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1. INTRODUCTION

The study of quasimolecular radiation should give one the possibility of investigating two-centre systems during adiabatic collisions. This has a great importance in view of the electronic structure of heavy quasiatoms with $Z \geq 100$ [1,2] and for observing new processes of quantum electrodynamics in very strong electromagnetic fields [3,4].

For heavy colliding particles the adiabatic conditions are fulfilled better than in the case of colliding systems with lower Z, where the orbital velocities of electrons are rather small and where the observation of quasimolecular 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. We were overcoming these difficulties by investigating the heavy collision systems Ge + Ge (81 *MeV*) [5], Nb + Nb (67 *MeV*), (96 *MeV*) [6,7], La + La (115 *MeV*) [8] and La + Xe (120 *MeV*, 150 *MeV*) [8]. We first showed that in these experiments an X-ray continuum can be observed, which consists of a low-energy and a high-energy component, denoted by us as (C1) and (C2), respectively [5,6]. The high-energy part (C2) has been identified as the quasimolecular KX-radiation sought for. For the low-energy continuum (C1), whose integral yield exceeds the yield of the continuum (C2) approximately by a factor of ten thousand, an explanation has recently been given in ref. [9].

Further, it has been shown that dynamic effects play an important role in the shape of the KX-ray continua observed in heavy ion-atomic collisions [10,11,12,13]. They cause a smearing of the quasimolecular 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 incoherently to the so-called spontaneous molecular transitions. As it is proposed by Greiner and coworkers /11, 12/, the sum of these two parts of quasimolecular X-radiations produces an anisotropy of the spectra with respect to the heavy ion beam axis. For the quasimolecular KX-radiation this anisotropy was first observed by Greenberg et al. /14/ in the Ni + Ni (70 *MeV*) colliding system and by Thoe et al. /15/ for the lighter systems Al + Al (30 *MeV*) and Si + Si (30 *MeV*).

For the Ni – Ni system, the measured angular asymmetry of the quasimolecular KX-radiation shows a clear maximum in the photon energy region where the K_α energies of the united atom ($Z = 56$) are expected /14/. Although the X-ray spectrum extends beyond this KX energy limit, only a single compact continuum was obtained, while in our experiments on the heavier collision systems /5 - 8/ two continuum components could clearly be distinguished. Further, the endpoint energy of the quasimolecular KX-continua is still an unsolved problem. Some authors believe that a final energy exists, while others assume that the endpoint energy increases with the measuring time and may extend to infinite values.

It is the purpose of this work to contribute to the solution of the open questions mentioned, in particular,

(1) to report new measurements of the colliding systems Zr, Nb, Mo + Nb (96 *MeV*);
(2) to describe measurements on the directional anisotropy of the system Nb + Nb (67 *MeV*) investigated earlier /6/;
(3) to repeat the Ni + Ni experiment under the same experimental conditions as described in ref. /14/, in order to measure the directional anisotropy of quasimolecular KX-rays and to search for two distinct X-ray continua obtained by us in the heavier systems mentioned;

(4) to search for an endpoint energy of the quasimolecular KX-radiation in the Nb + Nb and Ni + Ni colliding systems.

2. *EXPERIMENTAL TECHNIQUE*

All the experiments were performed at the U-300 heavy ion cyclotron of the JINR Laboratory of Nuclear Reactions. The pulsing of the cyclotron beam with 2 *ms* beam-on and 2 *ms* beam-off time offered the possibility of a simultaneous measurement of a prompt effect and delayed background by accumulating both spectra in a prompt-delayed regime.

Figure 1 shows the experimental arrangement used

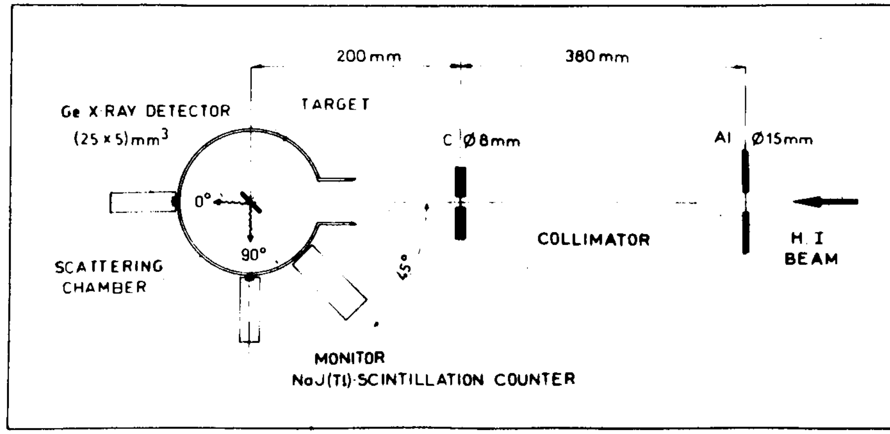

Fig. 1. The principal experimental arrangement.

for the measurements of the anisotropic emission of the quasimolecular X-rays in Ni + ^{60}Ni (67 *MeV*) collisions. The reaction chamber with a diameter of 100 *mm* and a wall thickness of 1 *mm* was made of Al. The ion beam was collimated by a collimator system consisting of an Al diaphragm (ϕ = 12 *mm*) and a C diaphragm

(ϕ = 8 *mm*). The data were obtained using an intrinsic (25 x 5) mm^3 Ge detector and a preamplifier with an optical feedback. The energy resolution was better than 200 *eV* at an X-ray energy of 10 *keV*. The solid angle used for X-ray detection was about $3 \times 10^{-3} \pi$ and the resolution for the emission angle amounted to $\Delta\theta = 6°$. The beam intensity was monitored by a NaI(Tl) crystal, positioned at 135° with respect to the beam direction.

