Emission of mixed x-ray electron radiation upon production of muonic uranium atoms

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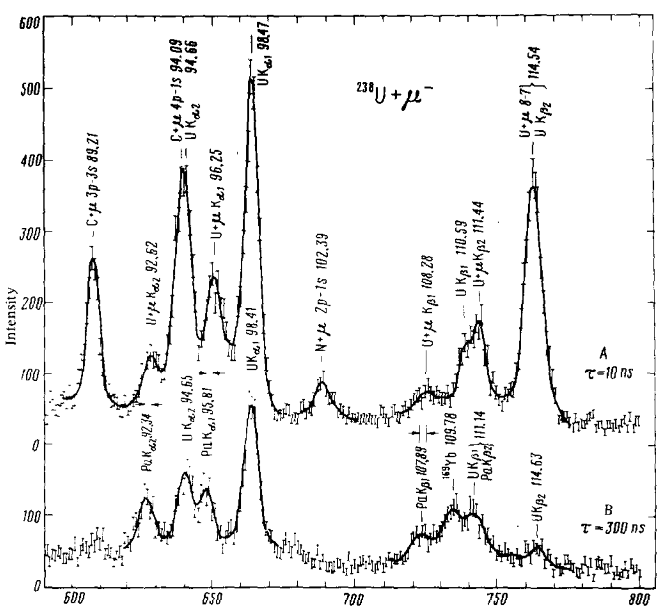
The emission of shifted x-ray electronic radiation was observed in the course of formation of muonic uranium atoms.

We investigated the spectrum of γ rays of energy from 14 to 500 keV, emitted by interaction between negative muons and metallic ^{238}U, in the muon channel of the synchrocyclotron of the Nuclear Problems Laboratory of the Joint Institute of Nuclear Research.

The measurements were performed with Ge(Li) detectors of volume 2.4 and 3 cm^3 at an energy resolution better than 1 keV for 100-keV γ quanta. The muons stopped in the uranium target were registered with a telescope of four scintillation counters operating in the customarily employed $123\bar{4}$ coincidence regime.

The temporal distribution of the counts from the Ge(Li) detector was measured with a time-amplitude converter. Digital discriminators operating on line with the HP 2116C computer were used to measure the energy spectra in different time ranges relative to the stopping of the muon and the target.

The detector was energy-calibrated by means of standard radioactive compounds[1] (^{169}Yb, ^{241}Am, ^{57}Co), and also against the mesic x-ray transition lines of light elements[2] (C, N, O) observed in the spectra, the energies of which were determined with good accuracy.



Spectrum of electron x-rays observed in the interaction of negative muons with uranium. The time interval between the prompt events (spectrum A) and the start of the registration of the delayed events (spectrum B) was 20 nsec. The numbers alongside the line symbols indicate their energy in keV. μZ stands for a muonic atom of the element Z.

The γ-ray lines from the standard radioactive compounds were registered with the Ge(Li) detector during the entire experiment, owing to random coincidences with the $123\bar{4}$ stopped-muon signals (the resultion time of the coincidences was 1.5 μsec). The measured spectra were analyzed with the aid of the GAMMA program, intended for the reduction of γ-ray spectra with the CDC 6200 computer. The line shape in the spectra was approximated by a Gaussian distribution. It was assumed that the background has a linear dependence in the case of single peaks and a quadratic dependence in the case of compound peaks.

The nonlinearity of their products was described by a polynomial of third degree.

The figure shows spectra of the γ rays for the prompt events and for those delayed relative to the muon stopping.

In the spectra of the prompt coincidence one can see mesic x-ray transitions of uranium and of light elements, and also electron x-radiation of uranium, due to stopping of the muons in the target. In the spectrum of the delayed coincidences one observed electron x-radiation of protactinium in nuclear capture of muons and uranium as a result of action on the protactinium of secondary particles emitted upon nuclear capture of the muon.

The electron x-radiation of protactinium and uranium vanishes with a lifetime $\tau \sim 80$ nsec, which is typical of the lifetime of the muon on the 1s orbit in heavy elements.

The x-ray energy of the uranium and protactinium measured by us agrees with sufficient accuracy with the published data (table).

At the same time, attention is called to the presence in the spectrum of prompt events of two lines whose positions and intensities recall the characteristic x-radiation of the protactinium ($Z = 91$), but is shifted

Electron x-radiation	Pa, keV (Ref. 3)	Pa [1], keV (expt)	μU, keV (expt)	μU–Pa, eV
$K_{\alpha 2}$	92.287	92.341 ± 0.056	92.616 ± 0.076	329 ± 76
$K_{\alpha 1}$	95.868	95.807 ± 0.055	96.250 ± 0.051	382 ± 51

towards higher energy by not less than two channels. The magnitude of these shifts in energy scale is indicated in the table.

It should be noted that the spectrum contains no unidentified lines.

The foregoing fact allows us to interpret the observed shifted lines as electron x-radiation of mesic atoms of uranium.

The vacancies in the K shell, the filling of which is connected with the appearance of shifted x-radiation, are formed as a result of the Auger process.

One can attempt to explain the shift observed in the described experiments relative to the x-radiation, in accordance with[4], as being due to incomplete screening of the unit atomic charge by the muon located on a sufficiently high orbit.

It should also be borne in mind that the observed shift can be partially due to the appearance of additional vacancies in the L shell during the time of the atomic KX transitions.

A similar situation is observed in the study of x-radiation in collisions of heavy atoms.[5]

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