Z')\,|\,\Phi\rangle|^2 \approx Z'^2\gamma.$$

Numerical calculations for the region $Z' \ll Z_c$ indicate that the $1s_{1/2}$ state sinks into the continuum at the rate $\Delta E_0 \approx -Z' \cdot 30$ keV, and that the resonance width is given by $\Gamma \approx (Z')^2 \cdot 0.05$ keV.

The consequences of this mixing of the discrete state with the continuum of Dirac states depend on whether the $1s_{1/2}$ state before merging with the continuum in the transition to $Z > Z_c$ is occupied by two electrons or is vacant. In the first case, when there are two electrons in the K shell, the electron structure of the atom changes only slightly on the transition to the supercritical state. The nucleus of such a supercritical atom is surrounded as before by an electron shell with charge $2e$. As regards its physical properties, the distribution of this charge does not differ much from that in the K shell for an ordinary atom with $Z < Z_c$. However, this distribution does not correspond to a single-particle wave function but rather to a vacuum density of charge localized near the supercritical nucleus. And there is this characteristic feature: If positrons are scattered off the system, one will observe a narrow resonance described by the Breit–Wigner distribution $|a(E)|^2$ of amplitudes given above. Thus, positron scattering would be a direct method of experimental determination of the parameters of the quasistationary exponentially decaying state that is the continuation of the discrete level when $Z > Z_c$.

But if the K shell of the atom when it enters the region $Z > Z_c$ is not filled with electrons (bare nucleus or an atom with vacancies in the $1s_{1/2}$ state), then the unfilled $1s_{1/2}$ level goes over into a quasistationary state and spontaneous emission of positrons occurs after a time $\tau \approx \hbar/\Gamma$. One can say that the Coulomb field of the bare nucleus with supercritical charge spontaneously creates two electron–positron pairs in the vacuum, the electrons forming a shell with charge $2e$ around the nucleus, while the positrons escape to infinity. This is a qualitatively new process in the sense that the normally neutral vacuum (under ordinary conditions) is transformed into an unstable state when $Z > Z_c$. When $Z > Z_c$, the vacuum becomes charged, with total charge $2e$, while the effective charge of the supercritical nucleus for an external observer is reduced to $Z - 2$.

Thus, the experimentally observed spontaneous emis-

sion of positrons in the Coulomb field of a nucleus with supercritical charge would enable one to investigate an interesting phenomenon such as the decay of the neutral vacuum, and this could provide a method for testing quantum electrodynamics under conditions of very strong electric fields. Such an experiment would be important for not only atomic physics but also for our understanding of such fundamental modifications of the vacuum in other very strongly bound systems of elementary particles. And although nature has no stable nuclei with charge $Z > Z_c \approx 172$, it is possible to investigate the effects of supercritical electric fields in heavy-ion collisions if the total charge of the nuclei forming the quasimolecule is $Z_1 + Z_2 > Z_c$. To treat the problem quantitatively, Müller *et al.*[15] solved the Dirac equation for a relativistic electron in the two-center Coulomb field of two nuclei (with allowance for the finite size of the nuclei).

For two uranium nuclei, the most strongly bound $1s\sigma$ state of a quasimolecule with effective charge $Z = 184$ of the nucleus reaches the energy of the negative continuum at the so-called critical distance $R_c = 35$ F between the nuclei. To make two uranium nuclei approach this close, one requires a kinetic energy $E_1 \gtrsim 600$ MeV of the ions (in the laboratory system). This energy is still a long way below the threshold of nuclear reactions and is sufficiently low for one to regard the process of approach to one another of the nuclei as quasistatic; for at this energy, the velocity of the relative motion of the uranium nuclei is $v_1/c \approx 0.05$, while the velocity of the orbital motion of the electrons in the $1s\sigma$ state is $u_K/c \approx 1$. The creation of positrons in heavy-ion collisions is illustrated in Fig. 2. This shows the energies of the $1s_{1/2}$ and $2p_{1/2}$ electron states of the quasimolecule as a function of the time. It is assumed that during the initial phase of the collision a vacancy was formed in the $1s_{1/2}$ state during the Coulomb interaction. At the time t when the distance between the nuclei reaches the critical value R_c the $1s\sigma$ state enters the continuum of negative energies, after which spontaneous emission of positrons can occur. However, the lifetime of the quasimolecule in the supercritical state is only $\tau \approx 0.2 \cdot 10^{-20}$ sec. Because of this and because the width Γ of the quasistationary supercritical state is comparatively small, only a small fraction (about 2%) of the vacancies give rise to an effect. The dynamics of the collision process makes possible not only spontaneous creation but also induced emission of positrons at the expense of the kinetic energy of the collision. Whereas the spontaneous creation requires fulfillment of the condition $R < R_c$, the induced emission of positrons can take place both before and after the $1s\sigma$ state enters the negative continuum. The induced emission can have a strong influence on the spectral distribution of the positrons observed in U + U collisions.

The absolute cross section for the production of positrons and their spectral distribution were calculated in Refs. 16 and 17. The largest uncertainty in the calculation of the absolute cross section is associated with our ignorance of the probability for the production of $1s$ vacancies in collisions of heavy ions such as uranium.

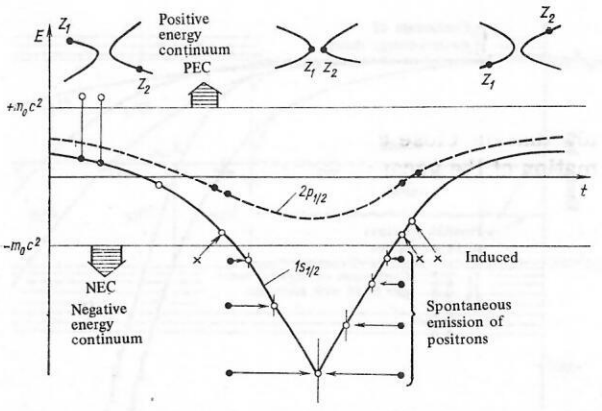

FIG. 2. Quasistatic creation of positrons in a quasimolecule with effective supercritical charge $Z_1 + Z_2 > Z_c$, which could be formed in U + U collisions. PEC and NEC are the positive and negative energy continua.

As yet, there are no experimental data on the probability, and extrapolation of it from data obtained in experiments with lighter ions gives values in the range from 10^{-1} to 10^{-5}. In their calculations, Greiner *et al.*[16] assumed purely formally that there is a 10^{-2} probability of $1s$-vacancy production in a U + U collision. Under this optimistic assumption, it is found that the absolute cross section for the emission of positrons in U + U collisions at energy 1600 MeV of the ions is $5 \cdot 10^{-28}$ cm^2. Analysis of background effects (principally, the possible production of positrons as a result of pair conversion of high-energy γ transitions, which can occur as a result of Coulomb excitation of the uranium nuclei) shows[18] that for this value of the cross section the spontaneous emission of positrons and the decay of the neutral vacuum in the Coulomb field of superheavy quasiatoms could be quite amenable to observation. In 1967, uranium ions were accelerated for the first time to an energy of about 5 MeV/nucleon with the new heavy-ion accelerator at Darmstadt in West Germany. Experimental results in this exceptionally interesting direction are to be expected in the future.

The investigation of very heavy quasimolecules is also of great interest for other reasons. It might be possible to extract information on the electron states of systems with effective nuclear charge $Z\alpha \gtrsim 1$ from the spectra of quasimolecular x rays. This would provide an experimental means for studying phenomena such as the very strong splitting of $2p_{1/2}$ and $2p_{3/2}$ levels in superheavy quasiatoms (about 250 keV at $Z \approx 160$) or make possible the detection of splitting of the $1s$ level in a very strong magnetic field, which arises locally in collisions of very heavy ions.[19] To get an idea of what might be achieved in the future by such investigations, let us consider the data so far obtained on quasimolecules from experiments with lighter ions.

2. FORMATION OF VACANCIES IN INNER ATOMIC SHELLS DURING HEAVY-ION COLLISIONS

It is obvious that emission of quasimolecular x rays is intimately related to the formation of vacancies in the inner electron shells of the atoms involved in a col-

lision. Vacancies are important not only as the prerequisite for the emission of quasimolecular x rays—they can be formed and filled in a single collision and must therefore be treated together. We shall show below that the close correlation in time between the formation of the vacancies and the emission of the quasimolecular x rays can have a strong influence on the spectral distribution of the x rays. As heavier and heavier ions right up to uranium are considered, we need to know how the cross sections for the ionization of the inner atomic shells depend on the energy of the ions and the atomic numbers Z_1 and Z_2 of the bombarding ions and the target atoms. To calculate the cross sections theoretically, we must know the mechanism by which the vacancies are formed. The "atomic model" of direct ionization of the inner electron states by the Coulomb field,[20] which gives satisfactory agreement with the experimental results for ionization of atoms by protons and alphas, does not apply to heavier ions. Only the "molecular model" developed by Fano and Lichten[1] on the basis of the theory of molecular orbitals[2] gives qualitatively correct results for the ionization of inner shells for heavier ions and $Z_1 \approx Z_2$. The most important assumption of the model is that the collision is regarded as adiabatic. Then the wave functions of the electron states change smoothly under the influence of the perturbation introduced by the comparatively slow relative motion of the nuclei and they go over to quasimolecular states. At given Z_1 and Z_2, the energies of the states depend only on the distance R between the nuclei. At the same time, the kinetic energy of the ions is sufficient to give rise to ionization of at least the most weakly bound outer shells. During the adiabatic approach of the two atoms, the degenerate electron states are strongly split when they become quasimolecular states (see, for example, Fig. 8 of the present review). Moreover, the molecular levels originating from different atomic shells may cross. Because of the interaction of the states at the crossing points, electrons may go over from one state to another. In particular, electrons of inner atomic shells that

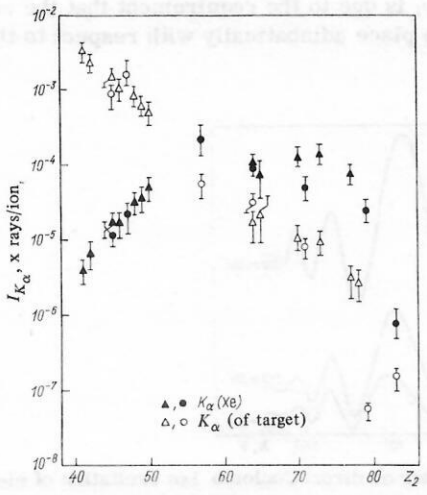

FIG. 3. Absolute yields of K_α x rays of xenon and target atoms as functions of the charge number Z_2 of the target.[23]

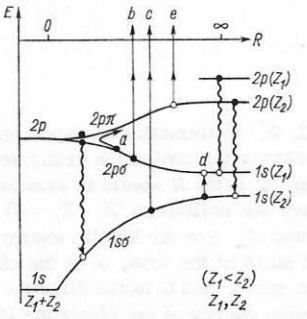

FIG. 4. Correlation scheme of 1s and 2p states of colliding atoms ($R=\infty$) and of the quasiatom ($R=0$) in the model of quasimolecular orbitals. The arrows indicate the electron transitions which lead to ionization of the inner atomic shells in the heavy-ion collisions.

cross an unfilled outer state may go over to that more weakly bound state, and then, during the collision, the inner states of the separating atoms may be vacant. This can also happen in the regions of so-called asymptotic crossings, where the quasimolecular states go over to atomic ($R \to \infty$) and quasiatomic ($R \to 0$) states. An example of the latter is the interaction of quasimolecular $2p\pi-2p\sigma$ states at short distances R through the rotational coupling of these levels. This interaction is very important for explaining the ionization of the K shell in heavy-ion collisions,[21,22] which is most interesting for us here in our further examination of the high-energy components of the quasimolecular emission.

