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The study of quasi-molecular radiation should give one a possibility of investigating two-centre systems during adiabatic collisions. This is of great importance in view of the electronic structure of heavy quasiatoms with $Z>100$ [1,2] and for observing new processes of quantum electrodynamics in very strong electromagnetic fields [3,4]. The latter makes especially attractive experiments using very heavy ions, which involve most strongly bound states of electrons in quasi-molecules. Therefore, during the recent two years our group at Dubna have been carrying out, in the first place, experiments to study some aspects of atomic characteristics and quasimolecular **KX** -rays of very heavy and symmetric collision systems such as Ni + Ni (39 MeV and 67 MeV) [5] , Ge + Ge (81 MeV) [6] , Kr + Kr (42 MeV), Nb + Nb (67 and 96 MeV) [7,8] , La + La (115 MeV) [9] and Bi + Bi (144 and 172 MeV). For these heavy colliding particles, the adiabatic condition is fulfilled better than in the case of collision systems with lower Z, where the orbital velocities of electrons are rather small and the observation of quasi-molecular radiation is more difficult due to the existence of some competing effects, such as radiative electron capture (REC), which also show continuous **X**-ray spectra.

All of our experiments were carried out on an external beam from the U-300 heavy ion cyclotron of the JINR Laboratory of Nuclear Reactions with an intensity ranging from 10^{10} to 10^{12} particles/sec. Figure 1 shows a typical X-ray spectrum observed in our experiments. It was measured in the collisions of 67 MeV **Nb** ions with the atoms of a target made of metallic pure niobium 1 mg/cm^2 thick. The emitted **X**-rays were detected at 90° with respect to the ion beam axis by an intrinsic **Ge** detector with an energy resolution of about 250 eV at 10 keV. The intensively excited **KX**-radiation of **Nb** atoms was strongly suppressed by using an absorber of 0.20 mm **Cu**. Due to a counting

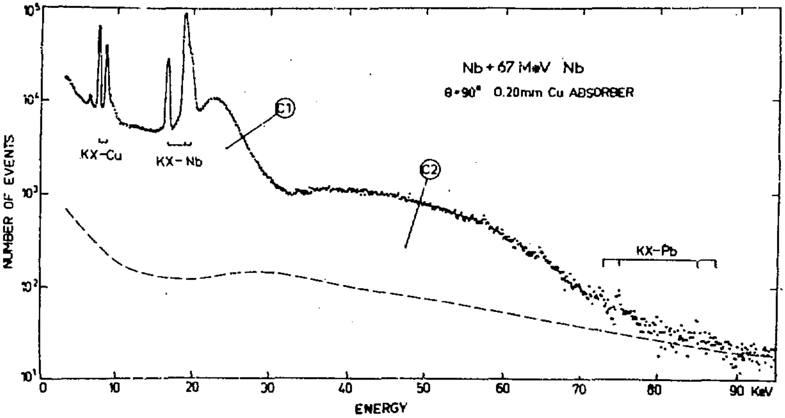

Fig. 1. The **X**-ray spectrum measured by bombarding the **Nb** target with 67 MeV **Nb** ions.

rate lower than 50 s^{-1} , no pile-up effects were expected in this measurement. Besides the intensive KX-lines of the Nb atoms and the absorber material, the spectrum contains a continuous intensity distribution, which ranges approximately up to the united-atom energy. We first showed in our experiments with Ge , Nb and La ions /6,9/ that this X -ray continuum consists of a low-energy and high-energy component, denoted by us as (C1) and (C2), respectively. In fig. 2 are plotted the absolute X -ray intensities corrected for absorption and detector efficiency taken in Nb + Nb collisions (67 MeV). The full line indicates the summed spectrum of the mean background measured and the calculated electronic bremsstrahlung /10/ . This figure shows also that the continuum (C1) is a real physical effect and the continuous X -ray spectrum has the two-component structure. The high-energy part (C2) of the continuum has been identified as quasi-molecular KX - radiation. Besides the properties of the component (C2), the physical nature of the low-energy continuum (C1) is of special interest. Electronic and nuclear bremsstrahlung cannot account for the continuum (C1). As an example, for Nb+ Nb collisions the integral yield computed for electronic bremsstrahlung in the energy range between 16 keV and 30 keV is four orders of magnitude smaller than the measured values. The calculated slope is also wrong. After the correction made for detector efficiency and absorber attenuation the linear extrapolation of the component (C1) in a logarithmic representation shows that the experimental yield Y (C1) goes down like E_x^{-n} with $n \approx 20$. This

