The probability of non-radiative decay of the 3d level in muonic 237Np

Citation for published version (APA):

DOI:
10.1016/0370-2693(86)91196-2

Document status and date:
Published: 01/01/1986

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 06. Apr. 2020
THE PROBABILITY OF NON-RADIATIVE DECAY
OF THE 3d LEVEL IN MUONIC $^{237}$Np

P. DAVID, J. HARTFIEL1, H. JANSZEN2, T. MAYER-KUCKUK, R. VON MUTIUS3

C.T.A.M. DE LAAT, A. TAAL, W. DUINKER, J. KONIJN
NIKHEF-K, NL-1009 DB Amsterdam, The Netherlands

J.F.M. D'ACHARD VAN ENSCHUT4
Physics Department, Delft University of Technology, NL-2629 JB Delft, The Netherlands

C. GUGLER, L.A. SCHALLER, L. SCHELLENBERG
Institut de Physique, Université de Fribourg, CH-1700 Fribourg, Switzerland

T. KROGULSKI
University of Warsaw, Branch in Białystok, 15-424 Białystok, Poland

C. PETIT JEAN, H.W. REIST
SIN, CH-5234 Villigen, Switzerland

and

W. MÜLLER
European Institute for Transuranium Elements, JRC Karlsruhe, Fed. Rep. Germany

Received 27 June 1986

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,
calculated by Teller and Weiss [8] for muonic $^{238}\text{U}$ to be about 15%, should be quite similar for muonic atoms of neighbouring nuclei such as $^{232}\text{Th}$, $^{235}\text{U}$ or $^{237}\text{Np}$. For $^{238}\text{U}$ 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 $^{238}\text{U}$, about 75% of all events are due to the $3d\rightarrow 1s$ radiationless transition [7]. The question then arises how the yield of prompt fission is shared between the $3d\rightarrow 1s$ and the $2p\rightarrow 1s$ radiationless transitions in muonic $^{237}\text{Np}$, where the total prompt fission rate per stopped $\mu^-$ is about 10 times higher than the corresponding figure for $^{238}\text{U}$. In order to clarify these points, we performed a measurement on $^{237}\text{Np}$ to determine the probability of the radiationless muonic $3d\rightarrow 1s$ transition, using the same experimental method as was used to determine the non-radiative decay of the $3d$ level in muonic $^{238}\text{U}$ [6,7].

From a comparison of X-ray singles spectra with coincidence spectra, in which the coincidence rate between the $2p\rightarrow 1s$ transition and other cascade lines is measured, the fraction of missing $3d\rightarrow 2p$ 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 $3d\rightarrow 1s$ transition and disregarding the very weak ($\leq 0.1\%$) $3d\rightarrow 2s$ 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 $7\times 10^5$ $\mu^-/s$. The muons were slowed down to stop in the $^{237}\text{Np}$ target by using a beryllium/polyethylene degrader. The target consisted of $\text{NpO}_2$, containing 9.981 g of $^{237}\text{Np}$, 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 $^{238}\text{U}$ has shown the necessity to take care of the unfavourable intensities of the weak $5\rightarrow 4$ and $4\rightarrow 3$ transitions and of the components in the $2p\rightarrow 1s$ complex as compared to the high Compton background. To match this problem the muonic $^{237}\text{Np}$ 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(T1) crystal, were used to record the $2p\rightarrow 1s$ transition in the muonic $^{237}\text{Np}$ cascade. In the off-line analysis these detectors were set to gate an energy interval from 4 to 8 MeV, which includes the $2p\rightarrow 1s$ transitions. The muonic $^{237}\text{Np}$ spectra were registered in both singles mode and in coincidence with the CsF and/or NaI(T1) counters. All three detectors were mounted around the target at 90° with respect to the $\mu$-beam direction. The data acquisition system is described in ref. [9].

In figs. 1–3 selected parts of the muonic $^{237}\text{Np}$ X-ray spectrum are presented. In the coincidence spectra of the Ge counter we observed a small amount of the $2p\rightarrow 1s$ transitions, due to accidental coincidences with the counting rate in the scintillation crystals. The observed yield of the $2p\rightarrow 1s$ 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 $4f\rightarrow 3d$ 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 $3d\rightarrow 2p$ transition measured in coincidence with the $2p\rightarrow 1s$ 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 $3d_{5/2}\rightarrow 2p_{1/2}$ hyperfine complex and the right-hand side complex represents the $3d_{3/2}\rightarrow 2p_{1/2}$ hyperfine complex.

Fig. 2. The muonic $^{237}$Np $4f\rightarrow 3d$ transition measured in coincidence with the $2p\rightarrow 1s$ 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 $3d\rightarrow 2p$ transition. The background has been subtracted (see text). The left-hand side muonic complex represents $4f_{7/2}\rightarrow 3d_{5/2}$ hyperfine complex and the right-hand side complex represents the $4f_{9/2}\rightarrow 3d_{3/2}$ hyperfine complex.
The coincidence spectrum, was used for all the other complexes. In a similar way, fig. 3 presents both spectra for the $5g \rightarrow 4f$ 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 $4f \rightarrow 3d$ and $5g \rightarrow 4f$ transitions in the muonic $^{237}\text{Np}$ X-ray cascade, when measured in coincidence with the $2p \rightarrow 1s$ transition, is clearly observed. For the separate L X-ray components in $^{237}\text{Np}$ 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 $^{238}\text{U}$ [6]. Because of the high background of the natural γ-ray activity of $^{237}\text{Np}$, the $6 \rightarrow 5$ transition was obscured and could not be used for the analysis.

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

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

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

As the muonic $2p \rightarrow 1s$ 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 $(28.3 \pm 0.3)$% and $(8.8 \pm 0.3)$% [11–14] for $^{237}\text{Np}$ and $^{238}\text{U}$, respectively, must be explained by the difference in height of fission barriers: $E_b(^{237}\text{Np}) = 5.50$ MeV and $E_b(^{238}\text{U}) = 6.35$ MeV [11–13]. In the case of $^{237}\text{Np}$,

Fig. 3. The $5g \rightarrow 4f$ transition in muonic $^{237}\text{Np}$, treated as mentioned in the caption of fig. 2. The left-hand side muonic complex represents the $5g_4^2 \rightarrow 4f_5^2$ hyperfine complex and the right-hand side complex represents the $5g_2 \rightarrow 4f_5$ 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 $\mu$-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.

We thank Professor Dr. J.P. Blaser and his staff for the encouraging support and for the excellent working conditions at SIN. This work is part of the research programme of, and made financially possible by, the following institutes and financially supporting organizations: Bundesministerium für Forschung und Technologie der Bundesrepublik Deutschland, Technische Hogeschool Delft, Foundation for Fundamental Research on Matter (FOM) and the Netherlands’ Organization for the Advancement of Pure Research (ZWO), Swiss National Foundation and the University of Warsaw. For preparing the target we thank Mr. K. Richter and his coworkers at the European Institute for Transuraniums, K.F.Z. Karlsruhe, W. Germany.

References

[12] P. David et., to be published.