Let us consider some experimental results. The absolute yields of the characteristic K_α emission of xenon and the target atoms as functions of the charge Z_2 of the target nuclei, obtained in experiments with 150-MeV xenon ions,[23] are shown in Fig. 3. The dependence obtained is typical for ionization of K shells in heavy-ion collisions. The ionization of the K shell takes place preferentially in the lighter of the colliding atoms. Ionization of the K shell of the heavier atom is maximal in symmetric collisions ($Z_1 \approx Z_2$) and decreases rapidly with increasing $|Z_1 - Z_2|$. This is in qualitative agreement with the model of quasimolecular orbitals.

Figure 4 is a schematic representation of the so-called correlation scheme of the 1s and 2p states of colliding atoms ($R=\infty$) and the quasiatom ($R=0$) with atomic number $Z=Z_1+Z_2$ if Z_1 and Z_2 are not too different. Also shown are all the electron transitions that can contribute to the formation of vacancies in the K shells when the two nuclei approach during the collision. In accordance with this scheme, the $2p\pi$ vacancies formed during the approach of the atoms can make a transition through the $2p\pi-2p\sigma$ coupling at short distances (transition a in Fig. 4) to the 1s state of the lighter atom and give rise to K x-ray emission after the collision. This explains the preferential ionization of the K shell of the lighter of the colliding ions, since ionization of the K shell of the heavier atom can occur in the quasimolecular model only by the additional electron transition d.

In Ref. 24, Meyerhof considered $1s\sigma-2p\sigma$ transitions of this type in a model of radial coupling of levels at mean distances R. Their amplitude has the value 0.5 in symmetric collisions, i.e., for the merging of the

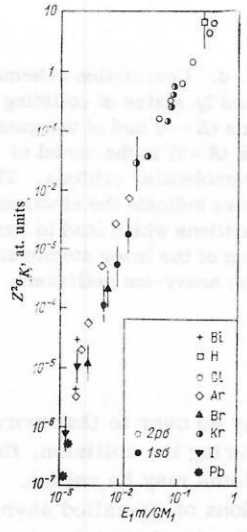

FIG. 5. Systematics of experimental data on the ionization cross sections σ_K of the K shells in symmetric heavy-ion collisions ($Z_1 = Z_2 = Z$). E_1 and M_1 are the kinetic energy and mass of the ions; m is the electron mass; and G is the effective binding energy of the electrons in the quasimolecular $1s\sigma$ and $2p\sigma$ states.[26]

$1s\sigma$ and $2p\sigma$ states into the $1s$ states of the individual atoms in the limit $R \to \infty$ in the scheme shown in Fig. 4. In the case of asymmetric collisions, the amplitude of these transitions decreases exponentially with increasing difference between the binding energies of the electrons in the $1s$ states of the two colliding atoms, i.e., it decreases rapidly with increasing $|Z_1 - Z_2|$. Thus, the basic experimental results find a qualitatively correct explanation in the framework of the simple adiabatic model. However, quantitative calculations[25] in this model for large Z_1 and Z_2 entail considerable difficulties. In principle, they require knowledge of the exact correlation schemes, i.e., calculation of the quasimolecular states in the two-center potential and the transition matrix elements with allowance for the dynamics of the collision process. In addition, it is not sufficiently known to what extent direct Coulomb excitation (transitions of the type b, c, and e in Fig. 4) affect the cross section for the formation of vacancies in the inner atomic shells when very heavy ions collide.

Some successes have been achieved in recent years in systematizing the experimental data on the cross sections of K-shell ionization in symmetric collisions of heavy ions.[26] As is shown in Fig. 5, all the experimental values of $Z^2\sigma_K$ from hydrogen to bismuth lie approximately on a single curve if they are plotted as a function of the dimensionless parameter $E_1 m/GM_1$. Here, E_1 and M_1 are the kinetic energy and mass of the ion; m is the electron mass; $Z = Z_1 = Z_2$; and G is the effective binding energy of the electron in the quasimolecular $1s\sigma$ and $2p\sigma$ states. If this curve is extrapolated to estimate the cross section for formation of K vacancies in U + U collisions at $E_1 = 1600$ MeV, the result $\sigma_K \leq 5 \cdot 10^{-25}$ cm^2 is obtained. This means that the total cross section for the emission of positrons in these collisions is measured only in microbarns[27] and is much less than was assumed in Ref. 16. On the other hand, the new theoretical investigations[28] of this question have shown that at short distances between the nuclei the amplitudes of transitions of electrons from the $1s\sigma$ state to the vacant $ns\sigma$ states by direct Coulomb excitation may have large values. The numerical results for these amplitudes as functions of the distance R between colliding uranium nuclei are shown in Fig. 6. The strong growth of the amplitudes immediately after the time of closest approach of the uranium nuclei during the collision can significantly raise the cross section of positron emission. All this indicates the importance of experimental investigation of the formation of K vacancies in U + U collisions at high energies of the ions right up to the Coulomb barrier.

Before we turn in the next section to presenting the experimental results of the investigation of quasimolecular x-ray emission, let us point out the following conclusion deduced from the quasimolecular model for the excitation mechanism of quasimolecular K x-ray emission. If the direct excitation of the $1s\sigma$ state by the Coulomb field is unimportant at comparatively low energies of the ions (≤ 1 MeV/nucleon), then vacancies in the quasimolecular $1s\sigma$ state and the corresponding quasimolecular K x-ray emission can occur only if the incident ion already has a vacancy in the $1s$ state. In the case of very heavy ions ($Z \geq 20$), this is improbable. Therefore, quasimolecular K x-ray emission can occur only in secondary collisions after vacancies from the outer states have gone over in the primary collisions through the $2p\pi - 2p\sigma$ coupling to the $1s$ state of the scattered ion.

3. X-RAY EMISSION OF QUASIMOLECULES

We first present some simple qualitative arguments. Quasimolecular x rays can be emitted if, on the one hand, quasimolecules really are formed in heavy-ion collisions and, on the other, if radiative transitions take place when there are vacancies in the states of these quasimolecules during the existence of the quasimolecules, i.e., during the very short collision time. Let us consider these conditions more closely. In Ref. 29, Armbruster *et al.* give the simple criterion $1.2 \cdot 10^{-3} Z/n > v_1/c > 2 \cdot 10^{-4} Z/n$ for the formation of quasimolecules in collisions of heavy ions with relative velocity v_1 of the ions, atomic number Z of the colliding particles (we assume here $Z = Z_1 = Z_2$), and principal quantum number n of the electron states of the quasimolecule in the limiting case of the quasiatom. The upper limit on v_1 is due to the requirement that the collision must take place adiabatically with respect to the

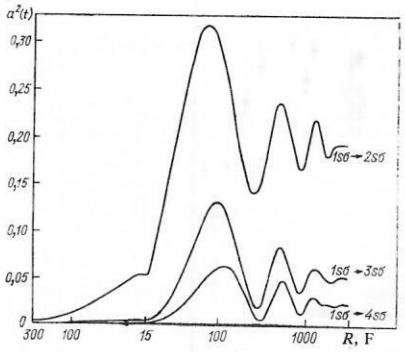

FIG. 6. Amplitudes of direct Coulomb $1s\sigma$ excitation of electrons to vacant $ns\sigma$ states in U + U collisions at 1600 MeV for different distances R between the nuclei.[28]

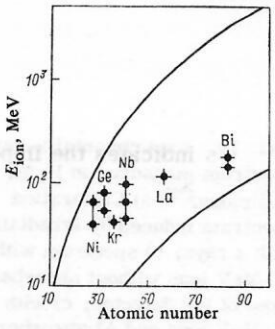

FIG. 7. Boundaries of the quasimolecular region of ion kinetic energies for K-shell electrons ($n=1$) in symmetric heavy-ion collisions ($Z_1=Z_2$). The plotted points show that the experiments made at Dubna with Ni, Ge, Kr, Nb, La, and Bi ions correspond to the conditions for formation of quasimolecules.

motion of the electrons for the given value of n; the lower limit corresponds to the minimal kinetic energy of the ions needed for the nuclei to approach each other in the collisions to distances less than the classical radius of the Bohr electron orbits, i.e., $R<a_n=a_0n^2/Z$ ($a_0=0.53\cdot10^{-8}$ cm). The "quasimolecular region" of (E_1, Z) values determined in this way for symmetric collisions of heavy ions and the most strongly bound ($n=1$) electron states—and it is these with which we shall be primarily concerned in what follows—is shown in Fig. 7. The points plotted in Fig. 7 correspond to the experiments made at Dubna with ions from Ni to Bi at energies $E_1<1$ MeV/nucleon and at ion-beam intensities ranging from 10^{12} particle/sec for Ni to 10^{10} particle/sec for Bi (Ref. 30).