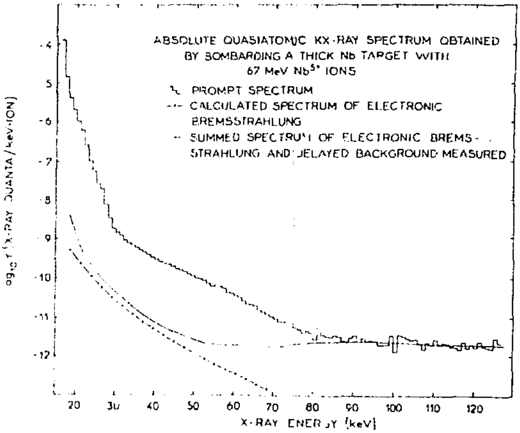

Fig. 2. The quasi-molecular X-ray spectrum of the Nb+Nb (67 MeV) system corrected for absorption and detector efficiency.

disagrees drastically with the calculated value of $n \sim 7$[10] for the electron bremsstrahlung. Further, it seems to be impossible to explain the nature of the continuum (C1) by radiative electron capture (REC), because the cross section of this process is sufficiently low for the atomic numbers of the collision systems investigated in our experiments. We shall revert to this problem later when we consider the results obtained for the Kr + Kr system in experiments with a gas target.

Recently, Hönig et al.[11] tried to give an explanation for the origin of the component (C1), which may take place during the transient formation of quasi-molecules. The

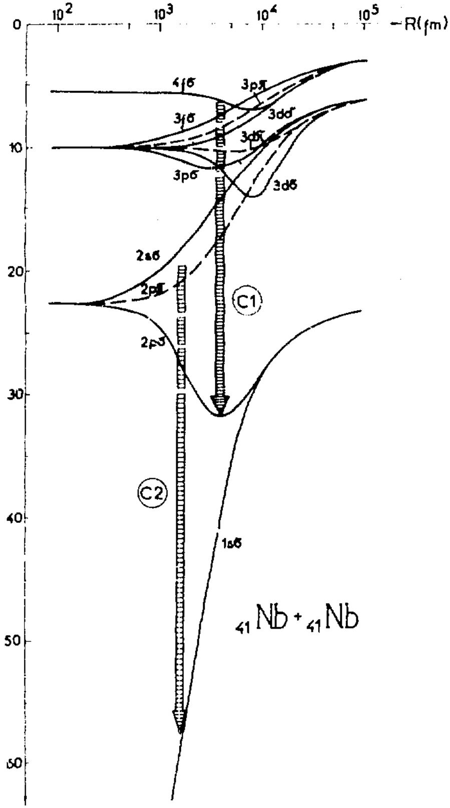

Fig. 3. Molecular level diagram of the Nb+Nb system.

authors pointed out that in all molecular correlation diagrams for medium atomic numbers Z_1 and Z_2 reported till now, the 2pσ term shows a relative minimum. This is shown in fig. 3 with the correlation diagram for quasi-molecular states of the system $_{41}$Nb+ $_{41}$Nb as an example. The energies of the quasi-molecular states are calculated here by N.Truskova [12] by solving a non-relativistic problem with a two-centre potential and a fixed internuclear distance. The 2pσ term joins the **L**- or **K**-shells of the colliding particles in the limits of the united or separated atoms, respectively. Therefore, in the electron promotion model the **L**-vacancies must be transferred in a collision via this term to the

K-shells of the separated atoms. A linear representation of other correlation schemes published demonstrates that allowed transitions from higher terms to the "$2p\sigma$ minimum" have a higher energy than the transitions owing to the characteristic lines. For that reason it is suggested by Heinig et al. /11/ that the continuum (C1) is produced by such transitions. According to these suggestions the high intensity of the continuum (C1) can be explained assuming that the vacancies in the $2p\sigma$ minimum were filled mostly in a first collision, whereas a second collision is assumed to produce the continuum (C2) /13/.

