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E7 - 10132

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OBSERVATION OF TWO-ELECTRON - ONE-PHOTON TRANSITIONS IN QUASIMOLECULAR KX-RAY MEASUREMENTS

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Introduction

Recently Wölfli et al. [1] have observed some peaks of weak intensity when Ni and Fe targets were bombarded with Ni and Fe ions. These peaks appear at an energy about twice the energy of the characteristic lines and have been interpreted with a high reliability [1] as two-electron - one-photon transitions, which can originate as dipole transitions [2] when the K-shells of the collision partners are doubly ionized. The authors [1] showed that the peaks considered do not arise in the impurities of the target material and cannot be explained either by the electron pile-up effect or by the γ-rays due to nuclear reactions. The energy differences ΔE_s, which occur between the measured peak energies and the values of $2E(K_\alpha)$ or $E(K_\alpha)+E(K_\beta)$ were explained by taking into account the variation of binding energies during the removal of the K electrons. The values of ΔE_s obtained experimentally are in good agreement with the results of Hartree-Fock calculations [3]. By measuring the quasimolecular KX-ray spectra of medium-weight collision systems, we have also found similar peaks (see, e.g., fig.1

of ref.[4] and fig. 8 of ref.[5]), independently of the observations mentioned above. Since the publication of ref.[1] we have examined all our experimental data on medium-weight collision systems to extract information on the possible two-electron - one-photon transitions. It is the purpose of this paper to give some preliminary results of this investigation.

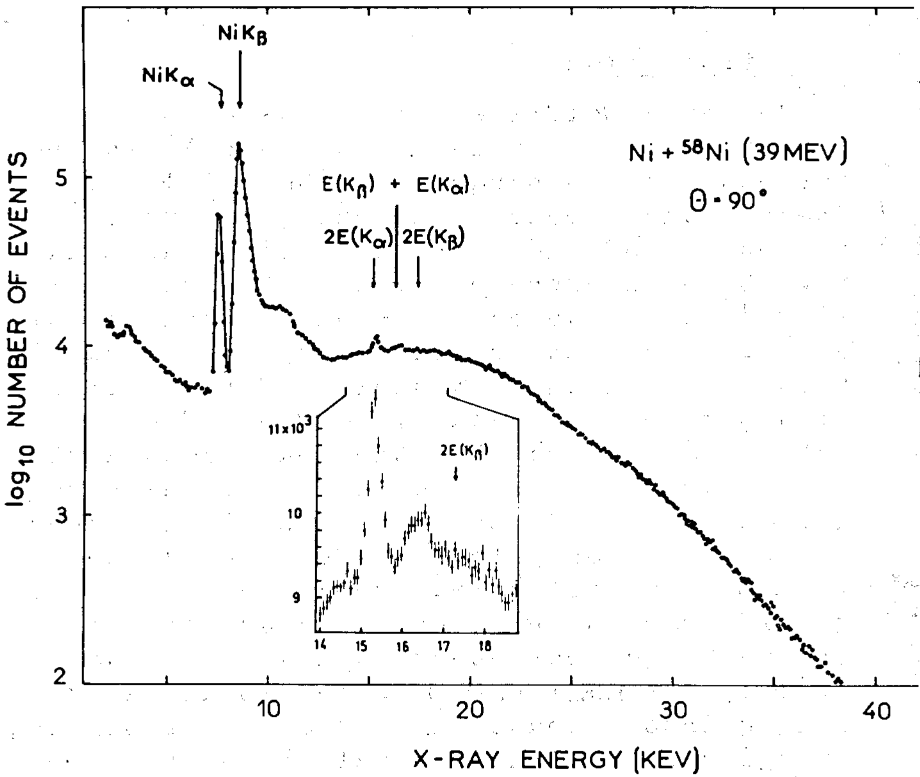

Fig. 1. The quasimolecular KX-ray spectrum obtained by the investigation of the collision system Ni + Ni (39 MeV). The insert shows in an expanded form the part of the spectrum lying at an energy about twice the energy of the characteristic transitions.

