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R.Arlt,[1] R.Engfer,[2] W.D.Fromm, Dz.Gansorig,
T.Kroguleki, H.-G.Ortlepp, S.M.Polikanov,
B.M.Sabirov, H.Schneuwly,[3] U.Schmidt

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[1] Technische Universität Dresden, GDR.
[2] Laboratorium für Hochenenergiephysik der ETH Zürich, Switzerland.
[3] Institut de Physique, Université de Fribourg, Switzerland.

Muonic spectra were in the past mainly investigated to check quantum electrodynamics, to determine the nuclear charge distribution and to study nuclear excitation and hyperfine interactions /1/. Only little interest however has been paid to the study of electronic X -rays also produced by the complex interaction of the muon and the atom.

Recently an energy shift of the electronic X -rays from muonic uranium atoms has been observed /2/. Also earlier measured spectra for Ir target at the CERN μ -channel were re-analysed and a shift was revealed too. The measurements were extended to other elements and were performed at the separated muon beam of the Dubna synchrocyclotron.

Metallic targets of Ta, Ir, Pb, Th and repeatedly U with thicknesses of about 2 g/cm^2 were irradiated. Two parameter (energy-time) gamma-ray measurements were provided using a conventional μ -stop telescope arrangement. Details of the apparatus are given in a forthcoming paper. Various Ge(Li)-detectors with volumes of 1.6 cm^3 to 2.4 cm^3 and corresponding energy resolutions of 700 to 900 eV at 122 keV and about 6 nsec FWHM time resolution were exploited. A great attention was paid to the stability and energy calibration of the system. Internal energy standards were used provided by the well-known muonic X -rays of the light elements C, N and O always present in the target box as well as radioactive samples placed close to the detector. In order to eliminate possible systematic deviations due to the time-dependent load in the spectroscopic tract, pulses from the radioactive isotopes were registered as chance coincidences in a wide time interval (± 1 μs) with respect to the μ-stop moment. The gamma-events were recorded typically 20 hours for each target and stored as one prompt, eight successive delayed and two calibration spectra by means of a two-dimensional analysis system working on-line with a computer.

The spectra were off-line analysed using a modified version of the computer-code GAMMA /3/ approximating the profiles of the measured lines by symmetric gaussian distributions and the background by a linear or quadratic polynome for single or overlapping peaks, respectively. The energy calibration was also performed using a polynomial expression, but in the small energy range under study a linear dependence delivers a chi-square less than one in every case.

Figure 1 shows the prompt and the sum over 6 delayed spectra for uranium target in the energy range from 70 to 106 keV recorded with 0.16 keV/channel. In the prompt spectrum muonic transitions of U , C and N are indicated as well as electronic X -rays from uranium produced by the muons stopping in the target. In the delayed spectrum additional X -rays from protactinium are observed. The intensity of both electronic components ($Z = 91, 92$) decays with $\tau \sim 80$ ns. This confirms the conclusion that the delayed electronic X-rays are produced in the mechanism of the nuclear capture of μ^- exciting the protactinium as well as the uranium atoms.

The only unidentified peaks in the prompt spectrum form, in respect to positions and intensity ratio, a pattern like Z = 91 electronic X-rays but shifted more than two channels with respect to the expected positions of such X -rays. The same behaviour was observed for the other elements too.

Therefore we think to have evidence for a large shift of the electronic KX -radiation emitted during the muonic cascade.

The results for all studied elements are shown in fig. 2 as the energy deviations of the electronic KX -rays in the prompt and delayed spectra with respect to the tabulated values /4/. One can conclude that the calibration