In order to obtain additional experimental information about the proposed quasi-molecular origin of both components (C1) and (C2) of the X-ray continuum, we have performed an experiment aimed at the determination of the velocity of the radiative system using the X-ray energy Doppler shift in the collisions Nb + Nb (67 MeV). A similar experiment has recently been carried out by Meyerhof et al. /14/ for the high-energy part of the continuum in the collisions Zr + Kr (200 MeV). The essence of this experiment is as follows. As a function of the velocity of the radiative system, the energies of the X-rays emitted obtain a Doppler shift which can be determined by detecting X-rays at different angles with respect to the ion beam direction. The Doppler velocity characterizes the radiative system irrespective of the details of the assumed production mechanism for the X-ray continuum. In particular, if radiation in a certain X-ray energy region is believed to originate from quasi-molecular processes, the Doppler velocity should be equal to the centre-of-mass velocity, $V_{c.m.}$, of the intermediate molecules. Figure 4 shows the principal experimental arrangement used to measure the Doppler velocity. The metallic Nb target, 1 mg/cm^2 thick, was placed at ±45° with respect to the ion beam. The measurements were made at the laboratory angles $\theta = -90°$, 45°, 90° and 135°. Each spectrum was normalized to the intensity of the Nb-K_α line which had an isotropic angular distribution. Figure 5 shows the results of these measurements. In figs. 5a and 5b we present the ratios of the normalized spectra at +90° and -90° and at 45° and 135°, respectively, as a function of the X-ray energy in the laboratory system. The asymmetry seen in fig. 5b occurs as a result of the fact that at angles of 45° and 135° the X-ray energy Doppler shift has an opposite sign. The ratios of the spectra at 45° and 135° taking into account the Doppler shift in the cases of the velocity $V_{c.m.}$ of the intermediate molecules Nb+Nb and V_∞ of the 67 MeV Nb projectiles are shown in figs. 5c and 5d, respectively. Figure 5c shows that in the energy

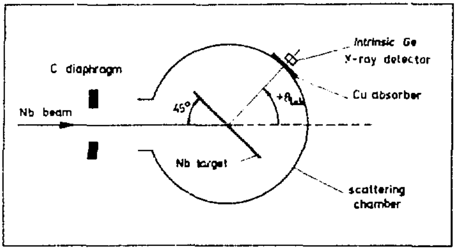

Fig. 4. The principal experimental arrangement for Doppler shift measurements.

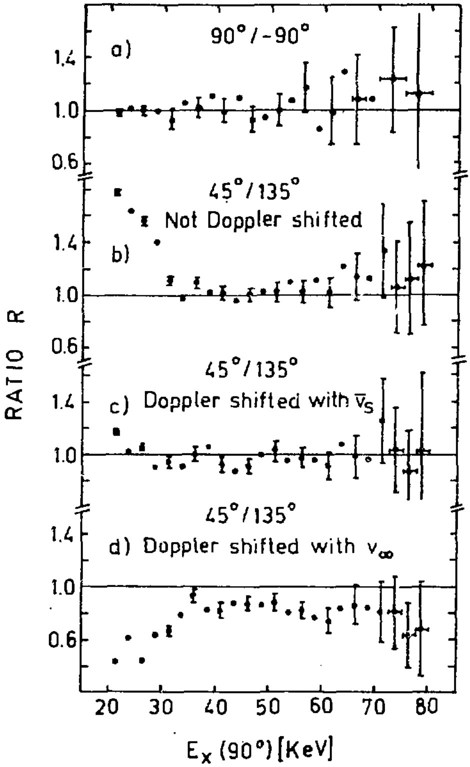

Fig.5. Ratios of normalized X-ray spectra from Nb+Nb (67 MeV) collisions, without (a)(b) and with (c)(d) the Doppler shift correction made.