From the point of view of the physics of the model of quasimolecules, it is desirable to carry out experiments to detect quasimolecular x rays at the lowest possible energies of the incident ions. But the cross sections for the formation of vacancies in the inner atomic shells and the corresponding yield of quasimolecular x rays decrease strongly with decreasing energy of the ions. For example, the cross section for the formation of K vacancies in collisions of heavy ions of medium mass depends on the kinetic energy of the ions approximately as E_1^n, where $n=4-6$ at energies $E_1\lesssim1$ MeV/nucleon. The ratio of the expected integrated yield of quasimolecular emission to the yield of characteristic K x-ray emission of the individual atoms in heavy-ion collisions can be estimated simply as equal to the ratio of the lifetime of the quasimolecule to the lifetime τ_K of $1s$-state vacancies against radiative transitions. The lifetime of the quasimolecule corresponds to the collision time as defined by the K-shell radius, $\Delta t\approx 2a_n/v_1$, and in the case $E_1\approx1$ MeV/nucleon ($v_1\approx10^9$ cm/sec) this is $\Delta t\approx10^{-19}$ sec. Since $\tau_K\geq5\cdot10^{-16}$ sec, the expected ratio is only $Y_K(\text{amol})/Y(\text{atom})\leq2\cdot10^{-4}$. Besides this comparatively low yield, the quasimolecular emission has one further undesirable property from the point of experimental investigation, due to the dynamics of the collision process. The energies of the quasimolecular transitions vary during the collision smoothly with the change in the distance between the colliding nuclei. Therefore, the quasimolecules do not emit characteristic line spectra but a continuous spectrum of x rays.

To get a clear idea of the possible components of the quasimolecular emission and their classification, Fig. 8 shows the scheme of adiabatic quasimolecular levels for different distances R between the nuclei for symmetric collisions of heavy ions with medium Z values. By analogy with classical x-ray spectroscopy, the different continuous components of the quasimolecular x rays are usually classified as K, L, and M radiation. This arbitrary classification is unique only at small R. At intermediate distances between the nuclei, there can also be components of intermediate type, such as the LK component, which is related to radiative transitions to the $2p\sigma$ state.

This classification is not suitable for studying superheavy quasimolecules because the strong spin–orbit coupling leads to a strong splitting of the levels at small R. To summarize: The quasimolecular x rays emitted during collisions of heavy ions have a complicated continuum consisting of several components. In the quasistatic approximation one can assume that the most energetic K component will have maximal energy in the region of the characteristic K emission of the atom with total nuclear charge $Z=Z_1+Z_2$.

The spectral distribution of the quasimolecular x rays depends not only on the particular adiabatic schemes of the quasimolecular levels but also on the dynamics of the collision process. Clearly, it is very important how the formation of vacancies in the quasimolecular states depends on the time, i.e., on $R(t)$. Meyerhof *et al.*[31] gave simple formulas for the differential cross section of quasimolecular K x-ray emission obtained under the assumption that these x rays can arise in both initial and subsequent collisions. If the vacancies are formed in the $1s\sigma$ state and the quasimolecular radiative transitions take place during a single collision, the differential cross section is given by

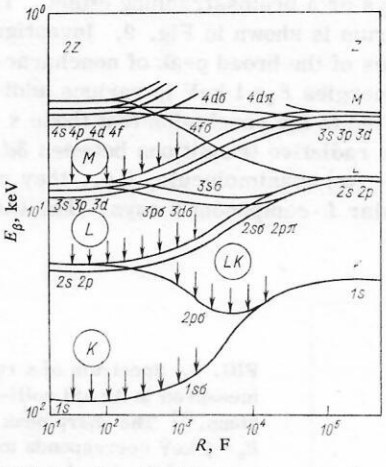

FIG. 8. Level scheme of quasimolecule formed in symmetric collision of two heavy ions ($Z_1=Z_2=Z$) at different distances between the colliding nuclei. K, L, M, and LM are the arbitrary designations of the different components of the quasimolecular x rays.

$$d^2\sigma_K^{(1)}/dE_x = 2\pi bdbP(b)\,(dR/dE_x)/v_R\tau_x(R),$$

where $2\pi bdb$ is the scattering cross section for the given collision parameter b; $P(b)$ is the probability of vacancy formation; v_R is the radial component of the ion velocity; $dR/v_R\tau_x = dt/\tau_x(R)$ is the probability of quasimolecular radiative transition for given $R(t)$.

The effect corresponding to single collisions is manifested in experiments with monatomic gases as targets. In solid targets, one must take into account the effect of subsequent collisions because the lifetime of the vacancies τ_K at ion velocity $v_1 \approx 10^9$ cm/sec is appreciably longer than the time of flight of the ions between their initial and subsequent collisions. The differential yield of quasimolecular K-component x rays in subsequent collisions depends additionally on the density n of the target atoms, the velocity v_1 of the ions, and the probability W of transition of the vacancies through $2p\pi - 2p\sigma$ coupling (see Sec. 2) to the $1s\sigma$ state after the initial collision:

$$d^2Y_K^{\Sigma}/dE_x = 2nv_1\tau_K 2\pi bdbW\,(dR/dE_x)/v_R\tau_x(R).$$

To obtain the spectra, it is necessary to integrate these expressions over all possible collision parameters with certain assumptions about the form of the functions $P(b)$ and the probability W. Analysis of the spectra of the quasimolecular K emission by means of these two expressions showed[31] that the two-stage mechanism of quasimolecular K emission predominates in the case of symmetric collisions ($Z_1 = Z_2$) at ion energies $E_1 \leq 1$ MeV/nucleon. However, for nonsymmetric collisions and at high energies, an important contribution is made by direct Coulomb excitation of the quasimolecular emission. After this introduction to the general properties of quasimolecular x-ray emission, let us consider the results of experimental investigation.

Detection of x-ray emission of quasimolecules. In 1972, Saris *et al*[3] observed for the first time in Ar(240 keV) + Si collisions a spectrum of noncharacteristic x rays that could not be attributed to known characteristic x rays or a bremsstrahlung effect. Their experimental spectrum is shown in Fig. 9. Investigation of the properties of the broad peak of noncharacteristic x rays at energies $E_x \approx 1$ keV in various additional experiments led to the conclusion that these x rays originate from radiative transitions between $3d$ and $2p$ states of an (Ar + Ar) quasimolecule, i.e., they represent quasimolecular L-component x rays. The (Ar

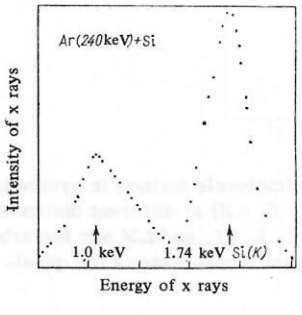

FIG. 9. Spectrum of x rays measured in Ar + Si collisions.[3] The sharp peak at $E_x \approx 1$ keV corresponds to L x rays of the Ar + Ar quasimolecule.

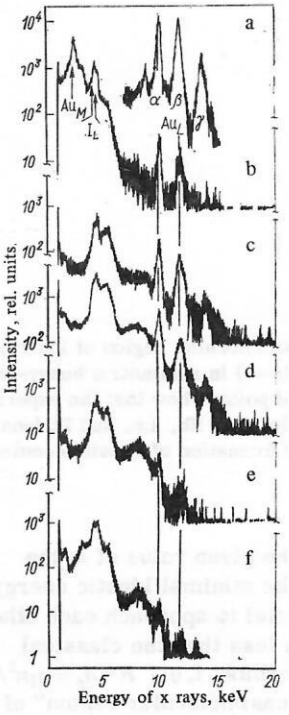

FIG. 10. Experimental x-ray spectrum measured in I + Au collisions.[32] a) Calibration spectrum induced by irradiation with x rays; b) spectrum with 57-MeV ions without absorber in front of the detector; c) with 57-MeV ions and Al absorber 40 μm thick; d) with 25-MeV ions and Al absorber 40 μm thick; e) with 11-MeV ions and Al absorber 40 μm thick; f) with 11-MeV ions and Al absorber 18 μm thick. The broad peak at $E_x \approx 8$ keV corresponds to M x rays of the superheavy quasimolecule I + Au ($Z = 132$).

+ Ar) quasimolecules were formed in these experiments by collisions of Ar ions with Ar atoms implanted in Si in the two-stage process Ar + Si → Ar($2p^{-1}$) and Ar($2p^{-1}$) + Ar → (Ar + Ar) ($2p\pi^{-1}$).

Armbruster *et al*[32] were the first to detect experimentally quasimolecular M x rays in I(11–57 MeV) + Au collisions, i.e., from a superheavy quasimolecule with effective charge $Z = Z_1 + Z_2 = 132$ of the nuclei. The x-ray spectra measured in these experiments are shown in Fig. 10. The broad peak around $E_x \approx 8$ keV corresponds to radiative transitions between $4f$ and $3d$ states of an (I + Au) quasimolecule. In subsequent experiments,[29,33] the same group also studied the M x rays of even heavier quasimolecules up to $Z = 145$.

The first experimental results for quasimolecular K x rays were obtained in 1973 by Meyerhof *et al*[34] at Stanford in Br + Br collisions and by our group at Dubna[35] in Ge + Ge collisions. After these first experiments, quasimolecular K x rays were observed in Ni + Ni (Ref. 36), Nb + Nb (Ref. 37), and La + La (Ref. 38) collisions. The cross section for the production of quasimolecular K x rays in heavy-ion collisions is many orders of magnitude less than for L and M x rays. However, it is of the greatest interest in connection with the problem discussed above of electron states in the very strong electric fields of superheavy quasimolecules.