2. Results

The results described in this paper were obtained in experiments performed at the U-300 heavy ion cyclotron of the JINR Laboratory of Nuclear Reactions. The data extracted from the available experimental material are listed in the table to follow. As an example, in figs.1 and 2 we present the quasimolecular KX-ray spectra, which we have measured in investigating the collision systems Ni + ^{58}Ni (39 MeV) and ^{74}Ge + ^{74}Ge (53 MeV). Both the spectra exhibit peaks which can be interpreted as the sought two-electron - one-photon transitions. These measurements were carried out in a 90^{o} geometry using an intrinsic Ge X-ray detector with a resolution of 240 eV at an X-ray energy of 15 keV. The targets were placed at an angle of 45^{o} with respect to the beam direction. The spectra taken in 0^{o} and $\pm$45^{o} geometry (presented neither in the figures nor in the table) show clearly that both the Doppler-shifted and the non-Doppler-shifted peaks have nearly the same intensities. Therefore, one can conclude that the observed peaks are produced by the jumping of two electrons in the target atom at rest as well as in the moving ions.

In all the measurements presented in the table, the intensively excited characteristic KX-ray transitions were attenuated by the reaction chamber wall and by additional Al absorbers. Due to the counting rate which was always lower than 70 s^{-1} and a time resolution below 4 μs, no pile-up effects were expected in the spectra described in this paper. This picture can be checked ex-

Table

The transition energies, absolute and relative yields of two-electron - one-photon transitions, obtained by investigating some medium-weight collision systems.

COLLISION SYSTEM	E_1 MEV	η_K	E_x KEV	$Y(E_x)$ PH./ION	$Y(K_{\alpha\alpha})/Y(K_\alpha)$	Ref.
$^{93}Nb + ^{93}Nb$	67	0.021	33.55 ± 0.09	$(6.7 \pm 4.5) 10^{-11}$	$(1.5 \pm 1.0) 10^{-7}$	5)
$^{74}Ge + ^{74}Ge$	53	0.035	20.18 ± 0.08	$(8.8 \pm 4.5) 10^{-9}$	$(5.9 \pm 3.1) 10^{-7}$	7)
$Ni + ^{58}Ni$	39	0.044	15.28 ± 0.08 16.40 ± 0.10	$(4.2 \pm 1.7) 10^{-9}$ $(1.1 \pm 0.6) 10^{-9}$	$(1.6 \pm 0.7) 10^{-6}$	
$Ge + ^{74}Ge$	84	0.055	19.98 ± 0.08	$(9.5 \pm 5.7) 10^{-8}$	$(2.8 \pm 1.9) 10^{-6}$	4)
$Ni + ^{60}Ni$	67	0.073	15.26 ± 0.05 16.36 ± 0.09	$(9.8 \pm 5.9) 10^{-8}$ $(1.5 \pm 0.9) 10^{-8}$	$(3.6 \pm 2.6) 10^{-6}$	5,6)