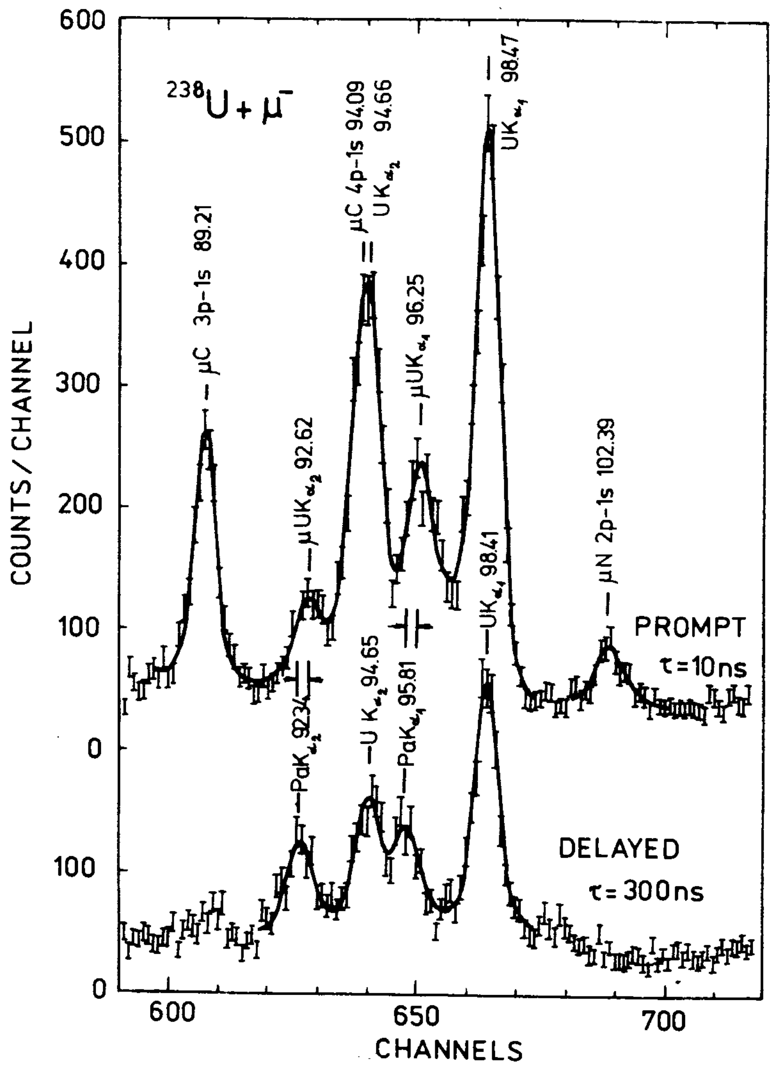

Fig. 1. X -ray spectrum observed by the interaction of negative muons with uranium. Between the prompt and the delayed spectrum a pause of 20 ns was inserted. The full lines indicate the result of the fit to the data points which are drawn with statistical errors.