A typical experimental spectrum of quasimolecular K x rays is shown in Fig. 11. It was measured in Nb(67 MeV) + Nb collisions by means of a pure Ge detector with sensitive volume 25×5 mm^3 and energy resolution 200 eV at x-ray energy 10 keV. In the spectrum, one sees not only the characteristic K x rays of the Nb atoms and of the Cu absorber in front of the de-

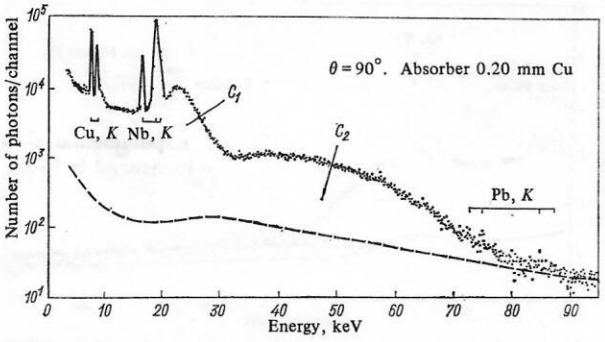

FIG. 11. Experimental x-ray spectrum measured in Nb + Nb collisions.[39] The dashed curve is the total effect of the background precesses. The broad distribution at energies higher than the Nb lines corresponds to K x rays of the Nb + Nb ($Z = 82$) quasimolecule.

tector but also a broad spectrum of x rays at energies $E_x > E$(Nb, K x rays) whose intensity decreases strongly with increasing E_x and goes over into the experimental background in the region of the energy of the characteristic K x rays $E(Z = 82$, K x rays) of quasiatoms with the double nuclear charge. The component C_2 of the continuum represents quasimolecular x rays corresponding to radiative transitions to the vacant $1s\sigma$ state of the quasimolecule. The origin of the component C_1, which was already detected in the first experiments with Ge ions,[35] has been finally clarified only recently. It corresponds to radiative transitions to the $2p\sigma$ state of the quasimolecule, i.e., in accordance with the above classification it is intermediate quasimolecular LK emission (see Fig. 8). We shall come back to discussing this structure of the high-energy quasimolecular spectrum somewhat later. In considering these continuum x rays, it is natural to ask to what extent other processes in heavy-ion collisions could give rise to such an x-ray continuum. Let us therefore examine how sure we are of the interpretation of these spectra as quasimolecular K x rays.

Analysis of background effects. Possible sources of an x-ray continuum in heavy-ion collisions at the considered E_1 and Z values are the following mechanisms:

bremsstrahlung of secondary electrons;
bremsstrahlung of the scattered nuclei;
radiative capture of electrons in vacant inner states of the incident ions;
Compton scattering of gammas due to Coulomb excitation of the nuclei;
the natural background in the neighborhood of the detecting system;

The last two sources of background x rays can be tested experimentally and eliminated from the following discussion. In actual experiments with Ni, Kr, Nb, and Bi ions, the penultimate effect is very small because these nuclei are near magic nuclei and have first excited levels at high excitation energies.

Bremsstrahlung in heavy-ion collisions (the first two processes) has been investigated on many occasions, both experimentally and theoretically.[40,41] We analyzed both of the first two effects in all our experiments with Ni, Ge, Kr, Nb, and La ions by calculating them in accordance with the method described by Gippner.[42] The differential cross section for bremsstrahlung by secondary electrons in the collision of an ion (Z_1, A_1, E_1) with target atoms (Z_2, A_2) is given by

$$\frac{d\sigma(E_x, E_1)}{dE_x} = \int_{E_x}^{\infty} dE_\delta \frac{d\sigma_e(E_\delta, E_1)}{dE_\delta} \int_{E_x}^{E_\delta} \frac{d\sigma_x(E_e, E_x)}{dE_x} \frac{dE_e}{m_e M_p A_2 S(E_e)},$$

where $d\sigma_e(E_\delta, E_1)/dE_\delta$ is the differential cross section for the production of δ electrons in the energy range E_δ to $E_\delta + dE_\delta$, and $d\sigma_x(E_e, E_x)/dE_x$ is the differential cross section of bremsstrahlung by an electron with energy E_e; $S(E_e)$ is the energy loss function of an electron in the target; and $m_e M_p A_2 = M_2$ is the mass of the target atom. The cross section for production of δ electrons in heavy-ion collisions can be calculated with sufficient accuracy by the approximate method given in Ref. 43.

The bremsstrahlung of the scattered nuclei was considered in the classical paper Ref. 44 by Alder *et al.* The differential cross section of its dipole component is

$$\frac{d\sigma_D(E_x, E_1)}{dE_x} = \text{const}\, Z_1^2 Z_2^2 \left(\frac{Z_1}{A_1} - \frac{Z_2}{A_2}\right)^2 \frac{A_1}{E_1 E_x} f_D(E_1, E_x).$$

The factor $(Z_1/A_1 - Z_2/A_2)^2$ in this expression shows that, in a completely symmetric collision in which nuclei of a single-isotope element collide, the dipole component of the bremsstrahlung of the scattered nuclei disappears. This is the case, for example, in the Nb + Nb collisions that we investigated. In these experiments we used targets with purification from impurities better than 10^{-6}. Higher multipole orders of the bremsstrahlung or the interference terms between them are several orders of magnitude weaker than the x-ray spectra of interest. Therefore, we shall not consider them here. The results of analysis of the bremsstrahlung in collisions between Nb ions ($E_1 = 96$ MeV, $Z_1 = 41$) and Mo ($Z_2 = 42$), Nb ($Z_2 = 41$), and Zr ($Z_2 = 40$) target atoms are shown in Fig. 12. They show that the continuous spectra observed in these experiments cannot be due to bremsstrahlung processes. For example, in the energy range 16 keV $\leq E_x \leq$ 30 keV the integrated yield of the bremsstrahlung is three orders of magnitude lower than the observed effect. At energies $E_x > 30$ keV, the experimental spectrum also appreciably exceeds the calculated bremsstrahlung components.

Let us now consider the radiative capture of electrons in vacant K shells of the incident ions, which was observed in experiments with light ions and gives rise in these collisions to relatively strong x-ray continua.[45] The spectrum of x rays emitted in S (90 MeV) + Al collisions, which exhibits the radiative-capture effect,[46] is shown in Fig. 13. This process can occur if the incident ions have vacancies in the K shell. They can be filled by capture of weakly bound or free electrons in the target and thus give rise to x-ray emission. The spectrum of this emission is determined by the difference between the binding energies of the electrons in the initial and final states and, in addition, by the energy of the translational motion of the electron relative to

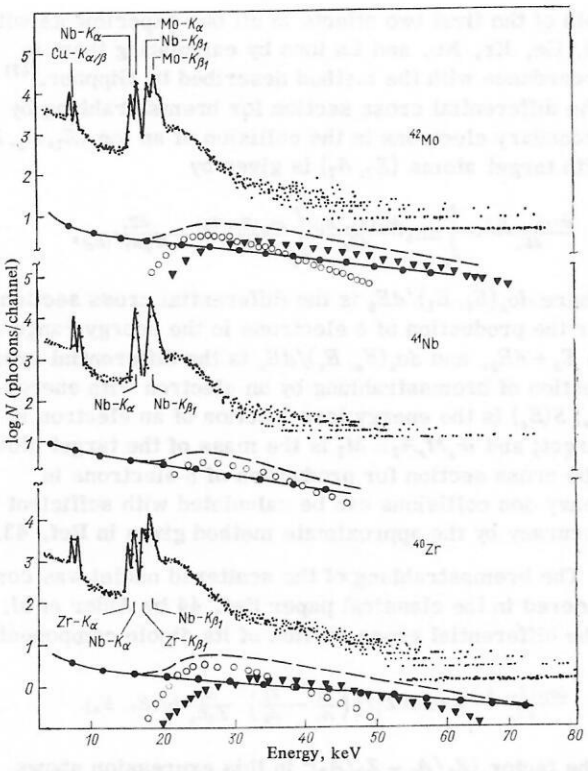

FIG. 12. Experimental x-ray spectra measured in Nb + Mo, Nb + Nb, and Nb + Zr collisions. The points are the calculated bremsstrahlung spectra from the scattered nuclei (solid triangles) and secondary electrons (open circles). The total effect from these precesses and the background (shown by the chain curve connecting the solid circles) is appreciably smaller than the observed quasimolecular x-ray continua.[42]

the incident ion, $m_e v_1^2/2$, and the momentum $(\mathbf{p}_e \cdot \mathbf{k}_e)/2m$ of the orbital motion. This leads to a comparatively broad energy distribution of the emitted x rays with a peak at $E_x \approx E(Z_1,\ K \text{ x rays}) + m_e v_1^2/2$.

It is obvious that the radiative capture of electrons, which at small Z_1 and large E_1 plays an important role, cannot have a large influence on the quasimolecular spectra of interest to us in adiabatic collisions of heavier ions; for the probability of formation of K vacancies in the incident ions decreases very strongly with increasing Z_1. Further, the spectrum of x rays due to radiative capture of electrons is shifted with increasing Z_1 further and further toward the characteristic x rays. At ion velocities $v_1 \leq 10^9$ cm/sec, the difference between the energies of the characteristic K x rays of the ions and the mean energy of the radiative-capture x rays is appreciably less than 1 keV, and the two effects virtually overlap. However, the theory of the spectral distribution of the radiative-capture x rays is not yet completely clear, especially with regard to the high-energy tails in the spectra. Therefore, in Ref. 39 this question was tested experimentally in Kr(42 MeV) + Kr collisions by means of a gas target. The measured spectrum and the arrangement of the experiment are shown in Fig. 14. The essence of the experiment is as follows. In the gas target, the mean distance between the atoms is so large that the time between two successive collisions of an ion with the target atoms is appreciably longer than the lifetime of the K vacancies. Therefore, in such collisions the radiative-capture process cannot take place. However, as Fig. 14 shows, the experiments with a gas target gave about the same x-ray spectrum as the experiments with solid targets. Thus, the radiative-capture process is eliminated as a source of the observed high-energy x-ray continuum.

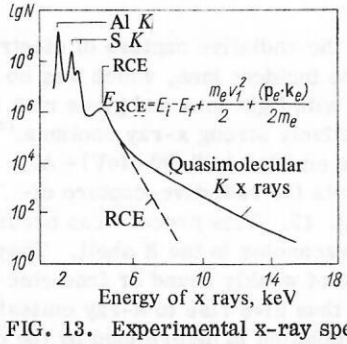

FIG. 13. Experimental x-ray spectrum measured in S(90 MeV) + Al collisions. The continuum at energies above the characteristic S x rays corresponds to the radiative capture of electrons in vacant K shells of the incident ions (RCE) and quasimolecular emission of the S + Al system.[46]

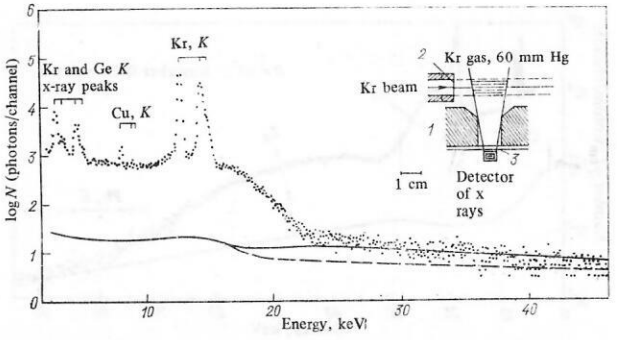

FIG. 14. Experimental x-ray spectrum measured in Kr(42 MeV) + Kr collisions. The upper part of the figure shows the arrangement of the experiment with the gas target[39]: 1) shield (Cu); 2) window (Ni); 3) 2mm Al absorber. The continuous curve is the total spectrum of the calculated bremsstrahlung; the dashed curve is the experimental background.