Besides the chamber wall and a 30 μm thick Be window, which separated the detector from atmosphere, no additional absorbers were used in the Ni + Ni measurements. The counting rates amounted to about 70 s^{-1} and were low enough to avoid considerable pile-up contributions. The measurements were carried out with a target placed at an angle of 45° with respect to the beam direction. A thin metallic foil of natural Ni with a thickness of 1 mg/cm^2 was used. The ^{60}Ni ions passing through this foil with an energy of about 37 *MeV* were stopped in the Al chamber wall. The characteristic Al KX-rays arising in Al as a result of the Al – Ni collisions were completely absorbed. The Ni KX-radiation originating in the chamber could not be separated from the target X-ray emission. On the contrary, no remarkable continuous X-ray contributions caused by the Al – Ni collisions in the chamber wall were observed.

For the measurements of the quasimolecular Nb + Nb spectra and the directional asymmetry of quasimolecular KX-rays originating in Nb + Nb collisions we used an arrangement similar to that described above. Because of much lower intensity of the MO radiation the distance between the focus and the detector was reduced to 21 *mm*. Therefore, in the Nb + Nb measurements the solid angle and the resolution of the emission angle amounted to about $1.8 \times 10^{-2} \pi$ and $\Delta\theta = 16°$, respectively. The target consisted of a 0.49 mg/cm^2 metallic foil with a Be stopper and was exposed at 45° with respect to the beam direction. The characteristic KX-rays were attenuated by the chamber wall (0.5 *mm* Al) and a 0.18 *mm* thick Cu foil added.

For the determination of the ion current we insulated

the entire chamber, which had only a small aperture for the entrance of the beam. This entrance slit and the escape of δ-electrons from the chamber against the beam direction influenced the accuracy of the ion current measurement.

3. *RESULTS OF EXPERIMENTS WITH ^{93}Nb IONS OF 67 AND 96 MeV ENERGY*

The results of our former measurements of the quasimolecular KX-radiation originating in the collision systems Zr, Nb, Mo, Rh + Nb (67 *MeV*) have been reported elsewhere /6/. Now we report the results obtained by bombarding natural Zr, Nb and Mo targets with Nb ions of an energy of 96 *MeV* /7/. ***Figure 2*** shows the X-ray spectra taken with the experimental arrangement described above and with a Si(Li) detector exposed at 90° with respect to the beam direction. The low-energy regions of all the spectra contain the well resolved characteristic KX-radiation of the Nb projectiles and the target atoms as well as the fluorescence radiation of the absorber material. In the direction of higher energies there adjoin two distinct X-ray continua, which we denote by (C1) and (C2). According to the results of our previous measurements /5,6,7/, we suppose that the continua (C2) for all the colliding systems we have investigated here are mainly formed by quasimolecular KX-radiation. The nature of the continua (C1) whose integral yields Y (C1) exceed the values of Y(C2) by four orders of magnitude (see the table) is discussed in chapter 5. ***Figure 3*** shows the absolute X-ray intensities corrected for absorption and detector efficiency. The delayed background measured has not been drawn. Circles and triangles represent the calculated spectra of electronic and nuclear bremsstrahlung /16/, whereas the full lines indicate the summed spectra of the mean delayed background measured and the calculated bremsstrahlung. It should be noted that the separation of the spectra into a low-energy part (C1) and a high-energy part (C2) can also be done after correction for detector

Table

CHARACTERISTIC ATOMIC KX-RAY AND CONTINUOUS X-RAY YIELDS IN BOMBARDMENT OF THICK TARGETS WITH Nb IONS. THE HIGH-ENERGY CONTINUUM C 2 IS INTERPRETED AS KX-RADIATION OF THE QUASIMOLECULES WITH $Z = Z_1 + Z_2$

