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Citation for published version (APA):
Laat, de, C. T. A. M., Taal, A., Duinker, W., Konijn, J., Achard van Enschut, d', J. F. M., David, P., Hartfiel, J., Janszen, H., Mayer-Kuckuk, T., Mutius, von, R., Piller, C., Schaller, L. A., Schellenberg, L., Krogulski, T., Petitjean, C., Reist, H. W., & Müller, W. (1987). The quadrupole moment and strong interaction parameters from muonic and pionic X-ray studies of 237Np. *Physics Letters B*, *189*(1-2), 7-11. https://doi.org/10.1016/0370-2693(87)91260-3

DOI:
10.1016/0370-2693(87)91260-3

Document status and date:
Published: 01/01/1987

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.
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THE QUADRUPOLE MOMENT AND STRONG INTERACTION PARAMETERS FROM MUONIC AND PIONIC X-RAY STUDIES OF ^{237}Np

C.T.A.M. DE LAAT [a], A. TAAL [a], W. DUINKER [a], J. KONIJN [a],
J.F.M. D'ACHARD VAN ENSCHUT [b], P. DAVID [c], J. HARTFIEL [c], H. JANSZEN [c],
T. MAYER-KUCKUK [c], R. VON MUTIUS [c], C. PILLER [d], L.A. SCHALLER [d],
L. SCHELLENBERG [d], T. KROGULSKI [e], C. PETITJEAN [f], H.W. REIST [f] and W. MÜLLER [g,h]

[a] *NIKHEF-K, NL-1009 DB Amsterdam, The Netherlands*
[b] *Physics Department, Delft University of Technology, NL-2629 JB Delft, The Netherlands*
[c] *Institut für Strahlen- und Kernphysik der Universität Bonn, D-5300 Bonn, Fed. Rep. Germany*
[d] *Institut de Physique, Université de Fribourg, CH-1700 Fribourg, Switzerland*
[e] *University of Warsaw, Branch in Bialystok, PL-15-424 Bialystok, Poland*
[f] *SIN, CH-5234 Villigen, Switzerland*
[g] *European Institute for Transuranium Elements, JRC Karlsruhe, D-7500 Karlsruhe, Fed. Rep. Germany*
[h] *CBNM, Euratom, B-2440 Geel, Belgium*

Received 17 December 1986

The X-ray spectrum of muonic and pionic ^{237}Np has been investigated with muons and pions stopped in a NpO$_2$ target. The nuclear spectroscopic quadrupole moment was determined to be $Q = 3.886 \pm 0.006$ b from the splittings of the muonic 5g→4f hyperfine complexes. The $B(\mathrm{E2})\downarrow$-values for the first and second excited states were evaluated as 3.17 ± 0.08 and 2.77 ± 0.10 $e^2\mathrm{b}^2$, respectively. A comparison between the muonic and pionic 5g→4f hyperfine complexes yields the strong interaction parameters for the pionic 4f state. For the first time a change of sign as function of Z for the strong interaction quadrupole shift $\epsilon_2(4\mathrm{f})$ has been observed. The standard optical model predictions agree reasonably well with the measured strong interaction monopole shift, $\epsilon_0(4\mathrm{f})$, and width, $\Gamma_0(4\mathrm{f})$, while they disagree with the experimental value for ϵ_2. A stronger s-wave repulsion in the optical potential could explain this effect.

From the study of muonic and pionic atoms of a deformed heavy actinide, interesting aspects can be learnt about electromagnetic and strong interactions. The latter induces shifts, ϵ, and widths, Γ, on pionic X-ray transitions, the observation of which has been used to construct a semiphenomenological optical potential [1]. This potential plays an important role, not only in pionic atoms but also in describing near-threshold photoproduction, radiative capture and in a slightly modified form low-energy pion–nucleus scattering. The non-spherical part of the strong and the electromagnetic interaction gives rise to a hyperfine splitting of each pionic or muonic level. Furthermore, by comparing the pionic and muonic hyperfine splitting patterns, strong interaction monopole and quadrupole parameters can be extracted. The results contribute to the investigation on the earlier observed deviations between experiment and theory in pionic atoms [2]. As pointed out by Dey et al. [3], errors reflecting uncertainties in the calculation of multi-electron systems and in estimating the electric field inhomogeneity at the nucleus and the effect of the polarization of the electron core do not exist in muonic and pionic atoms. In the domain of intermediate energy states for pionic and muonic atoms, where the orbit size is large compared with nuclear dimensions and yet small compared with the orbits of atomic electrons, the exotic atom is "hydrogen-like". The corrections for finite size, vacuum polarization, magnetic dipole, and electric hexadecapole effects applied to the quadrupole hfs are small for the 5g→4f transitions. They add up to only a few percent.

