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THE PROBABILITY OF NON-RADIATIVE DECAY OF THE 3d LEVEL IN MUONIC ^{237}Np

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The X-ray spectrum of muonic ^{237}Np has been investigated with stopped muons in a NpO_2 target, containing about 10 g of ^{237}Np. The probability of the radiationless muonic 3d→1s transition in ^{237}Np, (9 ± 4)%, was obtained by comparing the relative intensities of the main muonic X-ray transitions in singles and coincidence spectra. The coincidences were gated by the 2p→1s transitions.

The role of quadrupole 3d→1s radiationless transitions in nuclear excitation, leading to prompt processes like γ decay, neutron emission or fission [1–4], has been discussed in several papers [5–8].

There are two theoretical descriptions of the non-radiative width of the 3d level in heavy muonic atoms. A microscopical one [5] emphasizes the role of the compound nucleus mechanism, and a phenomenological one [8] describes it in terms of the isoscalar giant quadrupole resonance as an entrance channel for nuclear excitation accompanied by the radiationless 3d→1s transition.

If the phenomenological approach is correct, the probability of the radiationless 3d→1s transition,

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calculated by Teller and Weiss [8] for muonic ^{238}U to be about 15%, should be quite similar for muonic atoms of neighbouring nuclei such as ^{232}Th, ^{235}U or ^{237}Np. For ^{238}U this probability is found [5] to agree with the prediction [8]. However, so far no other experimental data are available. To provide such data was one of the motivations to perform the present experiment.

Experimentally there is a systematic and rapid increase in the probability of prompt fission with the value of the fissility parameter [1,3]. Regarding prompt fission of muonic ^{238}U, about 75% of all events are due to the 3d→1s radiationless transition [7]. The question then arises how the yield of prompt fission is shared between the 3d→1s and the 2p→1s radiationless transitions in muonic ^{237}Np, where the total prompt fission rate per stopped μ^- is about 10 times higher than the corresponding figure for ^{238}U. In order to clarify these points, we performed a measurement on ^{237}Np to determine the probability of the radiationless muonic 3d→1s transition, using the same experimental method as was used to determine the non-radiative decay of the 3d level in muonic ^{238}U [6,7].

From a comparison of X-ray singles spectra with coincidence spectra, in which the coincidence rate between the 2p→1s transition and other cascade lines is measured, the fraction of missing 3d→2p muonic X-rays is obtained, giving the total decay probability of the 3d level not populating the 2p level. Correcting this value for the radiative width of the 3d→1s transition and disregarding the very weak ($\leqslant$0.1%) 3d→2s transition, one obtains the non-radiative width of the 3d level.

The experiment was performed at the SIN cyclotron with a beam of negative muons, having a momentum of 85 MeV/*c*. The beam intensity, measured as the number of coincidences between the first two counters of the beam telescope, was about 7×10^5 μ^-/s. The muons were slowed down to stop in the ^{237}Np target by using a beryllium/polyethylene degrader. The target consisted of NpO_2, containing 9.981 g of ^{237}Np, with a thickness of about 0.92 g/cm ^{2}. To avoid pile-up, events in which two muons arrived within a time interval of 200 ns of each other were rejected.

The previous measurement [6] on ^{238}U has shown the necessity to take care of the unfavourable intensities of the weak 5→4 and 4→3 transitions and of the components in the 2p→1s complex as compared to the high Compton background. To match this problem the muonic ^{237}Np X-ray spectra were registered in a large volume (28%) intrinsic Ge detector, provided with a BGO-shield (13 cm$\times$13 cm$\times$15 cm) for Compton suppression. The suppression factor for the Compton background in the measurement was about five. The maximum energy registered (in 8192 channels) by the Ge counter, was about 10 MeV. Two large-volume scintillation counters, a CsF and a NaI(Tl) crystal, were used to record the 2p→1s transition in the muonic ^{237}Np cascade. In the off-line analysis these detectors were set to gate an energy interval from 4 to 8 MeV, which includes the 2p→1s transitions. The muonic ^{237}Np spectra were registered in both singles mode and in coincidence with the CsF and/or NaI(Tl) counters. All three detectors were mounted around the target at 90° with respect to the μ-beam direction. The data acquisition system is described in ref. [9].

In figs. 1–3 selected parts of the muonic ^{237}Np X-ray spectrum are presented. In the coincidence spectra of the Ge counter we observed a small amount of the 2p→1s transitions, due to accidental coincidences with the counting rate in the scintillation crystals. The observed yield of the 2p→1s transition corresponds to an admixture of the singles spectrum into the coincident spectrum of about 10–15%. After applying a correction for this effect the ratio of the gated to the non-gated L X-ray complexes are normalized to unity, using the summed contents of the main components of these transitions in the two energy intervals 3070–3095 keV and 3280–3360 keV (fig. 1). This correction on the coincidence spectrum gives an uncertainty in the final result that is negligible in comparison to the quoted accuracies. The above energy intervals, chosen for the summed components of the L X-rays, are selected to minimize the influence of the background and possible systematic errors. A change of less than 0.3% occurs in the normalization, when choosing the energy interval to be 2950–3410 keV.