The analysis of the possible background processes accompanying heavy-ion collisions shows that none of them can explain the observed x-ray continuum, so that they do not contradict the interpretation of the continuum as x rays emitted by quasimolecules. A direct experimental proof of the quasimolecular nature of these spectra was obtained in the experiments of Meyerhof *et al.*[47] in Kr(200 MeV) + Zr collisions and in the experiments of Frank *et al.*[48] in Nb(67 MeV) + Nb collisions by determining the velocity of the radiation source from the Doppler shift of the x-ray energies.

Properties and structure of the quasimolecular K x-ray spectra. There are now available an appreciable number of experimental results on quasimolecular K x-rays obtained in experiments with ions from N ($Z_1 = 7$) to La ($Z_1 = 57$). Some characteristic properties of the spectra of these K x rays of quasimolecules, in particu-

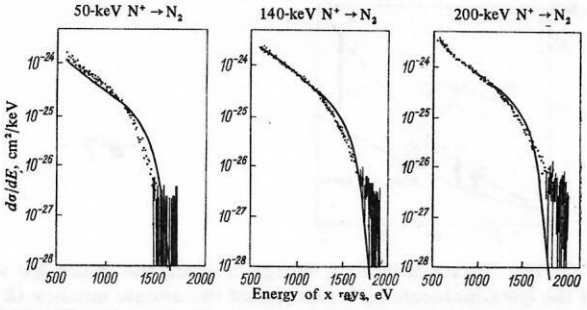

FIG. 15. Spectra of x rays measured in N + N_2 collisions at ion energies 50, 140, and 200 keV. The continuous curves are the spectral distributions of the x rays of the N+N quasimolecules in the adiabatic model.[49]

lar the profile of the spectra as a function of the ion energy, are clearly revealed in experiments with light ions. Such spectra obtained from N + N_2 collisions at different ion energies[49] are shown in Fig. 15. At ion energies $E_1 = 50$ keV, at which the adiabaticity condition is best satisfied ($v_1/u_K = 0.07$), the spectrum of the quasimolecular K x rays has a limiting energy which corresponds to the characteristic K x-ray energies of the double system with $Z = 14$. In this case, the experimental spectrum is reproduced in both shape and absolute magnitude by a calculation in accordance with the quasistatic model under the assumption of a two-stage process of formation of $1s\sigma$ vacancies in a quasimolecule. In the given case, this process can be readily calculated because the ratio between initial and subsequent collisions is determined by the fixed distance between the atoms of the N_2 molecule. As the ion energy is raised to 200 keV, the agreement between the experiment and the quasistatic theory becomes less good. The influence of dynamic effects such as dynamic broadening of the quasimolecular levels during the collision process and the appearance of induced transitions with higher frequencies rapidly increases with increasing ion energy. Basically, they broaden the spectrum of the quasimolecular K x rays to higher energies beyond the limit of the characteristic K x-ray energy of the quasiatom with twice the nuclear charge. This dynamical

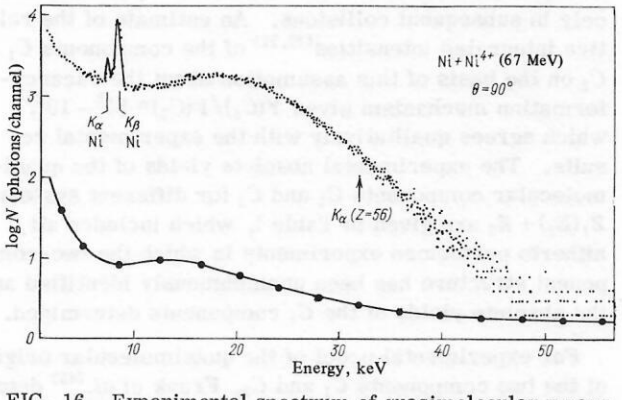

FIG. 16. Experimental spectrum of quasimolecular x rays measured in Ni(67 MeV) + Ni collisions at angle $\theta = 90°$ to the direction of the beam. The lower curve is the total effect of the background precesses.[50]

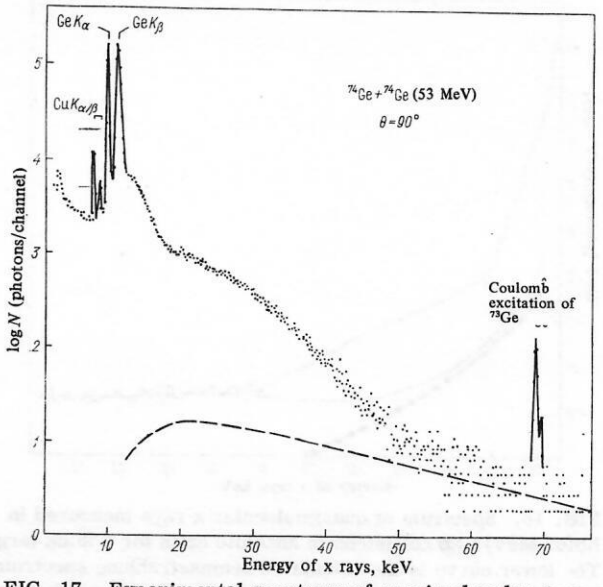

FIG. 17. Experimental spectrum of quasimolecular x rays measured in Ge(53 MeV) + Ge collisions at angle $\theta = 90°$ to the beam direction. The dashed curve is the total effect of the background precesses.[30]

effect is expressed even more strongly in the spectrum of the K x rays of the system Ni(67 MeV) + Ni (Ref. 50), which is shown in Fig. 16. The lower curve is the total spectrum of the experimental background and the calculated bremsstrahlung of secondary electrons and the scattered nuclei. The spectrum of the quasimolecular K x rays extends in this case ($v_1/u_K = 0.27$!) tens of keV beyond its quasistatic limit, and its profile can be reproduced only by a calculation based on a consistent dynamical theory of the ion collision process.[56] We shall come back to dynamical effects once more when we consider the anisotropy of the quasimolecular spectra.

Experiments[30,35,37,38] with the heavier ions Ge, Nb, and La revealed a two-component structure of the continuum of quasimolecular K x rays. As an example, Fig. 17 shows the x-ray spectrum measured in ^{74}Ge(53 MeV) + ^{74}Ge($v_1/u_K = 0.14$) collisions. This structure is manifested even more clearly in Nb(67 MeV) + Nb($v_1/u_K = 0.14$) collisions, for which the x-ray spectrum is shown in Fig. 11. Both in the one case and the other one can clearly see two components of the continuum, to which we have given the names C_1 and C_2. Whereas the properties of the component C_2 identify it as quasimolecular K x-ray emission, i.e., as due to radiative transitions to the $1s\sigma$ state of the quasimolecule, the origin of the component C_1 remained obscure for a comparatively long time. For a more detailed analysis of these components, we show in Fig. 18 the absolute spectrum of the quasimolecular x rays of the system Nb(67 MeV) + Nb deduced from the experimental spectrum after allowance for the detector efficiency and the attenuation of the x-ray intensity by the absorber.

Figure 18 shows that the two components in the quasimolecular spectrum are not due to a fortuitous instrumental effect and cannot be explained by the background

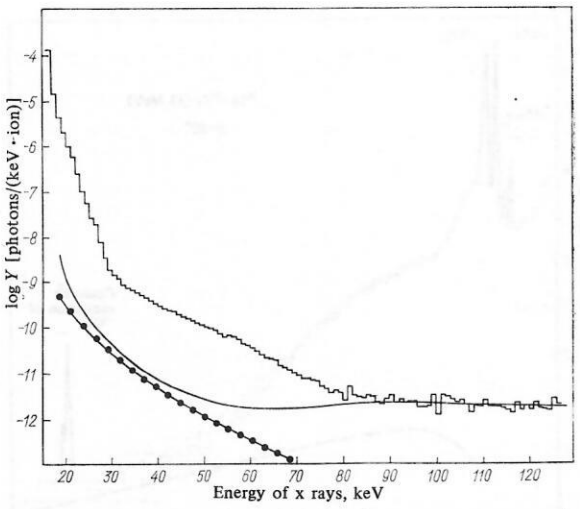

FIG. 18. Spectrum of quasimolecular x rays measured in Nb(67 MeV) + Nb collisions in absolute units for a thick target.[50] The lower curve is the calculated bremsstrahlung spectrum of secondary electrons; the continuous curve is the total effect of the bremsstrahlung of the secondary electrons and the detector background in the absence of the beam.

x-ray spectrum. The point is that the decrease in the C_1 intensity with increasing energy E_x takes place much more rapidly and is approximately proportional to E_x^{-20}. For bremsstrahlung, $I(E_x) \sim E_x^{-7}$. Radiative capture of electrons is also ruled out as a source of the component C_1. This was shown above when we discussed the experiment with the gas target (see Fig. 14). The physical interpretation of the component C_1 was proposed by Heinig *et al.*[51] They analyzed the schemes of the quasimolecular levels of various symmetric quasimolecules and drew attention to the relative minimum in the dependence of the energy of the quasimolecular $2p\sigma$ state on the distance R between the nuclei at intermediate values of R.

