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OBSERVATION OF DIRECTIONAL ANISOTROPY OF QUASIMOLECULAR KX-RAYS EMITTED IN 67 MeV Ni + Ni COLLISIONS

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OBSERVATION OF DIRECTIONAL ANISOTROPY OF QUASIMOLECULAR KX-RAYS EMITTED IN 67 MeV Ni + Ni COLLISIONS

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Наблюдение угловой анизотропии квазимолекулярного KX-излучения в столкновениях Ni+Ni при энергии 67 МэВ

При облучении естественной мишени Ni ионами $^{60}Ni^{4+}$ с энергией 67 МэВ наблюдался сплошной спектр квазимолекулярных X-лучей, который распространяется до энергии выше чем энергия KX-лучей квазиатома с Z =56. Этот сплошной спектр имеет сильную угловую асимметрию, максимум которой наблюдается при KX-энергии гипотетического объединенного атома.

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Observation of Directional Anisotropy of Quasimolecular KX-Rays Emitted in 67 MeV Ni+Ni Collisions

By bombarding natural Ni targets with 67 MeV $^{60}Ni^{4+}$ ions a quasimolecular X-ray continuum has been obtained, which extends beyond the KX-ray energy of the quasiatom with Z =56. This continuum shows strong directional asymmetry with a maximum at the KX-ray energy of the hypothetical united atom.

The investigation has been performed at the Laboratory of Nuclear Reactions, JINR.

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Dubna 1975

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1. Introduction

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/1-4/ . They cause a smearing of the quasimolecular X-ray distributions beyond the "classical" K energy limit of the united atom and lead to induced transitions between molecular electronic states. These induced transitions, which originate as a result of the rotation of the internuclear axis, add incoherently to the so-called spontaneous molecular transitions with an intensity growing with increasing photon energy. As it is proposed by Greiner and coworkers/2,3/ the sum of these two parts of quasimolecular X-radiations produces an anisotropy of the spectra with respect to the heavy ion beam direction. This anisotropy was first observed by Greenberg et al./5/ for the KX-radiation in the $^{58}Ni + {}^{58}Ni$ (70 MeV) colliding system. Recently, Thoe et al./6/ have pointed out such directional anisotropy for KX-rays, emitted in Al + Al (30 MeV) and Si + Al (30 MeV) collisions, whereas Kraft et al./7/ have published evidence for the anisotropic emission of quasimolecular M-radiation in low energy I-Au collisions.

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 KX-rays of the united atom ($Z = 56$) are expected to arise[5]. Further, the continua extend beyond this KX energy limit. However, the spectra obtained in ref.[5] exhibited only a single compact continuum, whereas in our experiments performed using the heavier collision systems such as Ge + Ge (81 MeV)[8], Nb + Nb (65 MeV, 96 MeV)[9,10], Xe + La (85 - 150MeV) and La + La (115 MeV)[11] two continuous components can clearly be distinguished. We repeated the Ni - Ni experiment under the same experimental conditions as described in ref.[5], in order to measure the directional anisotropy of quasimolecular KX-rays and to search for the two distinct X-ray continua obtained in the heavier collision systems mentioned.

2. Experimental Technique

At the U-300 heavy ion cyclotron of the JINR Laboratory of Nuclear Reactions, $^{60}\mathrm{Ni}^{4+}$ ions were accelerated to an energy of 67 MeV. Fig. 1 shows our experimental arrangement. For the measurements of anisotropic emission of noncharacteristic X-rays an Al chamber with a diameter of 100 mm and a wall thickness of 1 mm was used. The ion beam was collimated by a collimator system, which consisted 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. An 30 μm thick Be window separated the detector from atmosphere. The energy resolution of the detector used was better than 200 eV at an X-ray energy of 10 keV. The distance between the focus in the middle of the target and the Be window was 51 mm. Therefore 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 NaJ(Tl) crystal and a photomultiplier, positioned at 135° with respect to the beam direction (see fig.1).