In fig. 2, superimposed on each other, the gated and non-gated spectra of the 4f→3d transitions are shown and normalized as just discussed (this normalization value, obtained from the ratio of the total sum of the L X-ray complex in the singles to that of the

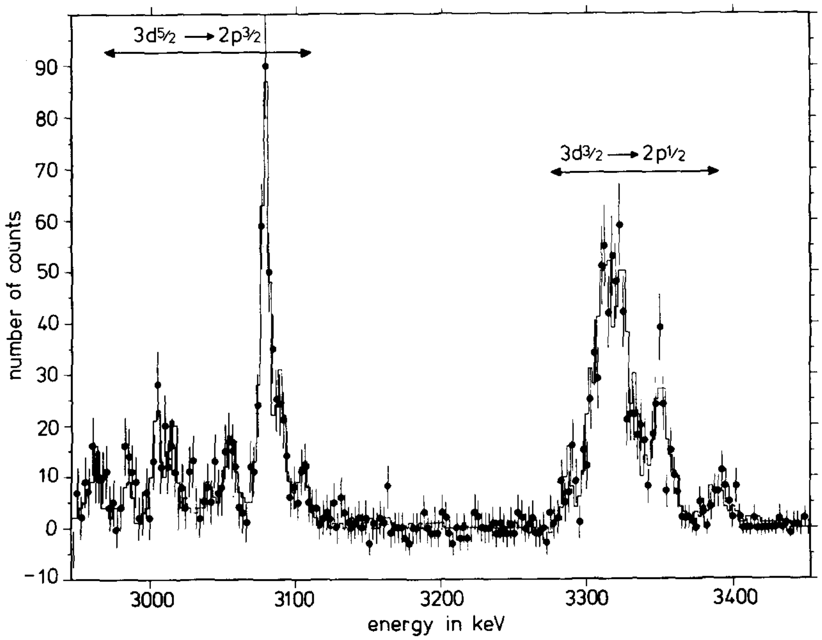

Fig. 1. The muonic [237]Np 3d→2p transition measured in coincidence with the 2p→1s transition. The solid line (histogram) represents the singles spectrum normalized to the coincidence data. The background has been subtracted. The left-hand side muonic complex represents the $3d_{5/2}\to 2p_{3/2}$ hyperfine complex and the right-hand side complex represents the $3d_{3/2}\to 2p_{1/2}$ hyperfine complex.

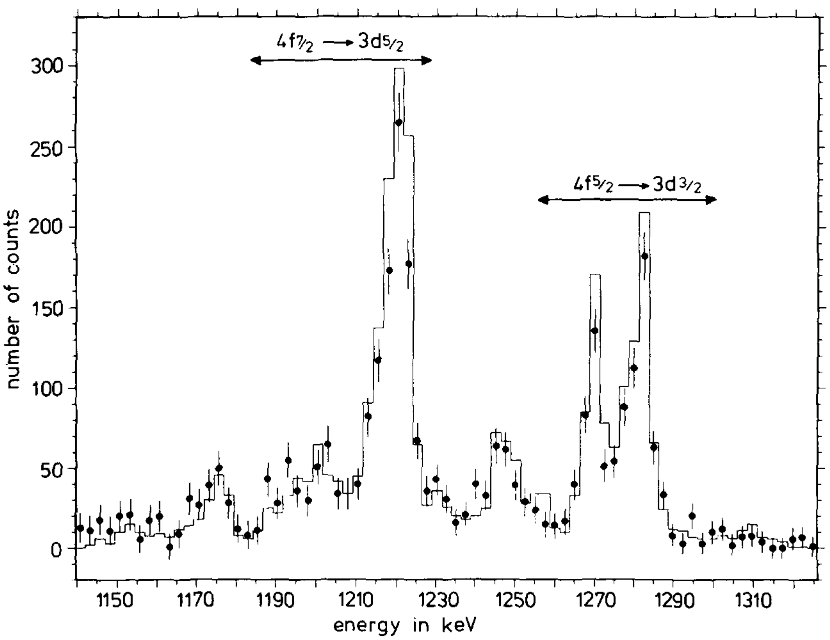

Fig. 2. The muonic [237]Np 4f→3d transition measured in coincidence with the 2p→1s transition. The singles spectrum (solid line histogram) was normalized to the coincidence data by multiplying the content of the original spectrum with the normalization factor, obtained from the ratio of gated to non-gated spectra of the 3d→2p transition. The background has been subtracted (see text). The left-hand side muonic complex represents $4f_{7/2}\to 3d_{5/2}$ hyperfine complex and the right-hand side complex represents the $4f_{5/2}\to 3d_{3/2}$ hyperfine complex.

coincidence spectrum, was used for all the other complexes). In a similar way, fig. 3 presents both spectra for the 5g→4f transitions. The background for the different X-ray transitions has been defined by a step-function as described e.g. by Taal et al. [10]. However, the data have also been analysed with a linearly decreasing background. The difference in the results for the two cases was within the quoted errors.