The present experiment not only serves to measure the nuclear spectroscopic quadrupole moment from muonic and pionic ^{237}Np atoms but is also aimed at investigating the behaviour of strong interaction parameters $\Gamma_0(4f)$ as well as $\epsilon_0(4f)$ and $\epsilon_2(4f)$. In earlier studies a change in sign for ϵ_2 has been observed, when going from the 4f to the 3d level in the nuclei Ta and Re [4]. As the pionic states populated in ^{237}Np are much more bound than those in Ta, Re, Au, Pt, Pb and Bi [2,4], deviations in the strong interaction parameters such as a possible change of sign in ϵ_2 within the pionic 4f level, therefore, are best looked for in the mass region of the heavy actinides.

The experiment was performed with muon and pion beams at SIN, Switzerland. The pion beam was tuned to 100 MeV/*c*, whereas the muons had a momentum of 50 MeV/*c*. Stop rates of approximately $10^6\,\pi^-$/s and $10^5\,\mu^-$/s were obtained in a 0.92 g/cm^2 thick NpO_2 target, containing 9.981 g of ^{237}Np. The experimental set-up includes a multidetector BGO Compton suppression spectrometer. The measuring technique has been described earlier [2]. The energy calibration was taken from accurately known energies of muonic X-rays and nuclear γ-ray transitions induced in the target and its aluminum encapsulation by the incident particle beam. The neutron induced background transitions were well separated in time from the prompt X-rays, by using a time-of-flight path of about 60 cm between target and detector.

Regarding the muonic 2p→1s, 3d→2p and 4f→3d transitions one should note that several low-lying excited states belonging to the rotational band of the Nilsson ground state configuration $\frac{5}{2}^+[642]\uparrow$ in ^{237}Np are mixed appreciably with the muonic 3d, 2p and 1s states. Therefore, the spectroscopic nuclear quadrupole moment is derived by fitting the observed hyperfine splitting in both the muonic 6g→4f and 5g→4f transitions, which have energies in the region of 0.86 and 0.55 MeV, respectively. This method has the advantage of not being sensitive to the finite nuclear size and the dynamical mixing of nuclear states. The K, L and M X-ray data were only used to determine approximate nuclear charge distribution parameters, namely the Fermi parameters $c=7.00$ fm and $t=2.3$ fm, respectively. In fig. 1 we present the hyperfine splitting of the $5g_{9/2}\to 4f_{7/2}$ and $5g_{7/2}\to 4f_{5/2}$ muonic X-rays, the transitions of which occur with a much higher transition rate than the 6g→4f complexes. From the latter a moderately accurate value