This feature in the behavior of the quasimolecular $2p\sigma$ state is shown in Fig. 19, in which we have plotted

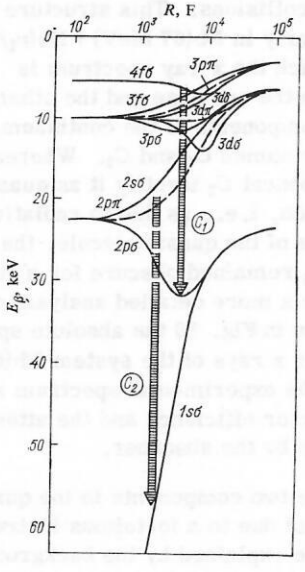

FIG. 19. Energy levels of the (Nb + Nb) quasimolecule as a function of the distance R between the colliding nuclei in accordance with the nonrelativistic calculation of Ref. 52.

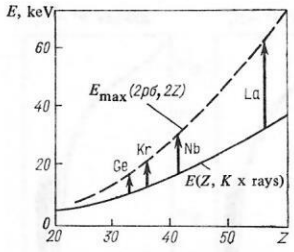

FIG. 20. Maximal binding energy of electrons in the $2p\sigma$ state of the quasimolecule as a function of the atomic number ($Z_1 = Z_2 = Z$) of the colliding ions. The continuous curve is the upper limit of the energy of the characteristic K x rays; the arrows show the experimental energy extension of the C_1 continuum in Ge + Ge, Kr + Kr, Nb + Nb, and La + La collisions.[30]

the energy of the (Nb + Nb) quasimolecular levels as functions of the distance R between the nuclei on the basis of Truskova's nonrelativistic calculation in Ref. 52. The binding energy of the electrons in the $2p\sigma$ state at the distance $R \approx 4 \cdot 10^3$ F reaches about 30 keV, which appreciably exceeds the energy of the characteristic K x rays of Nb and is approximately equal to the limiting energy of the C_1 component in the Nb + Nb collisions. The coincidence of the maximal energy of the C_1 component and the maximal binding energy of the electrons in the $2p\sigma$ state was also established in experiments with other ions. This qualitative agreement between the experiment and the proposed interpretation of the C_1 component is shown in terms of the energy in Fig. 20. It can also be seen in Fig. 20 that detection of the component C_1 when $Z \leq 30$ is made difficult by the fact that with decreasing Z it overlaps ever more closely the very strong characteristic K x rays of the individual atoms. The ratio of the integrated intensities of the two components C_1 and C_2 also favors the proposed interpretation.

If the vacancies in the $1s\sigma$ state of the quasimolecule are formed predominantly by the two-stage process considered above, then in initial collisions the vacancies of outer states go over through $2p\pi - 2p\sigma$ coupling to the $2p\sigma$ state of the quasimolecule and can give rise to radiation transitions in the component C_1. In contrast, the component C_2 can be produced by the formation of vacancies in the $1s\sigma$ state of the quasimolecule only in subsequent collisions. An estimate of the relative integrated intensities[30,51] of the components C_1 and C_2 on the basis of this assumption about the vacancy-formation mechanism gives $Y(C_1)/Y(C_2) \approx 10^2 - 10^3$, which agrees qualitatively with the experimental results. The experimental absolute yields of the quasimolecular components C_1 and C_2 for different systems $Z_1(E_1) + Z_2$ are given in Table I, which includes all hitherto performed experiments in which the two-component structure has been unambiguously identified and the absolute yields of the C_1 components determined.

For experimental proof of the quasimolecular origin of the two components C_1 and C_2, Frank *et al.*[48] determined for the system under consideration (Nb + Nb) the velocity of the source of the x rays from the Doppler shift in the x-ray energies. The arrangement of the

TABLE I. Absolute yields $Y_K(Z_1)$ and $Y_K(Z_2)$ of x rays, and intensities of the quasimolecular components for different systems of colliding heavy ions.

Z_1 (MeV) + Z_2	Target, mg/cm²	Absolute yield of x rays, photons/ion			
		$Y_K(Z_1)$	$Y_K(Z_2)$	Y_{C_1}	Y_{C_2}
Ni (39 MeV) + Ni	1000	1.8 (−2)	—	1.6 (−5)	2.0 (−7)
Ge (54 MeV) + Ge	500	3.6 (−2)	—	4.3 (−5)	6.3 (−7)
Kr (43 MeV) + Kr	185	2.0 (−5)	—	6.0 (−8)	5.0 (−11)
Nb (47 MeV) + Kr	185	5.4 (−7)	2.3 (−5)	1.9 (−7)	≤ 6 (−12)
Kr (43 MeV) + Nb	200	1.9 (−4)	2.8 (−6)	1.4 (−6)	9.0 (−10)
Nb (67 MeV) + Nb	200	2.0 (−4)	—	9.7 (−7)	3.5 (−9)
La (115 MeV) + La	≥ 10⁴	9.6 (−6)	—	3.7 (−6)	4.0 (−10)

experiment is shown in Fig. 21 (see Ref. 47). Depending on the angle of observation and the velocity of the emitting system, the x rays emitted in the heavy-ion collisions will have different Doppler shifts. At angle $\theta = \pm 90°$ relative to the direction of motion of the emitting system the shift is zero. If the x rays are detected at angles 45 and 135°, the Doppler shift has the opposite sign, and its absolute magnitude is determined by the velocity v_1 of the emitting system. If the x-ray spectra are now measured at these angles and their ratio $R(E_x) = N(E_x)_{\theta 1}/N(E_x)_{\theta 2}$ is found, then in the case $\theta = \pm 90°$ we must have $R(E_x) = 1$, while for $\theta = 45$ and 135° we can have $R(E_x) = 1$ only if allowance is made for the Doppler shift of the spectra with the appropriate correct value of v_1. The results of the experiment are shown in Fig. 22. It can be seen that within the experimental errors $R(E_x) = 1$ in the complete range of energies of components C_1 and C_2 only when the Doppler-shift correction to the spectra is made with the mean velocity $\bar{v}_s = (\pi/4)v_\infty/2$ of the quasimolecule. It follows that both components C_1 and C_2 really are emitted by the (Nb + Nb) quasimolecule.

In the experiments of Ref. 53 with Kr and Nb ions, a two-stage process of formation of $1s\sigma$ vacancies in quasimolecules under the conditions $Z_1 \approx Z_2 \approx 40$ and $E_1 \approx 0.5$ MeV/nucleon was assumed. For this, Kr(43 MeV) + Nb and Nb(47 MeV) + Kr collisions, which are virtually identical in the center-of-mass system, were investigated. But in the second case the target is a gas, which precludes formation of $1s\sigma$ vacancies of the quasimolecules in subsequent collisions. Results of the experiment are shown in Fig. 23. It can be seen that the spectra are identical as regards the component C_1, but that C_2 is excited only in the case of the solid target, i.e., when the probability of subsequent collisions is greater. Thus, the assumption of a two-stage formation of $1s\sigma$ vacancies is completely justified and

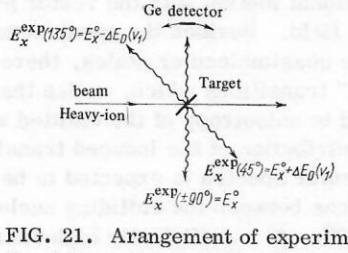

FIG. 21. Arrangement of experiment for determining the velocity of the system emitting the quasimolecular K x-rays from the Doppler shift of the x-ray energy.

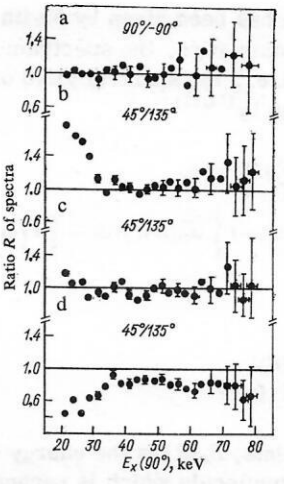

FIG. 22. Ratios of normalized spectra of quasimolecular K x rays measured in Nb(76 MeV) + Nb collisions at different angles[48]: a) and b) without correction of the spectra for the Doppler shift; c) and d) after correction of the spectra for the Doppler shift under the assumption that the velocity of the x-ray source is equal to the velocity $\bar{v}_s$ of the quasimolecule or the velocity $v_\infty = v_1$ of the incident ion.

the above interpretation of the two-component structure of the quasimolecular K x-ray spectrum is confirmed.

Calculation of the spectral distribution of quasimolecular K x rays. Heinig *et al*[54] have calculated the spectral distribution of quasimolecular K x rays for heavy systems like Ni + Ni, Ge + Ge, and Nb + Nb. The calculation is based on a dynamical theory of the formation of intermediate quasimolecular states in heavy-ion collisions, developed by Macek and Briggs[55] when considering quasimolecular K x-ray spectra in collisions of lighter ions. In contrast to them, Heinig *et al.*[54] also took into account the possibility of radiative transitions to the $2p\sigma$ state of the quasimolecules, i.e., the component C_1 of the quasimolecular spectrum, and also the interference between the quasimolecular $2p\sigma$ transitions and atomic $1s$ transitions in the initial collisions. A detailed description of the dynamical theory

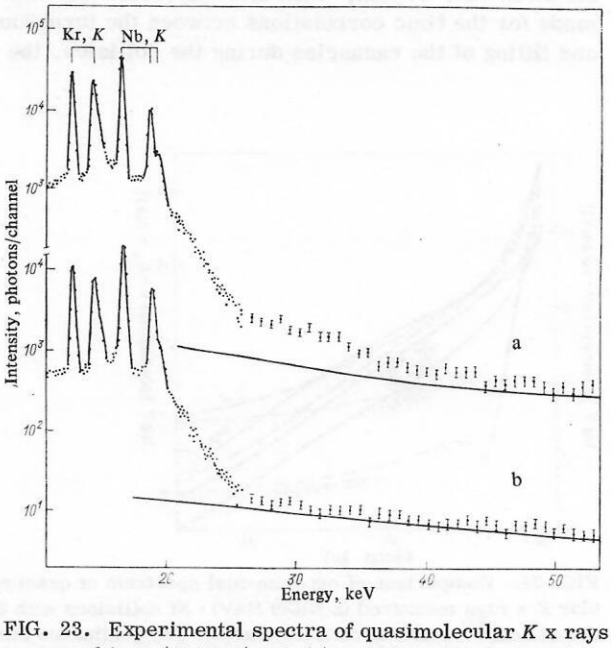

FIG. 23. Experimental spectra of quasimolecular K x rays measured in Kr(43 MeV) + Nb (a) and Nb(47 MeV) + Kr (b) collisions. The continuous curves are the total effect of the background processes.

of quasimolecular emission has been given by Smith *et al.*[56] In the dipole approximation, the spectrum of quasimolecular emission, i.e., the spectral yield of x rays per vacancy, is given by[54,55]

$$I_i(\omega)=\frac{4e^2\omega}{3c^3\hbar}\sum_f |D_{fi}^e(\omega)|^2,$$

$$D_{fi}^e(\omega)=(2\pi)^{-1/2}\int_0^\infty D_{fi}(R(t))\exp\left[i\omega t - i\int_0^t \overline{\omega}_{fi}(R(t'))\,dt' - \frac{\Gamma}{2}t\right]dt,$$

where

$$\hbar\overline{\omega}_{fi}(R(t))=E_i(R)-E_f(R);$$
$$D_{fi}(t)=\langle f|\mathbf{v}|i\rangle=-i\overline{\omega}_{fi}(t)\langle f|\mathbf{r}|i\rangle$$

are the dipole matrix elements; $E_i(R)$ is the energy of the initial state of the quasimolecule which is vacant and has total decay width Γ.