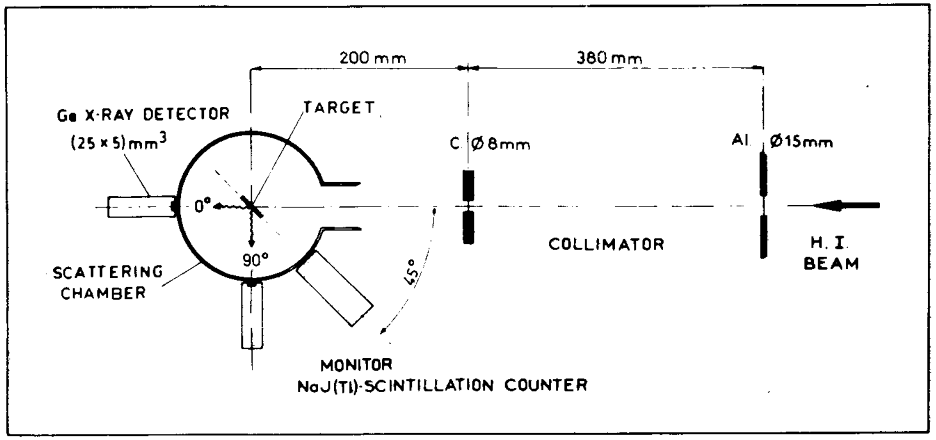

Fig. 1. The experimental arrangement.

Besides the chamber wall and the Be window, no additional absorbers were used. 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 to eliminate differential self-absorption of X-rays at emission angles of 0° and 90° . A thin metallic foil of natural Ni (with a thickness of 1 mg/cm^2) was used. The ^{60}Ni ions passing through this target foil with an energy of about 37 MeV, were stopped in the Al chamber wall. The characteristic Al X-rays arising in Al as a result of the Al-Ni collisions had an energy lower than 1.5 keV and were completely absorbed. The Ni KX-radiation originating in the chamber wall could not be separated from the target X-ray emission.

No remarkable continuous X-ray contributions caused by the Al-Ni collisions in the chamber wall were expected.

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 mainly influenced the accuracy of the ion current measurements. We obtained an average number of incident particles per second of 3.6×10^{10}.

The beam pulsing of 2 ms beam-on and 2 ms beam-off time offered the possibility of measuring the delayed background by accumulating the spectra in a prompt-delayed regime.

3. Results

The continuous X-ray spectra measured in this experiment and the evaluated curve for the angular distribution asymmetry agree well with those obtained by Greenberg et al.[5].

Figure 2 shows the X-ray spectrum taken under an X-ray emission angle θ = 90°. The low-energy region of this spectrum contains the well resolved characteristic KX-radiation of Ni, while in the direction of higher energies an intensive X-ray continuum adjoins, which reaches beyond the united atom K_α energy limit. There is no hint of any intensity oscillations, which were observed by Greenberg et al.[5] . The little peaks at energies of 15.5 keV and 16.6 keV are certainly the pile-up of impulses, which correspond to the KX-radiation of Ni . The dashed-dotted line in fig. 2 represents the summed spectrum of the average background measured in a delayed regime and the evaluated nuclear and electronic bremsstrahlung[12] arising in the natural Ni target and in the wall of the reaction chamber.

Figure 3 shows the X-ray spectrum measured in the beam direction (0° -geometry). Here, the dashed-dotted line denotes the sum of the mean delayed background and the spectra of the evaluated nuclear bremsstrahlung in the collision systems ^{nat}Ni + ^{60}Ni (67 MeV) and Al + ^{60}Ni (37 MeV), respectively.

Figure 4 presents the yield of photons obtained from the 90° measurement after correction for the detector efficiency and normalization to the ion flux measured. As can be seen from this figure, the X-ray continuum has an exponential form and goes to a nearly constant background at an energy of about 50 keV. The logarithmic presen-