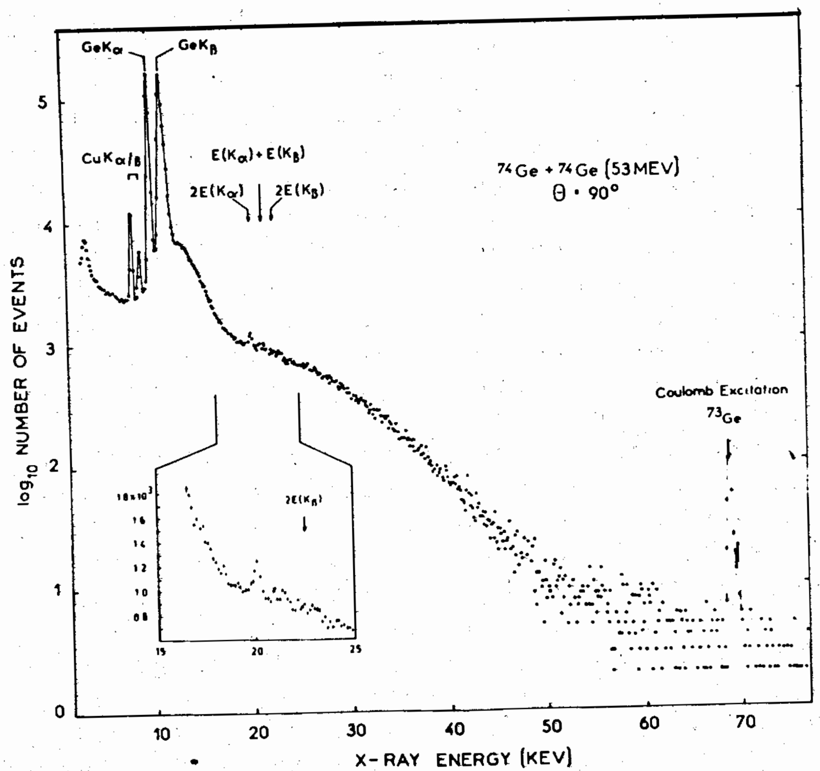

Fig. 2. The quasimolecular KX-ray spectrum obtained by measurements in the collision system $^{74}Ge + ^{74}Ge$ (53 MeV). The insert shows the part of the spectrum lying at an energy about twice the K_α energy. The line at 68 keV arises from the Coulomb excitation of the 68 keV level of ^{73}Ge, admixed to the enriched ^{74}Ge target material.

perimentally. In figs. 1 and 2 the arrows denote the energies at which the pile-up peaks of the characteristic lines should appear. Since the K_α -lines are attenuated to a greater extent than the K_β-lines, the K_α pile-up is expected to be the dominant effect. Generally, no K_β pile-up peaks have been observed in any of our measurements. Therefore, we can conclude that pile-up is not responsible for the origin of the peaks considered. It should be noted that the results presented here are obtained at different solid angles. For that reason we are presently unable to estimate the probability for the appearance of the so-called correlated two-electron - two-photon transitions in all the measurements.

The table presents the investigated collision systems as a function of the increasing generalized coordinates $\eta_K = E_1/\lambda U_K$. Here, E_1 is the energy of the incident ions considered, $\lambda = M_1/m_e \approx 1836.6\ A_1$ is the ion-electron mass ratio and U_K is the K-shell binding energy of the target atoms. η_K is identical with the ratio $(v_1/v_K)^2$, where v_1 is the ion velocity and $v_K = \theta_K Z_2 v_0 = Z_{2K} v_0$ is the electron velocity on the target K-shell. The energies of the two-electron - one-photon transitions are presented in column 5 of the table. The estimated errors are lower than 1% and should permit, in principle, comparison with the results of the HFS calculations for allowed two-electron - one-photon dipole transitions. This may be the subject of another paper. The absolute yields $Y(E_x)$ and the relative yields $Y(K_{\alpha\alpha})/Y(K_\alpha)$ are compiled in columns 6 and 7, respectively. The ratios $Y(K_{\alpha\alpha})/Y(K_\alpha)$ should be of special interest, because one expects that such target properties as the thickness and the backing materials are neglected to a large extent. In fig. 3 the