E_0 (MeV)		TARGET	ABSOLUTE X-RAY YIELDS (1) PER 10^9 PROJECTILES								RELATIVE YIELDS	
			Y(KX$_\alpha$-TARGET)		Y(KX$_\alpha$-Nb)		Y(C 1) (2)		Y(C 2) (3)		Y(C2)/Y(KX$_\alpha$-Nb)	
Nb^{5+}	Nb^{6+}		Nb^{5+}	Nb^{6+}	Nb^{5+}	Nb^{6+}	Nb^{5+}	Nb^{6+}	Nb^{5+}	Nb^{6+}	Nb^{5+}	Nb^{6+}
65	-	$_{33}As$	-	-	9.4×10^3	-	0.9×10^4	-	<1	-	$\leq 10^{-4}$	-
65	96	$_{40}Zr$	5.1×10^5	7.1×10^5	2.7×10^5	4.5×10^5	1.0×10^5	1.9×10^5	8.2	23.5	$(3.0 \pm 0.6) \times 10^{-5}$	$(5.2 \pm 1.2) \times 10^{-5}$
65	96	$_{41}Nb$	2.3×10^5	8.1×10^5	2.3×10^5	8.1×10^5	6.2×10^4	2.6×10^5	7.0	25.2	$(3.0 \pm 0.6) \times 10^{-5}$	$(3.1 \pm 0.8) \times 10^{-5}$
65	96	$_{42}Mo$	3.4×10^5	4.9×10^5	5.8×10^5	7.4×10^5	2.4×10^5	4.9×10^5	15	26.4	$(2.7 \pm 0.5) \times 10^{-5}$	$(3.6 \pm 0.8) \times 10^{-5}$
65	-	$_{45}Rh$	4.4×10^4	-	4.6×10^5	-	1.8×10^5	-	4.3	-	$(0.9 \pm 0.2) \times 10^{-5}$	-

1 Maximal error = ±30%   2 Y(C1): 16 keV ≤ E_x ≤ 30 keV

3 Y(C 2): $E_x \geq 30$ keV

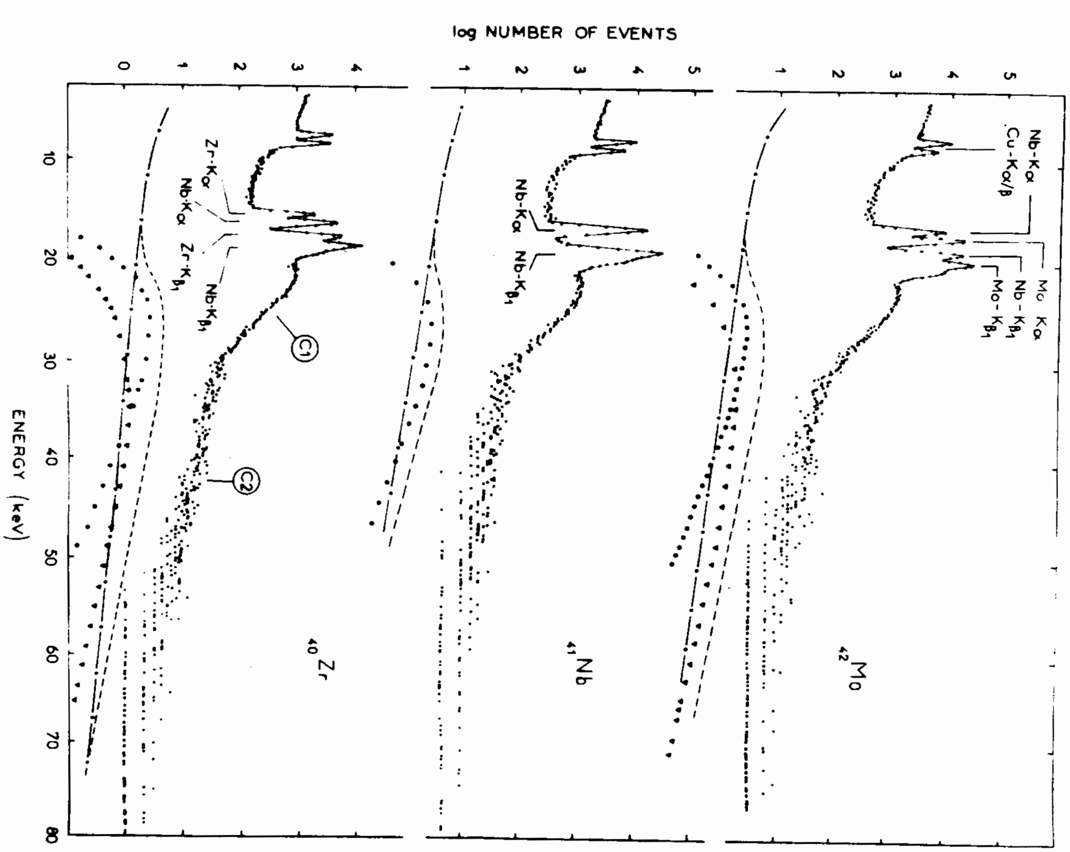

Fig. 2. The X-ray continua obtained in the reactions Zr, Nb, Mo + ^{93}Nb (96 MeV) /7/. The spectra are normalized to the same ion flux. The dashed-dotted lines represent the mean background measured in a delayed regime. The triangles and circles denote the calculated spectra of nuclear and electronic bremsstrahlung. The dashed lines are the summed spectrum of the delayed background and bremsstrahlung.