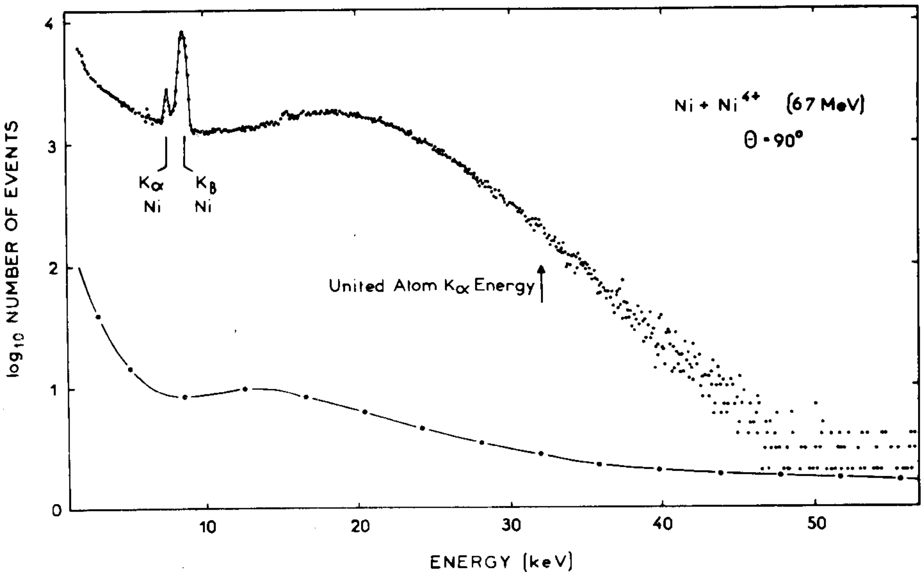

Fig. 2. The X-ray spectrum measured at 90° with respect to the ion-beam axis. The dashed-dotted line represents the sum of the delayed background measured and the evaluated electronic and nuclear bremsstrahlung in the natural Ni target.

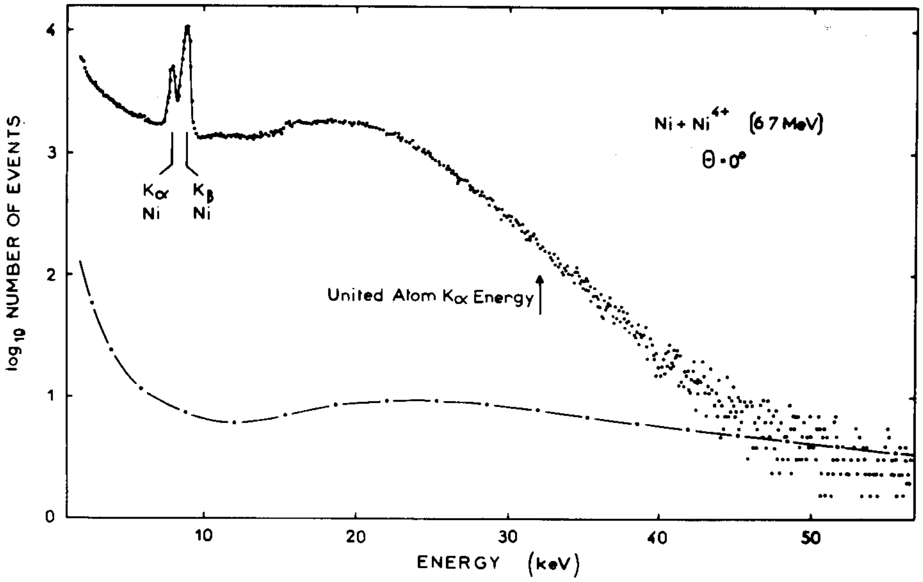

Fig. 3. The X-ray spectrum measured at 0° with respect to the ion-beam axis.

The dashed-dotted line denotes the sum of the delayed background measured and the evaluated E1 component of nuclear bremsstrahlung in the colliding systems ^{nat}Ni + Ni (67 MeV) and Al + Ni (38 MeV).

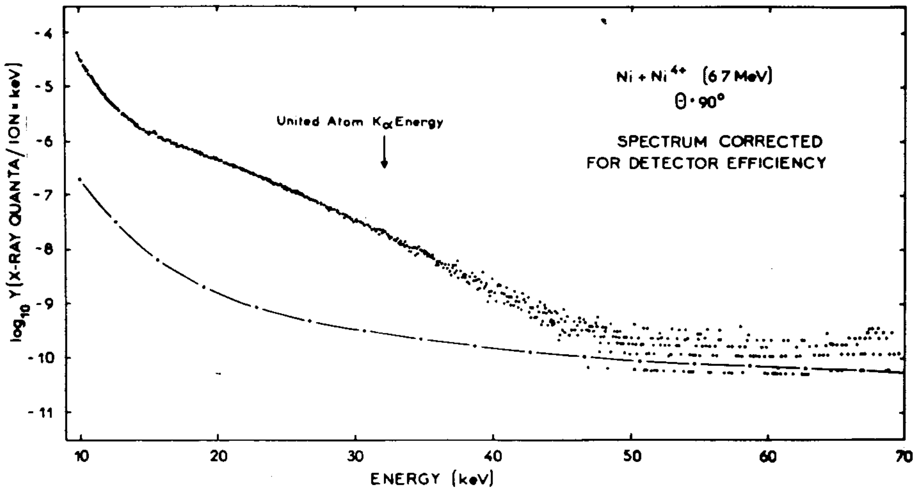

Fig. 4. The X-ray spectrum measured at 90° and corrected for the detector efficiency.
The dashed-dotted line represents the summed spectrum of the delayed background corrected for the detector efficiency and the evaluated electronic and nuclear bremsstrahlung.

tation in fig. 4 gives no evidence for the existence of two distinct continua in the spectrum.

