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DIRECT INNER SHELL IONIZATION
ACCOMPANYING NUCLEAR FUSION REACTIONS WITH HEAVY IONS

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Probabilities for K-shell ionization prior to fusion (half-trajectory collisions) are determined for ^{51}V, ^{59}Co, ^{62}Ni target atoms and 4.5 MeV/u ^{40}Ar projectiles. Also measured are energy shifts of the K_α and K_β X-ray lines of residue atoms resulting from multiple inner shell ionization.

Inner shell ionization induced by a projectile undergoing a nuclear reaction is of interest for nuclear as well as atomic physics. Thus e.g. a comparison of the time scales for the atomic and nuclear processes may provide a clock for nuclear reaction studies for times ranging from $10^{-(16-18)}$ s (the K-shell vacancy life-times) to $\sim 10^{-21}$ s (the atomic collision times) [1,2]. A measurement of the K-shell ionization probability accompanying a nuclear fusion reaction provides a test of theoretical predictions for atomic collisions under particularly simplified conditions, i.e., for central collisions with no interference between the in- and outgoing waves (half-trajectory collisions).

Most of the available information on the ionization in such collisions is derived [3,4] from α-decay considered as the time reversed α–nucleus fusion process. This is supplemented by a study [5] of a reaction of 10 MeV protons on ^{138}Ba. Ionization accompanying low energy proton induced reactions has been used [6–9] in order to deduce nuclear reaction times. The values derived depend strongly [7] on the assumed input values for ionization probability by the ingoing projectile, P_{in}. Another difficulty encountered in those studies is that the P_{in} values are small, of the order of 10^{-4} (cf. recent reviews in refs. [10,11]).

The aim of the present work was to extend the information on ionization in half-trajectory collisions to heavy ions. Here the ionization probabilities are much larger than for protons ($P_{in} \sim Z_p^2/Z_t^2$, where Z_p, Z_t are the atomic numbers of the projectile and the target, respectively). Therefore the process, while being of interest in its own right, may moreover provide observables much easier to use than in the case of light projectiles.

The P_{in} values can be determined by measuring the KX-ray yields for fusion evaporation residues. Two processes contribute to these yields: the direct ionization (DI) by the projectile and the internal conversion (IC) of γ-rays deexciting the residues. A signature of the origin of the observed KX-rays can be derived from the time scales on which these processes occur. Since the K-shell vacancy is filled promptly ($\sim 10^{-16}$ s for $Z \approx 40$) with respect to the stopping time of the recoils in solids ($\sim 10^{-12}$ s) the DI KX-rays will experience full Doppler shifts. The IC KX-rays, in contrast, are emitted on a time scale characteristic for low energy γ-decay, $\geqslant 10^{-10}$ s, so that the recoils can be stopped or slowed down before the conversion takes place. By the same token, the KX-ray emission following IC process occurs in atoms with inner shell vacancies refilled even if there is a cascade of highly converted γ-transitions. In

contrast, prompt multiple inner shell vacancy production is a dominating feature for central atomic collisions with heavy projectiles [12]. As a result, the DI KX-ray spectrum is split into a large number of closely spaced "satellites" [13] observable with solid state detectors as net positive energy shifts. The shifts are sensitive mainly to the presence of L-shell vacancies. The K_α/K_β intensity ratios may be affected as a result of changes in the L- to M-shell occupancy ratios.

The recoils which are not stopped but ejected into vacuum are as a rule highly stripped. At the time of the IC KX-ray emission, however, they will be in their ground state configurations. Under the conditions of this work they are expected to have the L-shell filled completely and the M-subshells only partly depleted. The IC KX-rays should thus have their characteristics close to those of singly ionized atoms.

The present work made use of both the Doppler and the multiple ionzation energy shifts as signatures. Targets of ^{51}V, ^{59}Co and ^{62}Ni were bombarded with 4.5 MeV/u ^{40}Ar ions from the Groningen AVF cyclotron. Selfsupporting, ~ 1.5 mg/cm^2 metallic targets were placed in the center of a 40 cm long 40 cm diameter NaI "sum-spectrometer" separated into halves consisting of 3 segments each. Two Ge X-ray detectors were positioned between these halves at 45° and 135° with respect to the beam. A large Ge detector was placed at 90° for monitoring purposes. Fusion reactions were identified by requiring coincidences with large total energy, high fold events in the sum spectrometer.