In Ref. 54, Heinig *et al.* calculated the spectra of quasimolecular K x rays in accordance with this expression under the assumption that vacancies in the $2p\sigma$ and $1s\sigma$ states are formed in the two-stage process described above. Without going into the details of the calculation, let us give some of their results. The result of the calculation of $I(\omega)$ for Ni(39 MeV) + Ni collisions is shown in Fig. 24 and compared with the experimental spectrum. In the energy range $E_x = 10-25$ keV, there is good agreement between the results of the calculation and the experiment, even in the absolute values of $I(\omega)$. The deviation of the theoretical curve $I(\omega)$ from the experimental spectrum at energies $E_x > 25$ keV is due to the large contribution of the dynamical tails of the characteristic atomic lines K_α and K_β, which lead to enhanced values of the $3d\pi - 2p\sigma\ (+K_\alpha)$ and $4d\pi - 2p\sigma\ (+K_\beta)$ transition matrix elements. If, for example, these are ignored, then the $I(\omega)$ distribution shown in Fig. 24 by the dot-dash-dot curve is obtained. It is shown in Ref. 57 that, when more accurate allowance is made for the time correlations between the formation and filling of the vacancies during the collision, the

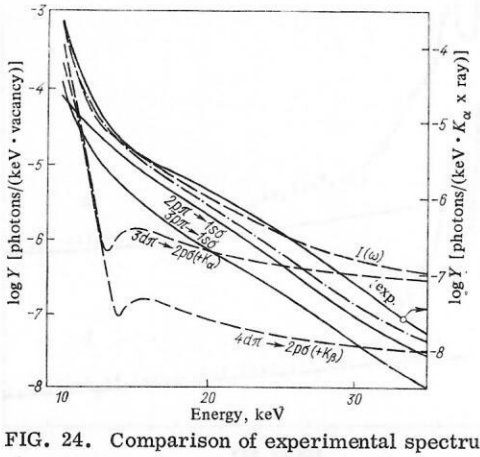

FIG. 24. Comparison of experimental spectrum of quasimolecular K x rays measured in Ni(39 MeV) + Ni collisions with the theoretical[54] spectral distribution $I(\omega)$. The continuous curves are the experimental results; the dashed curves are the calculated components of the theoretical spectrum; the dot-dash-dot curve is the distribution $I(\omega)$.

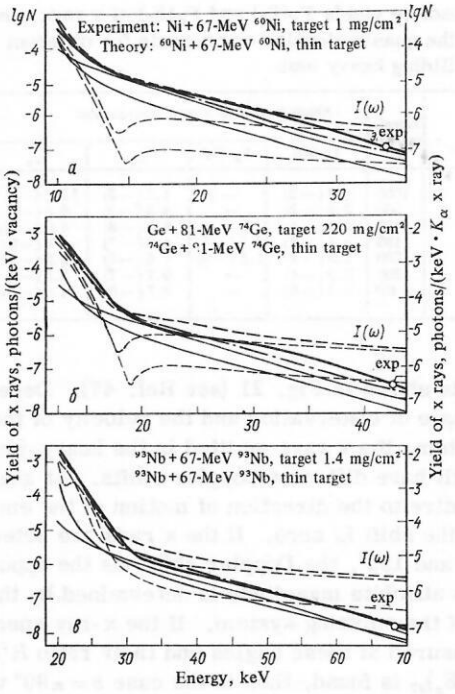

FIG. 25. Quantitative comparison of experimental spectra of quasimolecular K x rays measured in Ni + Ni, Ge + Ge and Nb + Nb collisions in thick targets with the theoretical[54] spectral distributions $I(\omega)$. The continuous curves give the experimental results; the dashed curves give the calculated components of the theoretical spectrum (see Fig. 24).

contribution of the lines K_α and K_β really is reduced significantly and agreement with experiment is obtained in the entire range of energies E_x. The good agreement between the theory and the experiment shows once more that the assumptions made in the calculations about the physical origin of the two-component structure in the spectra of the quasimolecular K x rays and the two-stage process of vacancy formation are correct. The results of calculations for other systems are given in Fig. 25. The comparison with the experiments is here qualitative in nature since the experiments were made using thick targets. The notation in Fig. 25 is the same as in Fig. 24, and the conclusions are analogous.

Angular anisotropy of the quasimolecular K x rays. The dynamics of the heavy-ion collision process leads to the anisotropy of the angular distribution of the emitted quasimolecular x rays that depends on the energy of the x rays. This effect was predicted by Müller *et al,*[58] who took into account the rotational motion of the system of nuclei in the collision and the Coriolis interaction of the rotational motion with the vector potential of the radiation field. Besides the spontaneous transitions between the quasimolecular states, there are then also "induced" transitions which, unlike the spontaneous ones, lead to anisotropy of the emitted x rays. The relative contribution of the induced transitions to the quasimolecular spectra is expected to be largest at short distances between the colliding nuclei, and then reaches 10–20%. At a sufficiently high energy of the incident ions, the observed anisotropy of the quasimolecular spectrum has a maximum in the region

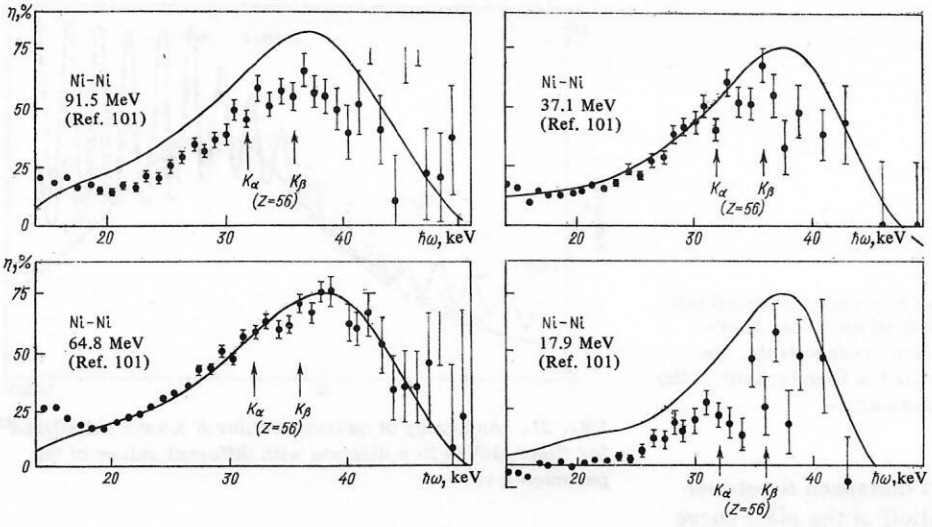

FIG. 26. Anisotropy $\eta = [I(90°)/I(0°)] - 1$ of the quasimolecular K x rays measured in Ni + Ni collisions at different ion energies as a function of the x-ray energies.

of the characteristic K x-ray energy of the quasiatom with the double nuclear charge. A proposal was therefore made in Ref. 4 to use the anisotropy effect for spectroscopic investigation of the electron levels of superheavy quasiatoms. First experimental results on the anisotropy of the quasimolecular x rays were obtained in Refs. 36 and 59. Further experiments were made by the authors of Refs. 60 and 61 and by our group at Dubna.

The results of the investigation of the anisotropy $\eta(E_x) = [I(90°)/I(0°)] - 1$ of the quasimolecular K x rays in Ni + Ni collisions at different ion energies[62] are given in Fig. 26. The experimental results of our investigations[30,48,50] of Ni + Ni, Ge + Ge, and Nb + Nb quasimolecules are given in Figs. 27–29, respectively. Note that to determine the actual anisotropy from the experimental spectra, it is necessary to correct the spectra measured at the angle $\theta = 0°$ for the Doppler shift in the energy of the x rays. The general conclusion drawn from all the presented results is that in all cases the anisotropy $\eta(E_x)$ is indeed observed to attain a maximal value at the energies of the characteristic K x rays of the quasiatoms with the double nuclear charge, i.e., at the maximal binding energy of the $1s\sigma$ electrons in the quasimolecule. Moreover, in experiments with Ge and Nb ions it was found that $\eta(E_x)$ has a clearly expressed second maximum at an energy E_x that corresponds just to the maximal binding energy of the $2p\sigma$ electrons at intermediate distances R between the nuclei of the quasimolecule. The maximal values of $\eta(E_x)$ are about 50%, and they cannot be explained in the framework of a simple theory of induced transitions.[58]

Analysis of the experimental results in Fig. 26 in the framework of an improved dynamical theory,[62] and especially of $\eta(E_x)$ as a function of the ion energy E_1, led to the following conclusions. Ordinary spontaneous transitions in quasimolecules due to interactions of the electron states with the rotational motion of the system of two nuclei also lead to anisotropy of the angular distribution of the quasimolecular spectra, the absolute magnitude and E_x dependence of the anisotropy depending strongly on the distribution of the electrons and vacancies over the states participating in the radiative transitions. The continuous curves in Fig. 26 are the calculated $\eta(E_x)$ curves obtained, for example, under the arbitrary assumption that of the three quasimolecular $2p$ states $[2p_{3/2}\pi,\ 2p_{3/2}\sigma,\ 2p_{1/2}\sigma]$ only the $2p_{3/2}\pi$ and $2p_{1/2}\sigma$ states contribute to the spectrum of quasimolecular K x-ray emission. In these calculations, allowance was also made for strong departure from adiabaticity of the motion of the electrons with respect

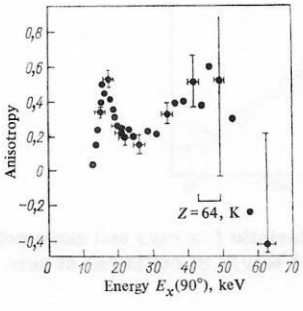

FIG. 27. Anistropy of quasimolecular K x rays measured in Ni(67 MeV) + Ni collisions[50] as a function of the x-ray energies.