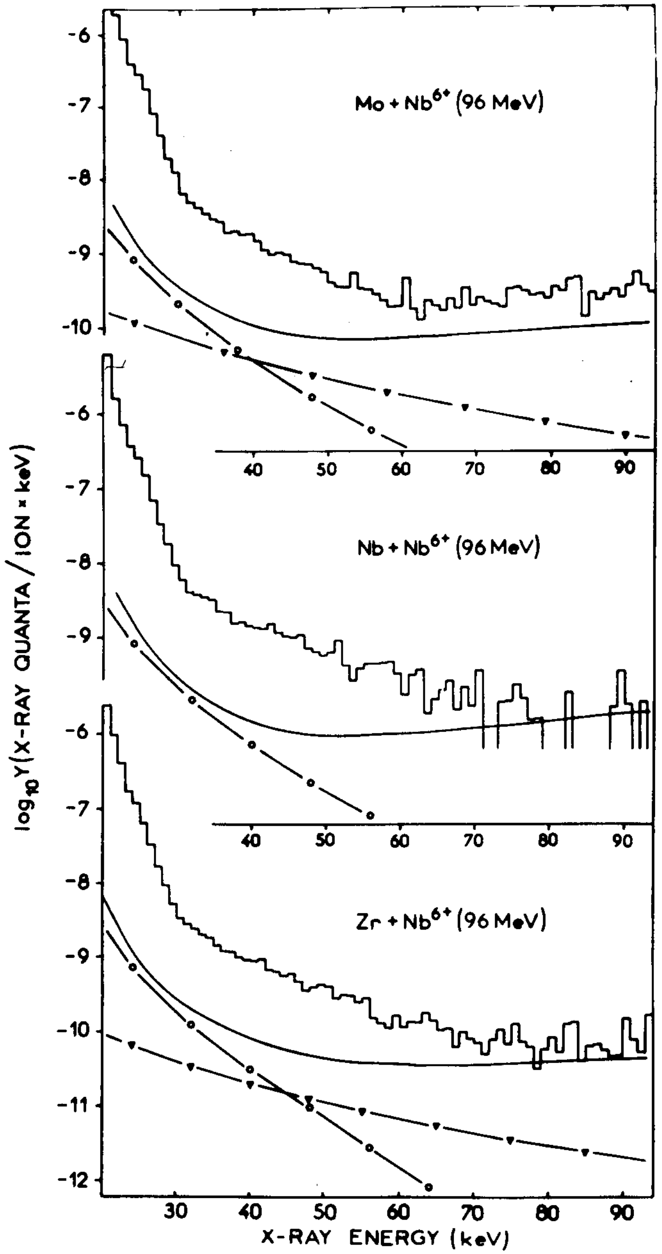

Fig. 3. The absolute quasiatomic X-ray spectra obtained in the reactions Zr , Nb , Mo + ^{93}Nb *(96 MeV), corrected for absorption and detector efficiency. For explanation of the symbols, see the text.*

efficiency. The table summarizes the absolute and relative yields of the atomic KX-radiation of both components (C1) and (C2), obtained by bombardment of thick targets with Nb ions of an energy of 67 *MeV*/6/ and 96 *MeV*. The yields are determined after the correction made for the detector efficiency and after subtraction of the summed background spectrum (see *fig. 3*). To evaluate the yields of the low energy components (C1), the energy region above 16 *keV* was only taken into account, because the shape of these contributions for energies lower than 16 *keV* is quite unknown. The separation of the continua (C1) and (C2) was carried out as indicated in ref./6/ .

Recently we have observed a directional anisotropy for the quasimolecular X -rays produced in Nb + Nb (67 *MeV*) collisions, which favors photon emission at 90° relative to 0° , measured with respect to the ion beam axis. *Figure 4* shows the asymmetry defined by $\eta = I(90°)/I(0°) - 1$ as a function of the X-ray energy.

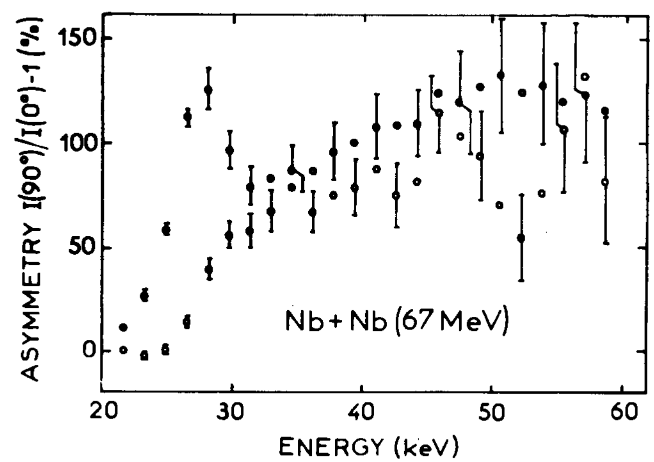

Fig. 4. The asymmetry $\eta = I(90°)/I(0°) - 1$ *of the quasimolecular KX-radiation obtained in the* Nb + Nb *(67 MeV) measurement. The open and closed circles show the* η *values, respectively, without and with the Doppler correction made.*