Fig. 1 shows an example of the KX-ray spectra for the ^{51}V + ^{40}Ar reaction, observed with the forward detector. The four strong peaks seen in the spectrum have a double structure. The spectra were fitted with a gaussian + exponential tail parametrization using the instrumental line shapes for initial decomposition and then varying the line width as a free parameter. The iodine K_α X-rays and a 40 keV background line measured in beam had the instrumental line shapes. The Doppler broadening due to the finite target thickness was determined separately by observing γ-ray spectra with a large Ge detector placed at 135°. The value obtained amounted to 1.2% of the γ-ray energy, to be compared with that of 1.0% calculated without corrections for straggling and particle emission. Similar broadening was also found for
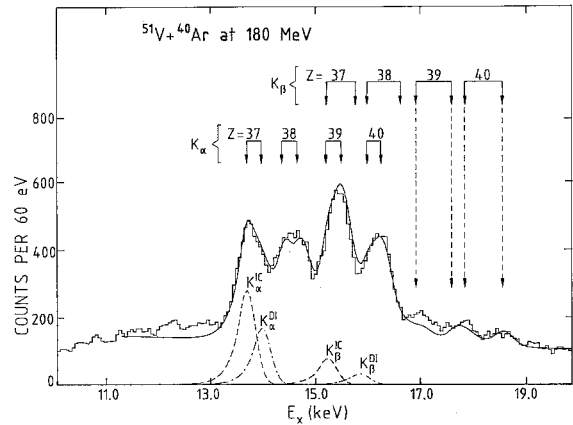

Fig. 1. KX-ray spectrum from ^{51}V + ^{40}Ar reaction measured with the forward detector in coincidence with at least five NaI segments at a high total energy condition (histogram). Smooth line represents the spectrum reconstructed using fixed intensity ratios and relative positions of the K_α and K_β lines (see text). Two such related pairs of IC and DI lines are shown for $Z = 37$ (broken lines). The excess of counts at $E_x \sim 12.3$, 12.8, and 17.0 keV yields upper intensity limits for K_α X-rays for $Z = 35$, 36 and 41, respectively.

the 35 and 46 keV γ-lines of ^{83}Sr and ^{82}Rb, respectively, observed in the X-ray detectors. Good quality fits for the X-ray spectra of the forward detector could only be obtained with the assumption that each of the main four peaks is a doublet of similarly broadened lines.

The fitting was done separately for various coincidence folds and energy slices in the sum spectra. Consistent results both for the energies and the relative intensities were obtained. The values for the KX-ray coincidence yields per gate event were found to vary systematically with the fold and energy, reaching saturation at fold five.

The results of the peak fitting procedure are indicated in fig. 1. The positions of the low energy components of each of the four strong double peaks agree with those expected for "normal" K_α X-rays with Doppler shifts attenuated by the same amount as observed for several reaction γ-rays (from 2.9% to about 2.2%). The energies of the remaining components are higher than expected for fully Doppler shifted KX-rays from singly ionized atoms. We attribute these extra shifts to the multiple L-(+M-) shell ionization. We note that the DI KX-rays are expected to have practically no Doppler broad-
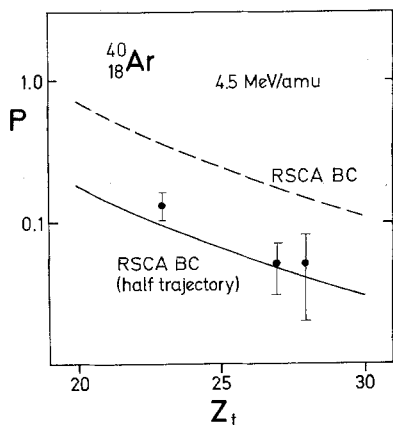
Fig. 2. Experimental and calculated (solid line) ionization probabilities for half-trajectory collisions of ^{40}Ar as functions of Z_t. Dashed line is calculated for full central collisions.

ening. Instead, there should be a broadening of about 220 eV associated with the distribution of the L-shell vacancies (assumed to be binomial).