regions of both continua, (C1) and (C2), X-rays are emitted from systems having velocity $V_{c.m.}$ of the quasi-molecule Nb + Nb. From this fact we conclude that both components of the X-ray continuum, (C1) and (C2), originate from quasi-molecular transitions. Thus, their previous interpretation is confirmed by this independent experiment with Doppler shift measurements.

It is important to determine the Doppler shift of the continuum X-rays from heavy-ion collisions also for another reason. In the interpretation of the Laboratory anisotropy of the continuum X-ray spectrum, which has first been found by P.Armbruster et al./15/, knowledge of the Doppler velocity is needed in order to compare the measured anisotropy with the theoretically predicted c.m. anisotropy of the quasi-molecular X-rays. It has been shown that dynamic effects play an important rôle in the shape of the X-ray continua observed in heavy ion-atomic collisions [16]. They cause a smearing of the quasi-molecular X-ray distributions beyond the K energy limit of the united atom and lead to induced transitions between molecular electronic states. These induced transitions originating as a result of the rotation of the internuclear axis add coherently to the so-called spontaneous molecular transitions. The sum of these two parts of quasi-molecular X-radiation produces the anisotropy of the spectra with respect to the incident beam direction. The rapid variation of the anisotropy near the united atom energy limit indicates a quasi-molecular phenomenon, but further experimental and theoretical developments are needed to clarify the origin of the anisotropy. Our Dubna group started investigations with the anisotropy of quasi-molecular KX-rays for the system Ni + Ni (67 MeV) and obtained the same results as those of Greenberg et al. [17]. Figure 6 shows that in Ni + Ni collisions the asymmetry η (E_x) of the quasi-molecular KX-radiation shows a maximum at an X-ray energy of $E_x \simeq 32$ keV, where the KX-radiation of the united atom ($Z = 56$) is expected. The values of η without and with the Doppler correction are of the same order of magnitude as those obtained by Greenberg et al. [17]. Recently, we have carried out measurements of X-ray asymmetry in the region of quasi-molecular continua (C1) and (C2) in the system Nb + Nb (67 MeV).

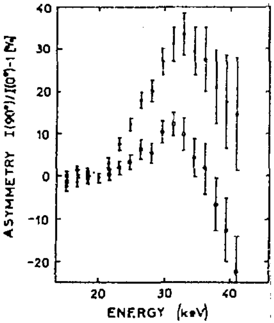

Fig. 6. The asymmetry $\eta = I(90^\circ)/I(0^\circ) - 1$ of the quasi-molecular KX-radiation obtained in the Ni + 67 MeV Ni measurement /5/ .

After determining the Doppler velocity for this case in the experiment described above one could correct the observed spectra for this effect and determine reliably the behaviour of the anisotropy as a function of the X-ray energy. The results of these experiments are shown in figs. 7 and 8. Open and closed circles denote the η values without and with Doppler correction, respectively. This correction was introduced by the formula $E_{i,m} = E_i(1 + \bar{v}_s/c\ \cos\theta)$, where $E_{i,m}$ is the energy measured within an energy interval{i}, $v_s = 1/2\ \pi/4\ v_\infty$ is the mean c.m. velocity in the system Nb + Nb (67 MeV) and θ is the photon emission angle. The v_s value has been calculated by integrating over all impact parameters corresponding to classical ion trajectories which intersect the K-shell radius of the Nb atom. One can see that the asymmetry has two maxima in the energy regions of 29 keV and 80 keV, which just correspond to the maximum energies of the two continuum components (C1) and (C2) of the quasi-