The spectra taken at detector angles of 90° and 0° were normalized to the whole intensity of the $Nb-K_{\alpha/\beta}$ lines which we assume to be isotropic. In order to get the points of *fig. 4* we summed the normalized spectra over an interval of 10 channels (1.5 *KeV*) and subtracted the delayed background and the calculated electronic bremsstrahlung. Open and closed circles denote the η values, respectively, without and with the Doppler correction made. This correction was carried out by the formula

$$E_{i,m} = E_i \left(1 + \frac{\bar{v}_s}{c} \cos\theta\right),$$

where the $E_{i,m}$ are the measured energies within an interval $\{i\}$, $\bar{v}_s = \frac{1}{2}\frac{\pi}{4} v_\infty$ is the mean velocity of the center of mass in the system Nb + Nb (67 *MeV*) and θ is the photon emission angle. The $\bar{v}_s$ 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. For X-ray energies $E_x > 60$ *KeV* the statistical errors in the spectra increase and we are quite unable to obtain information about the shape of the asymmetry curve in this energy region, where the KX-radiation of the united system exists and a relative maximum is expected /11,12/. Further experimental investigations with much better statistics in the continuum (C2) are required to provide evidence for the existence of this maximum. On the other hand, the relative maximum at 28 *KeV*, where the continua (C1) and (C2) overlap is a real effect.

To get information about the final energy E_{max} of the quasimolecular continuum (C2), we performed a Nb + Nb (67 *MeV*) run of more than 15 hours recording the accumulated spectrum each 3 hours. *Figure 5* illustrates the results of this measurement. Since the determination of E_{max} is drastically influenced by the room background use was made of a special Pb shielding surrounding the reaction chamber and the detector. Thus we reduced the rate of X-rays and low-energetic γ-rays in the beam-off time by more than a factor of ten against the measurements with 67 *MeV* Nb ions cited in ref./6/ .

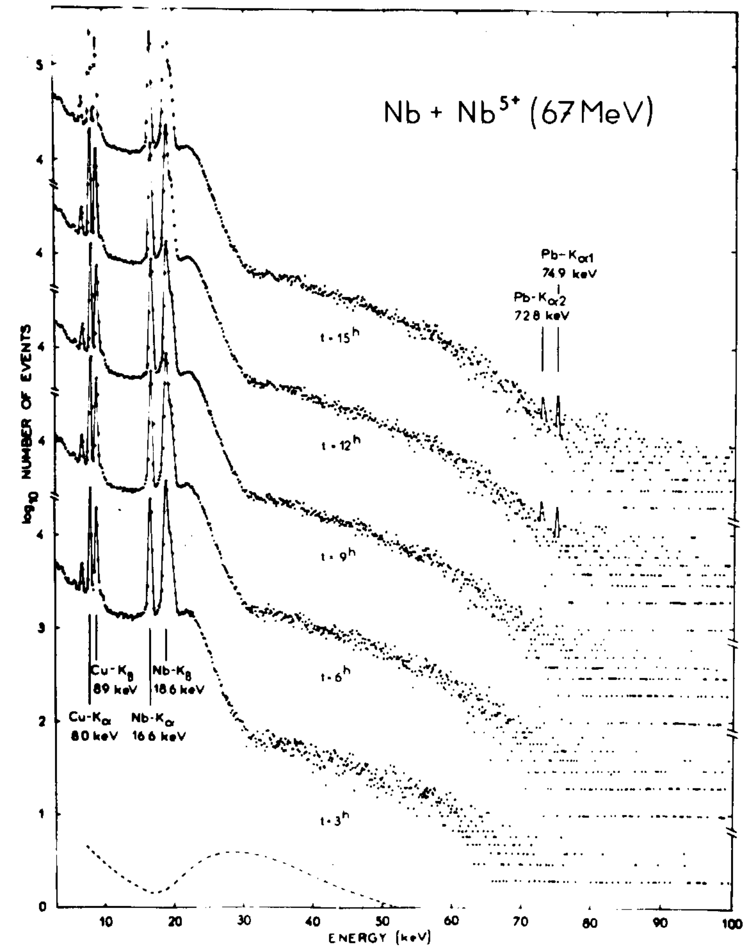

Fig. 5. The measured X-ray spectra of the collision system $^{93}Nb + {}^{93}Nb$ (67 MeV) as a function of the measuring time. The dashed line in the lowest spectrum indicates the sum of the delayed background measured and the calculated electronic bremsstrahlung.

In *figure 6* the full lines represent the X-ray spectrum and the delayed background, obtained in the 15-hour run but summed over an interval of 10 channels. The dashed lines denote the limits of the statistical errors.