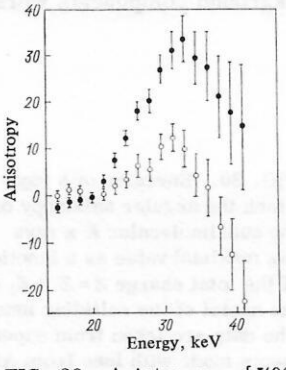

FIG. 28. Anistropy $\eta = [I(90°)/I(0°)] - 1$ of quasimolecular K x rays measured in Ge(54 MeV) + Ge collisions as a function of the x-ray energies with allowance for the Doppler shift for measurements at zero angle.[30] The open and black circles are, respectively, the spectra without and after correction for the Doppler shift of the x-ray energies for measurement at zero angle.

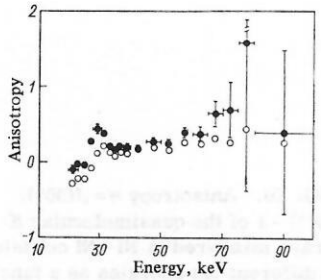

FIG. 29. Anistropy of quasimolecular K x rays measured inN Nb(67 MeV)+Nb collisions as a function of the x-ray energies.[48] The open and black circles are, respectively, the spectra without and after correction for the Doppler shift of the x-ray energies for measurement at zero angle.

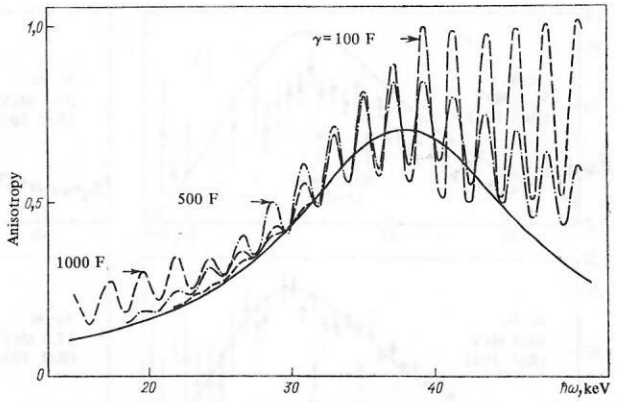

FIG. 31. Anistropy of quasimolecular K x rays calculated[28] for Ni(40 MeV) + Ni collisions with different values of the parameter γ.

to the rotation (slippage) at short distances R between the nuclei.[63] This leads to a falloff of the $\eta(E_x)$ curve at energies higher than the $1s$ energy of the united quasiatom. Overall, the theory of the anisotropy of the quasimolecular emission is not yet completely clear and requires further experimental and theoretical investigations.

Theoretical calculations of $\eta(E_x)$ with allowance for the $2p\sigma$ component of the quasimolecular emission have not yet been made and, at the present state of development of the theory, are complicated. However, these investigations are of great interest in connection with the question of the extent to which experimental investigations of the anisotropy of the quasimolecular spectra could provide a tool for spectroscopy of superheavy quasiatoms. The available experimental data justify a certain optimism. Figure 30 shows the energies E_x at which the anisotropy $\eta(E_x)$ of the quasimolecular K x rays for different systems $Z_1 + Z_2$ takes its maximal values as a function of the atomic number of the quasiatom with effective atomic number $Z = Z_1 + Z_2$ (Ref. 61). All the experimental points lie on the curve that corresponds to the energies of the K_α characteristic x rays of the atoms with nuclear charge Z. Experiments to determine $\eta(E_x)$ for the quasimolecular K x rays of superheavy quasimolecules have not yet been made. They entail great experimental difficulties because the ratio of the effect to the background components worsens seriously because of the strong decrease in the cross section for formation of K vacancies at large Z.

In the experiments of Greenberg *et al*[36] and Wölfli *et al*[61] oscillations were observed in the spectra and in the anisotropy $\eta = \eta(E_x)$ of the spectra as a function of the energy of the quasimolecular K x rays. These oscillations were widely discussed in the theoretical papers Refs. 28, 55, and 65. Oscillations may appear in the quasimolecular spectra because the amplitudes of the quasimolecular transitions are a coherent superposition of all transitions along the classical trajectory of the scattered ion. This can lead to interference between the x-ray transitions that occur during the approach and separation of the colliding nuclei. In Refs. 28 and 65, a study was made of interference effects and corresponding oscillations in the spectra when there are sudden rearrangements of the wave functions of the quasimolecular states at definite distances R between the nuclei. In this approach, the frequencies of the oscillations are determined by the values of R at which there is a strong rearrangement of the electron shells during the collision, and the amplitudes of the oscillations are determined by some width γ in the action of the perturbation.

Theoretical predictions of the relative effect of the

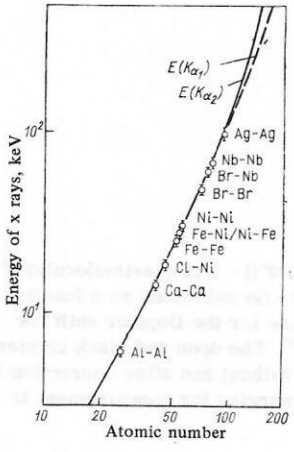

FIG. 30. Energies of x rays at which the angular anistropy of the quasimolecular K x rays has maximal value as a function of the total charge $Z = Z_1 + Z_2$ of the nuclei of the colliding ions. The data are taken from experiments made with ions from Al to Ag. The curves show the variation in the energy of the K_α x rays of the elements with atomic number Z (Ref. 61).

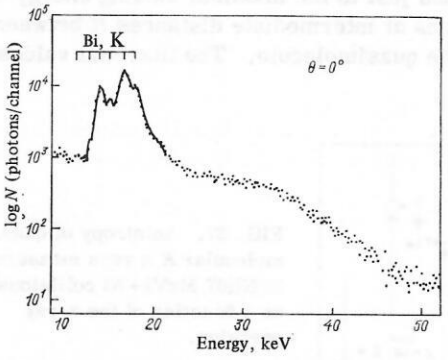

FIG. 32. Spectrum of characteristic L x rays and quasimolecular x rays measured in Bi(172 MeV) + Bi collisions at zero angle.

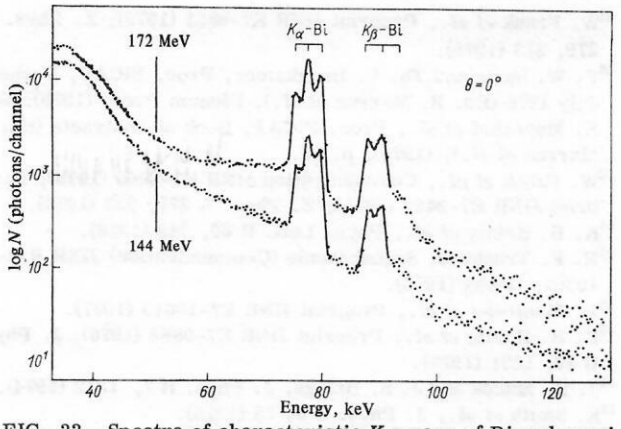

FIG. 33. Spectra of characteristic K x rays of Bi and quasimolecular K x rays measured in Bi+Bi collisions at ion energies 144 and 172 MeV at zero angle.[30]

oscillations in the anisotropy of $\eta(E_x)$ of the quasimolecular K x rays of the Ni(40 MeV)+Ni system[28] are shown in Fig. 31. Experimentally, the problem of the appearance of the oscillations in the quasimolecular spectra remains as yet unsolved. The experimental results of Greenberg *et al*[66] were not confirmed in the subsequent control experiments. In addition, it was found that the oscillations observed in Ref. 61 in the anisotropy of the quasimolecular K x-ray emission with the amplitude given in Ref. 61 were not manifested in our experiments with Cu and Ni ions. For clarification of this question, it would be more promising to make experiments that distinguish a definite collision parameter by measuring the quasimolecular spectra in coincidence with scattered ions. However, experiments of this type are very complicated[64] because of the relatively low yield of the quasimolecular K x rays.

CONCLUSIONS

During the five years that have elapsed since the observation of the first spectrum of quasimolecular x rays, a considerable amount of material on this phenomenon has been accumulated. The properties of different components of the quasimolecular x rays have been studied, and in particular the two-component structure of the quasimolecular K x-ray spectra has been observed and understood. New results have been obtained on the mechanism of formation of vacancies in inner atomic shells in heavy-ion collisions. Theoretical approaches have been developed for describing the complicated process of collision of two heavy ions. However, many questions, such as the angular distributions of the quasimolecular spectra or the dependence of the spectral distribution of the quasimolecular x rays on the collision parameter of the ions, are by no means fully resolved or even remain completely open. In our critical analysis of the available material, we have restricted ourselves mainly to considering the high-energy components of the quasimolecular x rays, which have the greatest interest for future investigations of superheavy quasimolecules. The first experiments in this direction have been begun with Bi ions at Dubna. The first spectra obtained are shown in Figs. 32 and 33. The K-shell ionization cross sections here were found to be small and the result is rather pessimistic with regard to the experimental detection of spontaneous positron creation in U+U collisions. However, the answer to this question will soon be obtained from the experiments that have already been begun on the new heavy-ion accelerator Unilac at Darmstadt. But irrespective of the success or failure of this particular experiment, the further study of quasimolecules and quasimolecular emission remains an interesting field of investigation for the coming years. Such experiments extend and enrich the physics of the inner atomic shells and may still provide interesting discoveries and applications in, for example, the solution of the problem of induced emission in the x-ray region.[67] Many charged-particle accelerators used earlier exclusively for nuclear physics are splendid tools for investigations in this direction.

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