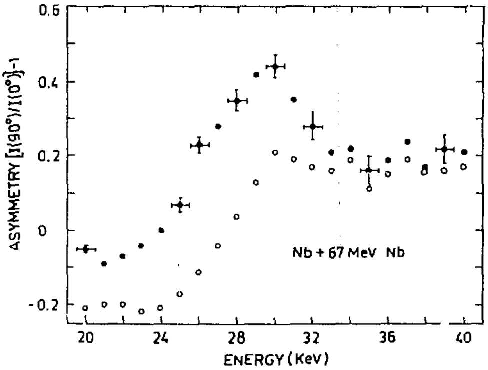

Fig. 7

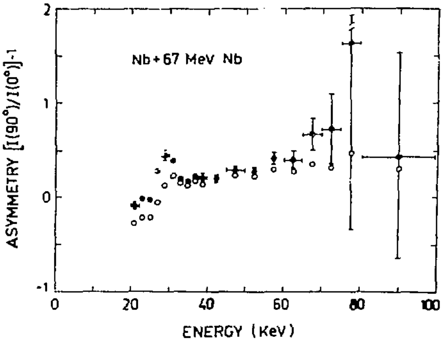

Fig. 8

The asymmetry $\eta = I(90°)/I(90°) - 1$ of the quasi-molecular X-ray spectra obtained in the Nb+67 MeV Nb measurement. The open and closed circles show the η values without and with the Doppler correction, respectively.

molecular spectrum observed by us. At the same time they correspond to the maximum energies of possible transitions of the quasi-molecule **Nb** + **Nb** to the $2p\sigma$ and $1s\sigma$ states at small internuclear distances (see fig. 3). This indicates that these new results on the angular asymmetry of quasi-molecular continua (C1) and (C2) provide at least additional independent experimental evidence in favour of the previous interpretation of quasi-molecular **KX** -ray spectra as having the two-component structure.

In order to obtain further information on the components (C1) and (C2), in particular, as to whether they get excited preferentially in one-step or two-step collisions, we investigated **X**-ray spectra by bombarding gas targets. Figure 9 shows the experimental set-up and the **X** -ray spectrum measured in the case of the system **Kr** + **Kr** (42 MeV).

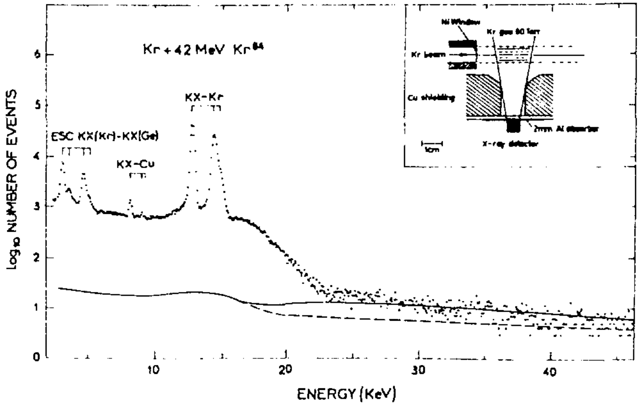

Fig. 9. The **X**-ray spectrum measured by bombarding the **Kr** gas target with 42 MeV **Kr** ions.

A ^{84}Kr ion beam with an incident energy of 73 MeV reaches, through a thin Ni foil, a target filled with gaseous Kr at a pressure of 60 torr. The experimental geometry is such that the Ge detector is capable of detecting only those X-rays which are produced in the gas volume located rather far from the Ni foil. Thus, the K-vacancies produced in the projectiles as they pass through the foil are already filled and cannot cause any effects in the spectra measured. Since the ions are retarded in the Ni foil and gas volume, their average velocity in the effective target volume is as low as about 42 MeV. The X-ray spectrum exhibits the characteristic atomic KX-lines of krypton and Cu absorber and, in addition, a continuum whose properties are similar to those of the low-energy components (C1). The high-energy component (C2) of this spectrum is strongly suppressed and practically absent as compared with the spectrum for the system Nb + Nb (67 MeV). The dotted line in fig. 9 shows the measured background without gas in the target. The solid line presents the total spectrum of the measured background and the calculated nuclear and electronic bremsstrahlung. In the table comparison is made of the absolute yields of separate components of the X-ray spectra obtained using a gas target (Kr + Kr (42 MeV)) and a solid target comparable in respect of Z and ion energy (Nb + Nb (67 MeV)). The absolute yields show that the cross sections for the production of K-vacancies remain nearly the same in both cases or decrease inconsiderably, whereas the absolute yields for both components (C1) and (C2) of the quasi-molecular spect-