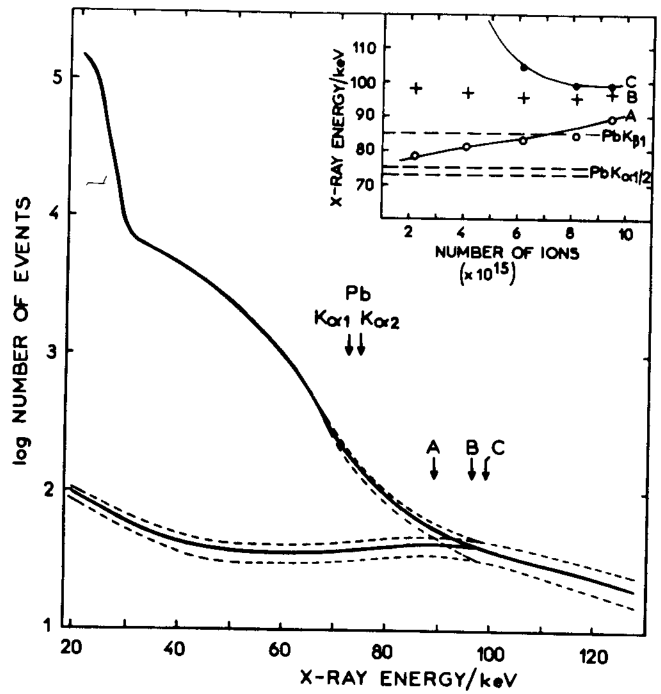

Fig. 6. The measured X-ray spectrum of the collision system ^{93}Nb + ^{93}Nb(67 MeV) taken after 15 h measuring time. The insert shows the dependence of E_{max} on the number N of incident ions. For explanation of the symbols see the text.

The point of intersection, B, between the delayed background and the continuous X-ray spectrum was interpreted by us as the endpoint energy E_{max} we looked for. The points A and C do limit the energy interval where E_{max} can be situated due to statistical errors. The insert of *fig. 6* shows the dependence of these point on the number N of incident Nb ions. The crosses represent

the endpoint energies, open and full circles the points A and C respectively. The crosses demonstrate that the endpoint energies approximated in connection with a rather low background vary only slowly. As one expects, the energy interval {A, C}, where E_{max} can be defined, decreases with increasing N. For a number of incident Nb ions, $N = 9.4 \times 10^{15}$, we obtained the value of $E_{max} = (96.6 \pm ^{2.5}_{3.5})$ *KeV*.

In *figure 7* are plotted the absolute X-ray intensities corrected for absorption and detector efficiency taken in Nb + Nb (67 *MeV*) collisions. The measured delayed background is not shown. The full line indicates the summed spectrum of the mean background measured and the calculated electronic and nuclear bremsstrahlung.

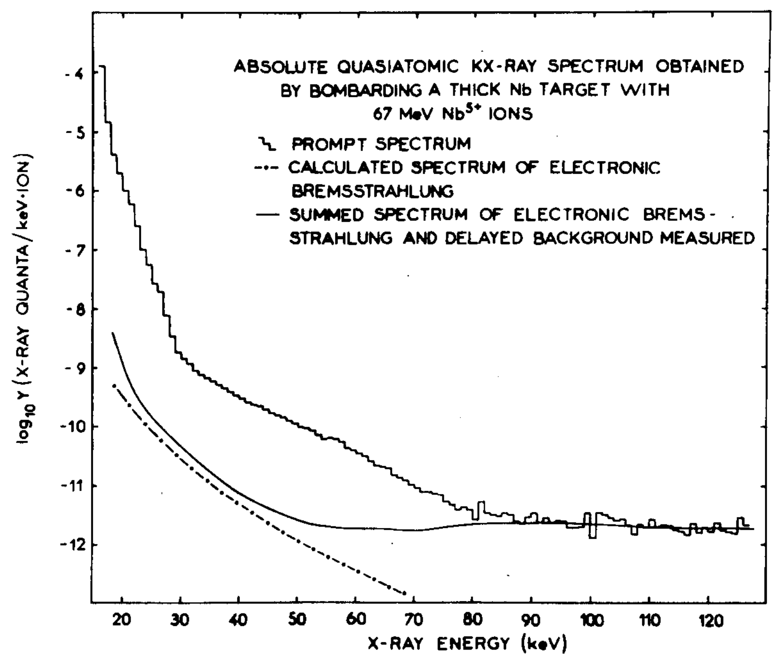

Fig. 7. The absolute X-ray intensities for ^{93}Nb + ^{93}Nb (67 MeV), corrected for absorption and detector efficiency.

4. RESULTS OF EXPERIMENTS WITH ^{60}Ni IONS OF 67 MeV ENERGY

In order to measure the directional anisotropy of the Ni $+^{60}$Ni quasimolecular KX-rays and to search for the two distinct X-ray continua, we repeated/17/ the experiments of Greenberg et al./14/ under the same experimental conditions as reported there. Further we were trying to study the intensity oscillations superimposed on the X-ray continuum, which were reported in refs./14,18/. *Figure 8* shows the X-ray spectrum taken at an emission angle of $\theta = 90°$ using the experimental arrangement described in chapter 2.