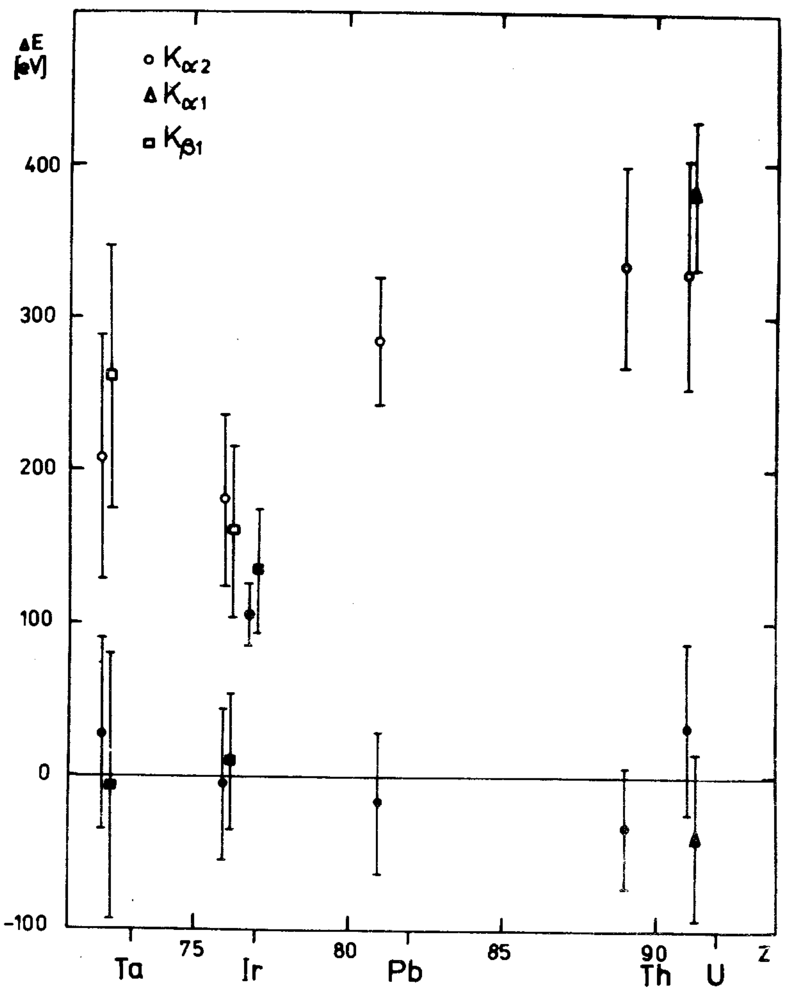

Fig. 2. Positions of (Z−1) KX-rays formed in the interaction of negative muons with heavy atoms. The energies are given as shifts with respect to the tabulated energies (= zero line). The results are marked with open or filled symbols for prompt and delayed X-rays respectively. The relative values derived from the CERN measurements are marked with a cross.

is consistent within limits of error. In many cases not all KX -transitions could be used to fix energy shifts since either muonic X-rays are present at this energy or the KX -components of Z and Z−1 overlap each other. The magnitude of the energy shift for the prompt $(Z+\mu^-)$ KX -rays seems to increase with Z.

From different spacings of the $K\alpha_1$ (Ir) line and $K\alpha_2$ (Os) line in the prompt and delayed parts of the CERN $Ir+\mu^-$ spectra a shift of (106±20) eV for $K_{\alpha 1}$ and of (133 ± 40) eV for $K_{\beta 1}$ was extracted in agreement with the Dubna results (see fig.2). The calibration of this measurement was performed only by muonic K-series from C and N. The intensity ratio of the $K_\beta / K_{\alpha 1}$ components has been found to be about 30% higher than expected from ref. /4/, however, the systematic experimental errors do not allow to draw a definite conclusion from this discrepancy.

Comparing the intensities of close lying muonic transitions and the shifted X-ray components we found as probability for the observation of electronic K_α X-rays from the muonic atom 25±10% and 65±35% per stopped muon for uranium and iridium respectively.

The holes in the electronic K-shell of the mesoatom are produced in the Auger transitions of the μ^- cascade short before radiative transitions become dominant /5/. At this stage of the cascade the screaning of one atomic charge unit by the muon is not complete and should be observed as energetic shift of the following electronic KX -transition if the latter is considerably faster than the muonic transitions /6/. In the work of Vogel /7/ the incompleteness of the muon screening and the mean number of holes in the atomic K-shell for different muon levels of the system Pb $\pm\mu^-$ are calculated. The shift estimated as the sum of the K-vacancy probability times K -electron binding energy difference for the several muon levels has the same order of magnitude as our experimental results. So a broadening of the shifted lines has to be expected.

Indeed, the analysis of the Ir -data gives an indication for a 90 eV broadening of the shifted components (line width 540 eV FWHM).

The same calculations for the L-shell predict the existence of extra vacancies since the probability of ejection is larger for L-shell in comparison with K-shell electrons, and the refilling process for the L-shell is about one order of magnitude slower. The emission of KX-rays in the presence of multiple L-vacancies has been studied in heavy ion collisions /8/ and shifts are also reported. In principle this effect should enlarge the KX-ray shifts in muonic atoms. A comparison of K_α and K_β shifts seems however to indicate that the latter effect is not dominating in muonic atoms. Otherwise one would observe a K_β shift 2.5 times larger than the K_α shift.

Investigating the observed phenomenon with better spectroscopic resolution (crystal bend spectrometer) one could determine the population of muonic orbitals in the region of $n \geq 6$ with good accuracy and in this way get a deeper understanding of the cascade process in its earlier stages.

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