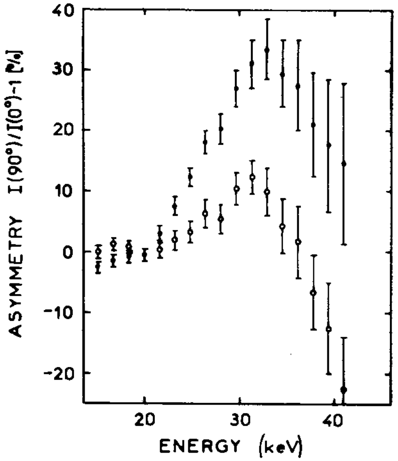

Fig. 5. The asymmetry $\eta = I(90^\circ)/I(0^\circ) - 1$ derived from the measurements at 90° and 0° with respect to the beam direction. The open and closed circles show the η values respectively, without and with the Doppler correction made.

Figure 5 shows the asymmetry defined by $\eta = \frac{I(90^\circ)}{I(0^\circ)} - 1$ in dependence of the X-ray energy. The photon energy intervals summed are 1.5 keV. For a good comparison between the asymmetry curve obtained in this experiment and the curve from ref.[5] we normalized our spectra to each other in the energy interval 15 keV $\leq E_x \leq$ 20 keV. This normalization leads in the designated energy region to $\eta(E_x) \approx 0$, which has also been obtained in ref.[5]. On the other hand, the normalization of our spectra to the same monitor rates yields an asymmetry curve of nearly the same shape but displaced to negative values by about 10% (see fig. 5). The normalization factors taken from the monitor rates and the ion currents agreed within an error of about 5%.

By evaluating η, the background plotted in figs. 2 and 3 was substracted.

The open and closed circles in fig. 5 show the asymmetry curve 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 $\{i\}$, $\bar{v}_s = \frac{1}{2}\cdot\frac{\pi}{4}v_\infty$ is the mean velocity of the center of mass in the system Ni + Ni (67 MeV) and θ is the photon emission angle. $\bar{v}_s$ has been calculated by integration over all impact parameters corresponding to classical ion trajectories which intersect the K shell radius of the Ni atom.

4. Conclusions

As was already mentioned, our results agree well with those of Greenberg et al./5/. The asymmetry η shows a maximum at an X-ray energy $E_x \approx 32$ keV, where the KX-radiation of the united atom with Z = 56 is expected. The values for η without and with the Doppler correction are of the same order of magnitude as those obtained in ref./5/. According to refs./2,3,5/, the asymmetry curve derived from the spectra measured is a good evidence for the interpretation of the noncharacteristic X-ray continua as due to the KX-radiation of quasiatoms transiently formed in adiabatic Ni + Ni collision.

Figure 4 demonstrates that the X-ray continuum obtained extends beyond the united atomic limit but it does not permit the separation into two continuous parts either before or after making correction for the detector efficiency. The spectrum seems to be a continuum with only single exponential decrease. On the other hand, in the Ge + Ge (Z = 64) colliding system the separation can be done after intensity correction/8/ and in the heavier systems such as Nb + Nb (Z = 82) and La + Xe (Z = 111) (see ref./9-11/) two continua can clearly be seen. In order to exclude the geometry and detector effects, we have done control measurements using the same intrinsic Ge detector for all the colliding systems mentioned above. Therefore we conclude that the existence of two distinct continua which we denote C1 and C2 is a real effect. In the future, investigations of the X-ray anisotropy in heavier systems will be performed to obtain further information about the origin and character of both continua.

It can be seen from figs. 2 and 3 that intensity oscillations superimposed on the X-ray continua/5/ were not observed. If these oscillations result from fluctuations in the molecular systems/13/ then their oscillating cross sections certainly depend on the energy of the incident particles. We used a target of natural Ni with a thickness of 1 mg/cm^2 (effective thickness of 1.4 mg/cm^2), which causes an 30 MeV energy loss of the 67 MeV Ni ions. In ref./5/ use was made of a ^{58}Ni target with a thickness of only 200 μg/cm^2 (effective thickness of 280 μg/cm^2) yielding an energy loss of only 8 MeV. Hence we are possibly observing a superposition of incoherent intensity oscillations caused by ions of a wide energy range, which yields finally a smooth intensity curve as plotted in figures 2 and 3.

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