Positions and intensities of the IC K_β lines relative to the observed K_α lines were assumed to be the same as for singly ionized atoms. Those of the DI K_β lines were measured for $Z = 39$, 40, where they could be separated clearly. This information was then extrapolated for $Z = 37$, 38.

Similar splittings and extra shifts are observed for ^{59}Co and ^{62}Ni though errors in the separation of the two components are larger because of the relatively larger contribution of IC.

The multiple ionization shifts should partially cancel the Doppler shifts in the backward detector. Indeed, only single lines with a width slightly larger than instrumental could be fitted to each of the four main peaks. The relative intensities agree with the corresponding sums of the resolved doublets in the forward detector.

Fig. 2 shows the DI probabilities plotted versus Z_t. The experimental values are obtained from the combined yields for all the products, $P_{in} = \Sigma Y^{DI}(Z)/[Y_\gamma \omega(Z)]$, where $Y^{DI}(Z)$ is the coincidence yield of DI KX-rays for residues of element Z and Y_γ is the corresponding singles count rate in the sum spectrometer. The fluorescence yields, $\omega(Z)$, for singly ionized atoms were used.

The P_{in} results are compared in fig. 2 with values calculated according to the prescription [4] as a product of the ionization probability for full central collision, $P(0)$, and of the reduction factor for half-trajectory collisions, R_{in}. The $P(0)$ values, shown as a separate entry in fig. 2, have been obtained within the semiclassical approximation, SCA, with relativistic (R), Coulomb (C), and binding (B) corrections [14]. The factor R_{in} has been calculated as in ref. [4] taking into account only the monopole contribution and using relativistic wave functions (see also ref. [2]). The values obtained for V, Co and Ni are 0.26, 0.31 and 0.31, respectively, to be compared with the classical value $R_{in} = 0.5$. The calculated P_{in} values agree well with the present data (cf. fig. 2). There seems to be no need to invoke mechanisms other than the direct ionization by impact, though one might expect an additional contribution to the ionization as the system approaches symmetry [10,11]. Ionization by the outgoing p and α particles and by the interaction of recoils with the target material is estimated as negligible.

Recently, the first results of a study of DI KX-rays of fusion reaction residues have been reported [15] for ^{54}Fe(^{58}Ni, 4p)^{108}Sn reaction at 4 MeV/u incident energy. The residue was selected by discrete γ-ray-X-ray coincidences and the Doppler shift signature was used to identify the ionization process. The P_{in} value calculated according to the present procedure for Ni is 0.03. Since the approximation used is not appropriate for this nearly symmetric system with inverse kinematics, the agreement with the measured value 0.031(6) may be fortuitous.

The results related to the multiple inner shell ionization effects in DI KX-rays for the V target are collected in table 1. Listed are the Doppler corrected energy shifts of the K_α and K_β lines with respect to the diagram values as well as the K_β/K_α intensity

Table 1
Energy shifts and K_β/K_α intensity ratios for DI KX-rays from ^{51}V + ^{40}Ar reaction residues.

Z	$\Delta E(K_\alpha)$ (eV)	$\Delta E(K_\beta)$ (eV)	$I(K_\beta/K_\alpha)$
37	163(20)		
38	168(20)		0.13(5)
39	199(25)	568(90)	0.10(4)
40	181(30)	550(70)	0.12(4)

ratios. The shifts correspond to about three L-shell vacancies at the time of the KX-ray emission [#1]. The (expected) presence of several M-shell vacancies should affect mainly the K_β/K_α intensity ratios.

In conclusion, we have measured the KX-ray yields from residues of ^{40}Ar induced reactions, both for the ionization originated by the interaction of the projectile with the target atom (DI) and for that due to the post-collisional effects (IC). The identification has been accomplished thanks to the different Doppler shifts associated with the two processes and to the multiple inner shell ionization effects being present only in the DI KX-rays. The ionization probabilities in half-trajectory collisions are found to be high enough to render the DI KX-rays as practical observables in nuclear reactions studies. The yield distribution of the DI KX-rays can be used as a measure of the elemental distribution of the residues if there is no significant delayed charged particle emission.

[#1] A relativistic calculation with the multi-configurational Dirac–Fock program of ref. [16] [17].

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