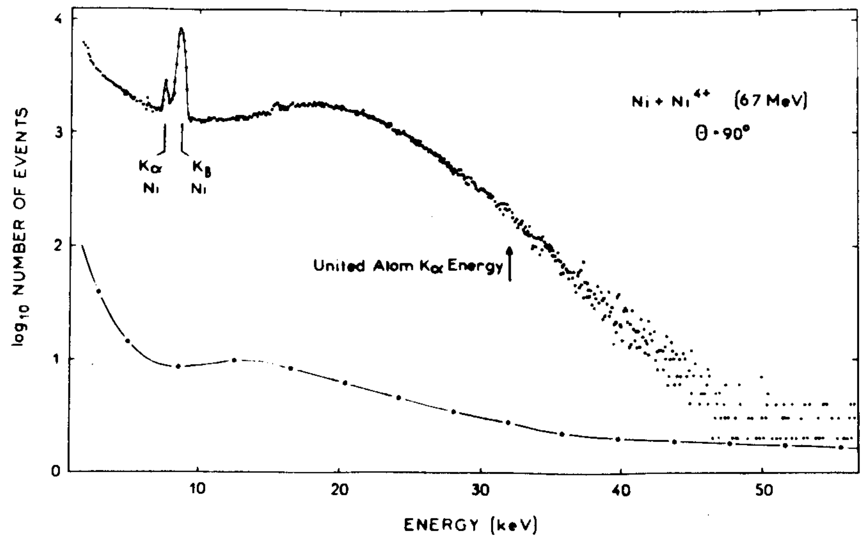

Fig. 8. The X-ray spectrum of Ni + ^{60}Ni *(67 MeV) measured at 90° with respect to the ion beam axis.*

The dashed-dotted line represents the summed spectrum of averaged background measured in the delayed regime and the evaluated nuclear and electronic bremsstrahlung arising in the natural Ni target and in the wall of the reaction chamber. The figure demonstrates that the X-ray continuum obtained does not permit the separation into two continuous parts (C1) and (C2). Further we did not find a substructure of the X-ray continuum after making correction for the detector efficiency (see *fig. 9*).

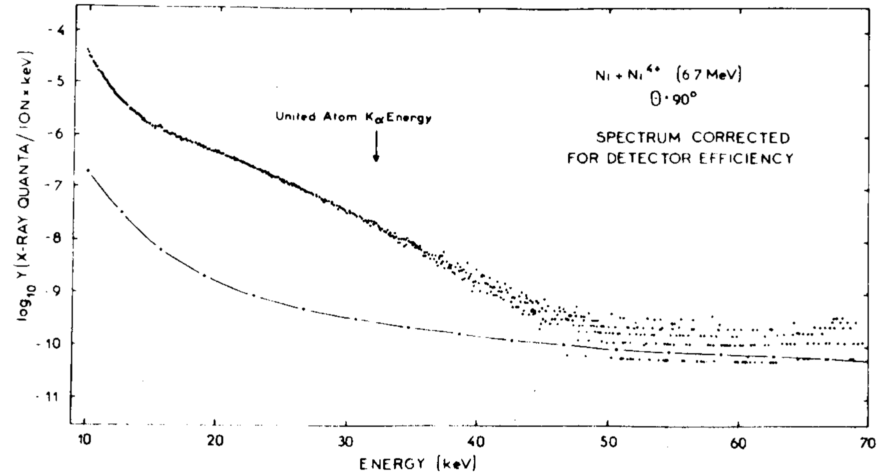

Fig. 9. The quasimolecular KX-ray spectrum of Ni + ^{60}Ni *(67 MeV) measured at 90° and corrected for absorption and detector efficiency.*

Figure 10 shows the asymmetry $\eta = I(90°)/I(0°) - 1$ as a function of the X-ray energy. Each point comprises the intensity of 10 channels (1.5 *KeV*). The open and closed circles show the asymmetry curve, respectively, without and with the Doppler correction made. By evaluating η, the measured background and the evaluated bremsstrahlung were subtracted. We normalized the 90° and 0° spectra to each other in the energy interval 15 *KeV* $\le E_x \le$ 20 *KeV*. This normalization leads, in the designated energy region, to $\eta(E_x) \approx 0$, which has also been obtained in ref./14/. On the other hand, the normalization of our spectra to the monitor rates yields an asymmetry curve of the same shape but displaced to negative values by about 10% (see *fig. 10*). The normalization factors taken from the monitor rates and the ion

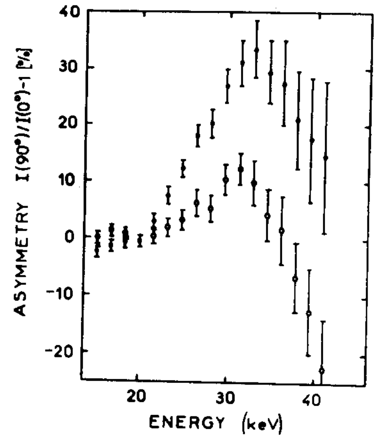

Fig. 10. The asymmetry $\eta = I(90°)/I(0°) - 1$ *of the quasimolecular* KX *-radiation obtained in the* Ni + Ni *(67 MeV) measurement.*

currents agreed within an error of about 5%. In order to get information about the endpoint energy E_{max} of the quasimolecular KX-ray spectra in the Ni + Ni collisions we performed a 15-hour run with $^{58}Ni^{3+}$ ions of an energy of 39 *MeV*. With the aid of the method outlined in *fig. 6* we deduced for E_{max} a value of 87 ± 18 *KeV*.