Table

Characteristic atomic KX-ray and continuous X-ray yields in bombardment of thick targets with heavy ions

COLL. SYSTEM	ABSOLUTE X-RAY YIELDS [PHOTONS/ ION] $Y(K_{\alpha}, Z)$	$Y(C1, E_X > E(KX,Z))$	$Y(C2, E_X > E(C1))$	$\Delta Y(C2, E_X = E(KX, 2Z))$ [PHOTONS/keV · ION]
Ni + 39 MeV Ni	2×10^{-2}	—	3.2×10^{-6}	2.3×10^{-10}
Ni + 67 MeV Ni	2.0×10^{-1}	—	4.9×10^{-5}	9.3×10^{-9}
Kr + 42 MeV Kr	1.8×10^{-4}	1.9×10^{-7}	$< 8 \times 10^{-11}$	—
Nb + 67 MeV Nb	4.6×10^{-4}	6.2×10^{-5}	7.0×10^{-9}	5.2×10^{-12}
Nb + 96 MeV Nb	1.6×10^{-3}	2.6×10^{-4}	2.5×10^{-8}	$< 2.8 \times 10^{-11}$
La + 115 MeV La	5.8×10^{-6}	5.7×10^{-8}	0.4×10^{-9}	5.6×10^{-14}
Bi + 144 MeV Bi	3.7×10^{-8}	—	—	—
Bi + 172 MeV Bi	2.7×10^{-7}	—	—	—

rum decrease, namely, by two orders of magnitude for (C1) and still more for (C2) in the case of the gas target. This indicates that quasi-molecular components (C1) and (C2) get excited in symmetric systems preferentially in two-step collisions. On the other hand, the obvious presence of the intensive component (C1) in experiments with a gas target provides evidence for the fact that this component cannot be caused by radiative electron capture.

The table also presents some quantitative data on the absolute intensities of separate components of the high-energy X-ray spectra for a number of other symmetric collision systems. The last column shows the differential yields of quasi-molecular KX -rays at the X-ray energy corresponding to the united atom energy limit. They show that the future experiments on the investigation of the asymmetry of quasi-molecular transitions in this energy region for very large Z will require ion beams with intensities higher than 10^{12} ions/sec. In our initial experiments with Bi ions we have so far measured only the cross sections for the production of K-vacancies. They turned out to be equal to σ (KX - Bi , 144 MeV) = 1.6×10^{-26} cm^2 and σ (KX - Bi , 172 MeV) = 1.2×10^{-25} cm^2 . The order of magnitude of these values agrees with the scaling law for higher-Z collisions, given by Meyerhof et al. /18/.

Finally, we sum up the main qualitative conclusions drawn from our experiments. They are:

i) In all symmetric collision systems with $Z_1 = Z_2 = Z \geq 32$ the X-ray continua observed at energies higher than the energy of the characteristics KX -radiation of separate atoms have a well-pronounced two-component structure.

ii) The experiments on the determination of the Doppler velocity of the radiative system, the measurements of the angular asymmetry of these spectra, as well as the experiments using a gas target indicate the quasi-molecular origin of both components. The features of these components established by us agree qualitatively with the assumption that the continuum (C1) is associated with transitions to the $2p\sigma$ states, and continuum (C2) with transitions to the $1s\sigma$ states of quasi-molecules with a double atomic number.

A quantitative verification of this picture by an exact theory may open up new possibilities for the spectroscopic investigations of superheavy two-centre systems.

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