The suppression of the 4f→3d and 5g→4f transitions in the muonic ^{237}Np X-ray cascade, when measured in coincidence with the 2p→1s transition, is clearly observed. For the separate L X-ray components in ^{237}Np the differences in yield between singles and coincidence spectra are negligibly small within the limits of the errors (fig. 1), whereas they were significantly different in the case of ^{238}U [6]. Because of the high background of the natural γ-ray activity of ^{237}Np, the 6→5 transition was obscured and could not be used for the analysis.

Based on the 4f→3d and 5g→4f results, the 2p level is bypassed by (13±5)% and (10±6)%, respectively, or on the average by (12±4)%. The quoted errors include inaccuracies due to background estimation.

The radiative, relative width of the 3d level in muonic ^{237}Np, is obtained from a comparison of the singles X-ray spectra of ^{237}Np and ^{208}Pb, resulting in a value of (3±1)% [14] and in good agreement with the calculated value for muonic ^{238}U [6]. As a consequence, the observed suppression of the 4f→3d transition in the coincidence spectrum corresponds to a probability of (9±4)% for a radiationless 3d→1s transition in muonic ^{237}Np.

Due to the rather large relative errors in both measurements, the smaller value of the radiationless 3d→1s transition in muonic ^{237}Np as compared to ^{238}U, where it was found to be (14±5)% [6], might not be statistically significant. These results show that the phenomenological model predictions [8] are quite good.

As the muonic 2p→1s transition energies are almost the same in these nuclei, the reason for the difference in the ratios of prompt to delayed muon induced fission yield, namely (28.3±0.3)% and (8.8±0.3)% [11–14] for ^{237}Np and ^{238}U, respectively, must be explained by the difference in height of fission barriers: $E_b(^{237}\mathrm{Np})=5.50$ MeV and $E_b(^{238}\mathrm{U})=6.35$ MeV [11–13]. In the case of ^{237}Np,

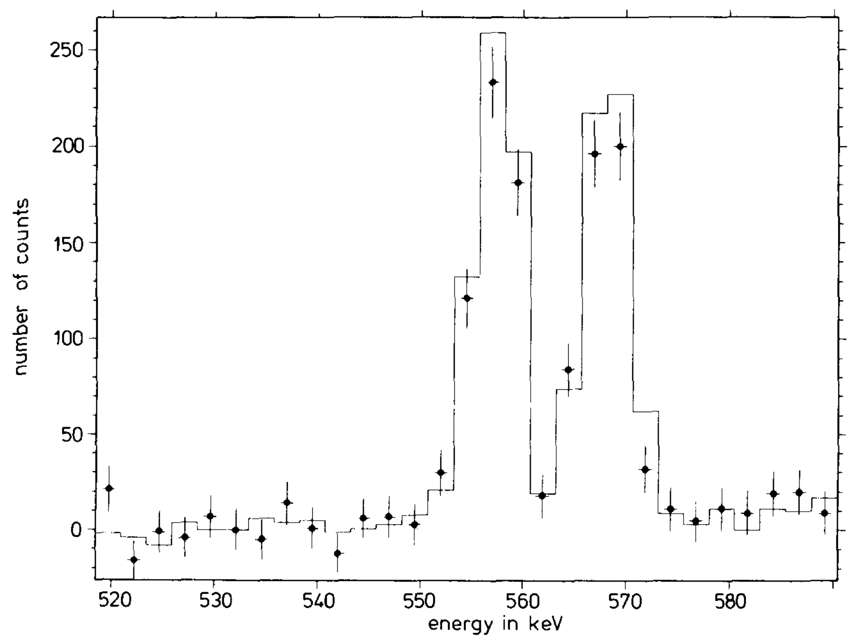

Fig. 3. The 5g→4f transition in muonic ^{237}Np, treated as mentioned in the caption of fig. 2. The left-hand side muonic complex represents the $5g\frac{9}{2}\rightarrow 4f\frac{7}{2}$ hyperfine complex and the right-hand side complex represents the $5g\frac{7}{2}\rightarrow 4f\frac{5}{2}$ hyperfine complex.

(22.0±0.2)% of all fission can be ascribed to prompt fission, resulting in a prompt fission probability of (2.7±0.3)% for ^{237}Np, when using a value of (12.4±1.0)% for the amount of total fission per μ-stop [3]. Assuming most of the radiationless 3d→1s transition probability to give rise to prompt neutron events, as in the case in ^{238}U [7], one may conclude that the radiationless 2p→1s transition plays a much more important role for prompt fission in ^{237}Np than is in the case in ^{238}U. This has, however, to be verified in a separate fission–X-ray coincidence experiment.

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