5. *DISCUSSION*

By investigating the Nb + Nb collisions we have demonstrated that the X-ray continua obtained exhibit a directional anisotropy represented by an asymmetry η derived from the 90° and 0° spectra (see *fig. 4*). It has been shown by Greiner and coworkers /11, 12/ that a maximum of η at the energy of the characteristic KX-radiation of the united system furnishes a unique proof of the quasimolecular nature of the measured radiation. For the reasons of statistics the behaviour of the asymmetry curve for $E_x > 60$ *KeV* is yet unclear. Nevertheless, we believe that the experimental results

prove the continuum (C2) to be due to quasimolecular KX-radiation, because this continuum extends beyond the KX-energy of the hypothetical united atom and shows the typical shape required /11, 12/ for the tail produced by dynamical effects in heavy ion collisions.

Besides the nature of (C2), the low-energy continuum (C1) is of special interest. We found this continuum first by investigating the collision system Ge + Ge /5/, where in the X-ray spectra, after a correction made for detector efficiency, two clearly distinct components occur. Furthermore, in all of our investigations of the heavy collision systems, e.g., Nb + Nb (67 *MeV*) /6/ , Nb + Nb (96 *MeV*) /7/ , La + La (115 *MeV*), La + Xe (120 *MeV*) and La + Xe (150 *MeV*) /8/ a high-energy part (C2) of the measured X-ray continuum can be separated from a much more intensive low-energy part (C1). We have checked this picture carrying out control measurements with different detectors and absorber materials. Therefore, we conclude that the continuum (C1) is a real physical effect. This component extends generally beyond the energies of the target and projectile characteristic X-rays and can only be separated from (C2) for symmetric and asymmetric collision systems with large atomic numbers Z_1 , Z_2 . Electronic and nuclear bremsstrahlung cannot account for the continua (C1) (see *figs. 2,3,5, 8,9*). As an example, for Nb + Nb collisions the integral yield computed for electronic bremsstrahlung in the energy region between 16 *KeV* and 30 *KeV* is four orders of magnitude smaller than the measured values /16/. Also the calculated slope is wrong. After the correction made for the detector efficiency and absorber attenuation the linear extrapolation of the components (C1) in a logarithmic representation shows that the experimental yield Y(C1) goes down like E_x^{-n} with $n \lesssim 20$. This disagrees drastically with the calculated value of $n \lesssim 7$ /16/ for the electron bremsstrahlung. Further, it seems to be impossible to explain the nature of (C1) by radiative electron capture (REC), because the cross section of this process is sufficiently low for the atomic numbers of the colliding systems investigated in this work /20/. Recently Heinig et al. /9/ tried to give an explanation for the origin of the component (C1), which may take place during the transient formation of quasimolecules. The authors pointed out that in all molecular correlation diagrams for medium-weight atomic numbers Z_1, Z_2 reported till now, the $2p\sigma$-term shows a relative minimum. This term joins the L- or K-shells of the colliding particles in the limit 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 the published correlation schemes 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, in ref./9/ it is suggested that the continua (C1) are produced by such transitions. According to these suggestions the high intensity of the continua (C1) can be explained assuming that the vacancies in the $2p\sigma$-minimum were filled mostly in a first collision, whereas for the origin of the continua (C2) a second collision must be accepted /21/.

So far, no precise theory for the origin of the continua (C1) is worked out. But if one takes into account the high (C1) intensities, an experimental proof of the model described above may give new outlooks for investigating the medium-weight and heavy two-centre systems spectroscopically.

For Ni + Ni collisions, the asymmetry $\eta(E_x)$ of the quasimolecular KX-radiation shows a maximum at an X-ray energy $E_x = 32$ *KeV* (*fig. 10*), 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 in ref./14/. *Figure 8* shows that intensity oscillations superimposed on the X-ray continua/14/ were not observed. If these oscillations result from fluctuations in the molecular system/18/, their oscillating cross sections should be dependent on the energy of the incident particles. We used a target of natural Ni with a thickness of 1 *mg/cm*^{2} (an effective thickness of 1.4 *mg/cm*^{2} because of the 45° geometry), which causes an 30 *MeV* energy loss of the

67 *MeV* Ni ions. In ref./14/ use was made of a ^{58}Ni target with a thickness of only 200 μ*g/cm*^{2} (effective thickness of 280 μ*g/cm*^{2}) yielding an energy loss of only 5 *MeV*. Hence we believed to have observed a superposition of incoherent intensity oscillations caused by ions of a wide energy range, which yields finally a smooth intensity curve as plotted in *fig. 8*. However, using the formulae of ref./18/ one can show that the dependence of the predicted oscillations on the projectile energy is not drastic. Taking into consideration the slowing-down of the Ni ions in the target used, an incoherent sum of the oscillating cross sections shows clear maxima and minima and cannot explain the missing oscillations in our measurements/19/. We repeated the experiment using a 200 μ*g/cm*^{2} thick Fe target evaporated on a Be stopper. By bombarding this target with 39 *MeV* ^{58}Ni ions we obtained an X-ray continuum similar to these of *fig. 8* but without any hint of oscillations.

Recently, oscillations were found by other group in measuring the asymmetry function of the Ni + Ni and Fe + Fe collision systems at photon energies higher than the K_α energy of the united atomic system/22/. The physical nature of this phenomenon is yet unclear. In future investigations we should be able to obtain the asymmetry $\eta(E_x)$ of the Ni + Ni system with much better statistics as we got till now and to support or refute the results of these measurements.

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