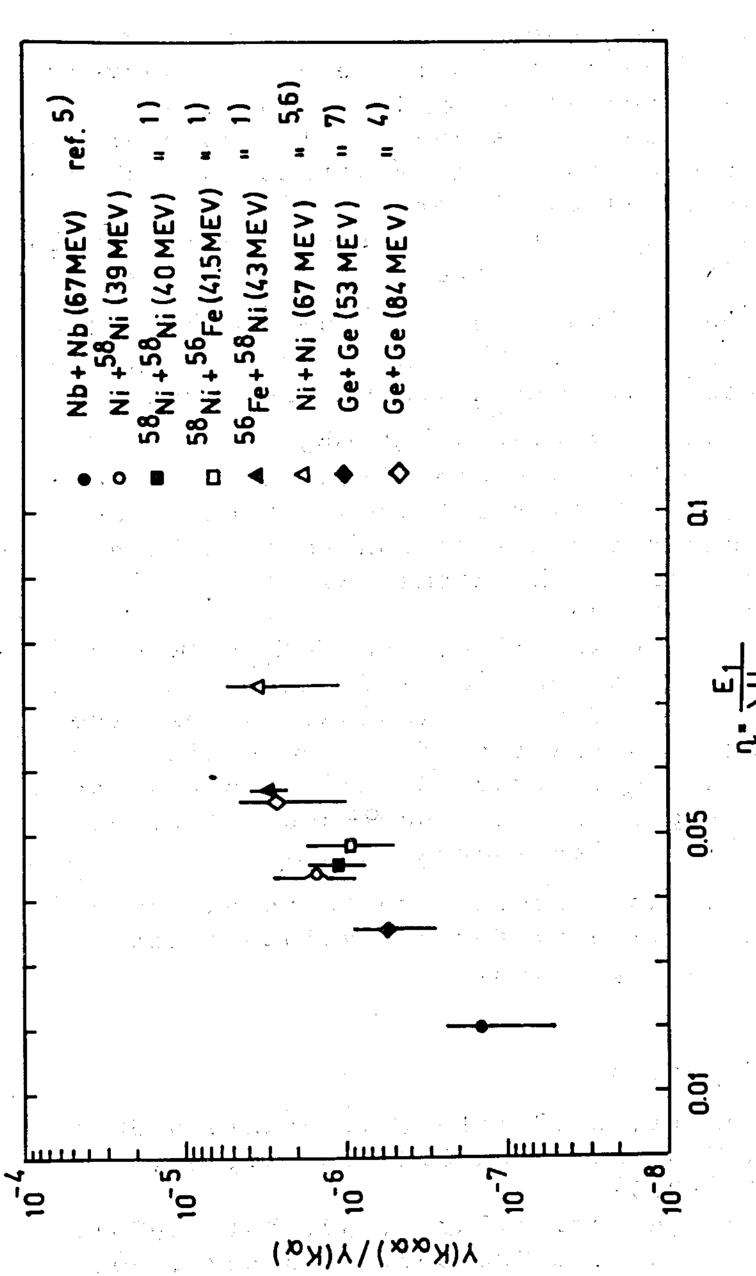

Fig. 3. The ratio $Y(K_{\alpha\alpha})/Y(K_\alpha)$ as a function of the generalized coordinate $\eta_K = E_1/\lambda U_K$.

values of $Y(K_{\alpha\alpha})/Y(K_\alpha)$ are plotted versus η_K. In the case, where we have observed two peaks beyond $E_x = 2E(K_\alpha)$, those with the highest intensities and the lowest energies are supposed to be the $K_{\alpha\alpha}$-transitions (see the table and the insert of fig. 1). In fig. 3 we also give the cross section ratio $\sigma(K_{\alpha\alpha})/\sigma(K_\alpha)$ for the collision systems $^{58}Ni + {}^{58}Fe$ (40 MeV) and $^{58}Ni + {}^{56}Fe$ (41.5 MeV) reported in ref. /1/. In doing so we assumed that the ratios $\sigma(K_{\alpha\alpha})/\sigma(K_\alpha)$ are equal to the relative yields $Y(K_{\alpha\alpha})/Y(K_\alpha)$. The value of η_K for the Fe projectiles in the $^{58}Ni + {}^{56}Fe$ (41.5 MeV) reaction has been calculated under the assumption that the ion is at rest and the Ni atoms have a kinetic energy of 43 MeV.

Generally speaking, the $Y(K_{\alpha\alpha})/Y(K_\alpha)$ ratio is expected to provide information about the probability of double ionization relative to single ionization of the K-shells for different η_K. Figure 3 indicates that this relative probability increases almost exponentially with increasing η_K.

The authors would like to thank Academician G.N.Flerov for his valuable interest in the problem.

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Received by Publishing Department
on September 29, 1976.