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RADIATIONLESS $3d \rightarrow 1s$ TRANSITION IN MUONIC ATOMS OF ^{238}U

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ABSTRACT

The probability of the radiationless muonic transition $3d \rightarrow 1s$ in ^{238}U has been determined. This was done by comparing the singles muonic spectrum with the one gated by the $2p \rightarrow 1s$ transition. The probability was found to be $(14 \pm 5)\%$.

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The presence of radiationless transitions in the muon cascade, leading to nuclear excitation, was clearly demonstrated by the observation that negative muons induced prompt fission [1] as well as the emission of prompt neutrons [2].

However, little is known about the probability for radiationless transitions in the actinide region. In a recent paper Teller and Weiss [3] calculated the probabilities for different radiationless transitions in ^{238}U . For the $3d \rightarrow 1s$ muonic E2 transition they treated the isoscalar giant quadrupole resonance as an entrance channel.

Regarding the role of the various transitions in inducing prompt neutron emission, Lohs et al. [4] came to the conclusion that the $3d \rightarrow 1s$ muonic transition was mainly responsible for the excitation of ^{207}Pb and ^{209}Bi leading to prompt neutron emission. These authors studied three different ways of nuclear excitation in their microscopic calculations -- direct, semi-direct, and compound-nucleus mechanisms; the last was found to give the main contribution to the experimentally observed intensities of prompt neutrons.

For the case of prompt fission in ^{238}U it was found by the present authors [5] that $(74 \pm 15)\%$ of the effect could be attributed to the $3d \rightarrow 1s$ radiationless transition.

The purpose of the present $\gamma\gamma$ -coincidence experiment was to measure the probability of the muonic $3d \rightarrow 1s$ radiationless transition in ^{238}U by determining the fraction of missing $3d \rightarrow 2p$ X-rays.

The experiment was performed at the SIN cyclotron in a μ^- beam with a momentum of 85 MeV/c. The beam was defined by slits and collimators to have an intensity of 3.4×10^5 muons/s, measured as coincidences between the first two counters of the muon telescope. A plexiglas Čerenkov counter vetoed the electrons present in the beam. The muon stop signal (12 $\overline{\text{C34}}$) was defined in time by the small third counter in front of the target. Using Be as a degrader the beam energy was lowered to stop the muons in a metallic uranium target of natural composition ($\emptyset = 5.0$ cm, thickness 4.76 g/cm²). The resulting stop rate was 3.8×10^4 s⁻¹. In order to avoid

distortion in the coincidence spectra, events where two muons occurred within 400 ns of each other were rejected.

The muonic X-rays produced in the target were viewed by three detectors. A CsF crystal ($\emptyset$ 12.7 cm, length 12.7 cm) was placed at a distance of 10 cm from the target. This detector was used to select the 6 MeV $2p \rightarrow 1s$ muonic X-ray in uranium, by gating the energy region 4-7 MeV. Two large germanium detectors (efficiencies 13.5 and 15%), in coincidence with each other and with the CsF detector, were mounted at 90° with respect to the muon-beam direction and the CsF crystal.

In order to check the possible influence of the angular distribution in the $\gamma\gamma$ -correlation measurement two geometrical arrangements were used, one with the setting described above and the other with one germanium detector turned 90° to become aligned with the CsF crystal. Within the limits of statistical errors there was no difference seen between the two cases.

Figure 1 shows a γ -ray spectrum (data points with error bars) measured in coincidence with the CsF detector. For comparison the solid curve represents the singles spectrum normalized to the $3d \rightarrow 2p$ transition intensity of the coincidence spectrum. One clearly observes the suppression of the $4f \rightarrow 3d$ and other transitions higher up in the muonic X-ray cascade when measured in coincidence with the $2p \rightarrow 1s$ muonic X-rays.

The data taking was divided into several shorter runs, in order to check possible drift of the electronics. The ratios given in Table 1 represent the weighted mean values from the separate runs. As can be seen from the table, the intensity of the $4f \rightarrow 3d$ transition in the coincidence spectrum is suppressed by 19% as compared to that of the singles spectrum. This value represents the probability that the $3d$ level decays via other channels than the $3d \rightarrow 2p$ transition. Neglecting the very small probability of decay to the $2s$ level the only possibility is the direct transition $3d \rightarrow 1s$, either radiative or non-radiative.

The observed suppression of intensities of higher transitions, $7 \rightarrow 6$, $6 \rightarrow 5$ and $5g \rightarrow 4f$, results from summing up the decay probabilities of $3d$, $4f$, and $n = 5$ levels

via channels bypassing the 2p level. Owing to the relatively large errors it is difficult to disentangle the three separate components coming from the different levels. The main contribution is given by the decay of the 3d level; the rest can probably be explained by decay via 4p, 4d and 3p levels, and subsequent radiative or non-radiative transitions.

The radiative $3d \rightarrow 1s$ transition intensity has been measured for ^{209}Bi and found to be 3% per μ -stop, a result which agrees with the theoretical predictions [6].

For ^{238}U calculations of the ratio of radiative widths for the 3d level: $\Gamma_Y(3d \rightarrow 1s)/\Gamma_Y(3d \rightarrow 2p)$ give values in the range 4 to 6% [7].

Using 5% for this value we come to the conclusion that the observed suppression of the $4f \rightarrow 3d$ transition in the coincidence spectrum corresponds to a probability of $(14 \pm 5)\%$ for the $3d \rightarrow 1s$ radiationless transition. This value is in good agreement with the theoretical estimate of 15% calculated by Teller and Weiss [3].

In our previous paper [5] we discussed the ratio of neutron to fission widths for the nuclear de-excitation following the $3d \rightarrow 1s$ radiationless transition. In that discussion an assumption was made about the probability for this transition. Our present result supports this assumption and thus the conclusion reached there about Γ_n/Γ_f is valid.

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Table 1

Ratios between the intensities of different muonic X-ray transitions in ^{238}U recorded in i) coincidence with the $2p \rightarrow 1s$ transition and ii) singles spectra. The ratio of the $3d \rightarrow 2p$ transition intensities was normalized to unity. In the present measurement the transitions $7 \rightarrow 6$ and $6 \rightarrow 5$ could not be resolved into separate components

Transition	$N_{\text{coinc}}/N_{\text{singles}}$
$7 \rightarrow 6$	0.60 ± 0.05
$6 \rightarrow 5$	0.62 ± 0.04
$5g \rightarrow 4f$	0.76 ± 0.04
$4f \rightarrow 3d$	0.81 ± 0.05
$3d \rightarrow 2p$	1.00

Figure caption

Fig. 1 : γ -ray energy spectrum measured with a germanium detector in coincidence with the CsF detector (the solid line represents the singles spectrum).

Fig. 1