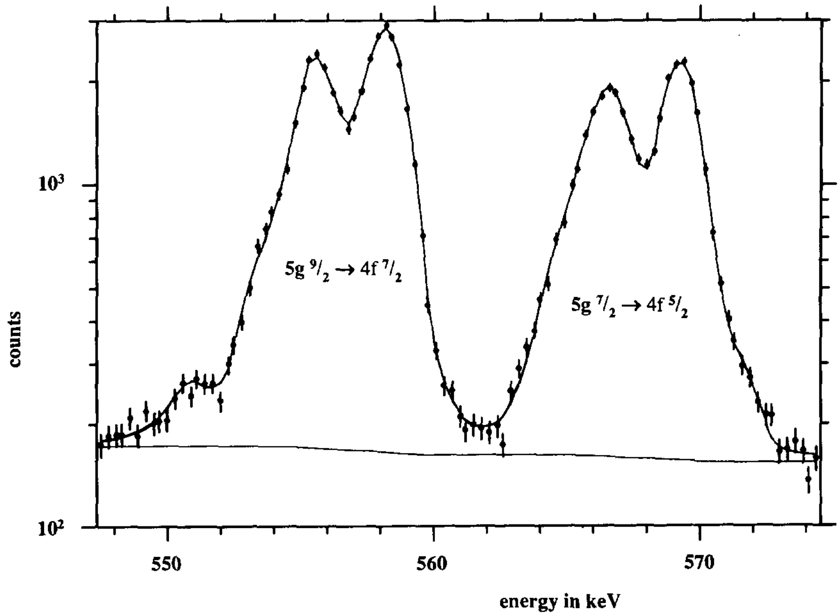

Fig. 1. The muonic 5g→4f hyperfine complexes of ^{237}Np are shown, the muonic $5g_{9/2}\to 4f_{7/2}$ complex to the left and the $5g_{7/2}\to 4f_{5/2}$ X-ray complex to the right. The hyperfine splitting of the two complexes is pronounced, the strongest two components of each complex being split by $\Delta E = 2.608 \pm 0.019$ keV and $\Delta E = 2.863 \pm 0.021$ keV, respectively. The solid line is the fit to the experimental data of the hyperfine complex, including some weak nuclear γ-ray transitions from ^{236}U and ^{237}U.

of $Q=3.864\pm0.055$ b is obtained from the measured energy splitting. The energy splitting of the two $5g\to4f$ complexes is 10.864 ± 0.022 keV between the main transitions. The splitting of the two main components of each complex allows for two independent determinations of the quadrupole moment. From the energy splittings of 2.608 ± 0.019 and 2.863 ± 0.021 keV for the $5g_{9/2}\to4f_{7/2}$ and $5g_{7/2}\to4f_{5/2}$ muonic complexes, respectively, a spectroscopic nuclear quadrupole moment of $Q=3.886\pm0.006$ b is derived.

Older results [5–8], though less accurate, agree well with the present result. The ground state of ^{241}Am and the 59.537 keV state of ^{237}Np have the same Nilsson quantum numbers: $\frac{5}{2}^-[523]\downarrow$. Therefore, within the framework of the collective model, the quadrupole moments of these two Nilsson states should be equal, except for a small correction due to a change in nuclear deformation and a size correction proportional to $A^{2/3}$. From nuclear γ-ray resonance measurements [9], the ratio of the quadrupole moment of excited state to that of the ground state and the results from muonic ^{241}Am [10] one arrives at a value of $Q=3.9\pm0.2$ b, following the same procedure as in ref. [8].

The present experimental result, $Q=3.886\pm0.006$ b, is an improvement in accuracy of more than an order of magnitude for the value of the spectroscopic nuclear quadrupole moment. The $B(E2)\downarrow$-values from the first and the second excited states were evaluated, using the transition energies of the muonic $4f\to3d$, $6g\to4f$ and $5g\to4f$ transitions. They amount to 3.17 ± 0.08 e^2b^2 and 2.77 ± 0.10 e^2b^2, respectively. These $B(E2)\downarrow$-values do confirm the old Coulomb excitation results, 3.1 ± 0.8 and 2.4 ± 0.4 e^2b^2, respectively, as reported by Newton [6] but are much more precise.

In the analysis of the hfs of the pionic $5g\to4f$ complex, i.e. the determination of the hyperfine splitting, lorentzian line width, energy and intensity, it is important to include the instrumental line shape of the photopeak, see ref. [4], since otherwise the obtained lorentzian line widths are not adequately represented by the fit. Subtracting from the fitted values the radiative widths of initial and final levels, we obtain a strong interaction monopole width of $\Gamma_0(4f)=3.88\pm0.26$ keV and a monopole shift of $\epsilon_0(4f)=5.26\pm0.14$ keV (with respect to the point Coulomb energy). These results have to be compared with the values predicted by the standard Kisslinger optical potential [11–13] $\Gamma_0(4f)_{th}=4.16\pm0.92$ and $\epsilon_0(4f)_{th}=4.54\pm0.75$, respectively. The present measurement on the pionic 4f level and earlier results in other nuclei [2,4] agree reasonably well with the calculated values, contrary to those for the 3d level [2].

A quantity much more sensitive to the interplay between s- and p-waves in the π–N interaction is the strong interaction quadrupole shift, $\epsilon_2(4f)$, about which very little information is available. Besides the strong interaction monopole shift and width, the observed hfs of the pionic $5g\to4f$ transition of the strongly deformed ^{237}Np nucleus also yields the effective electric quadrupole constant, $A_2^{eff}(4f)=3.80\pm0.08$ keV. This quantity is directly proportional to the effective spectroscopic quadrupole moment, Q^{eff}. From the difference between A_2^{eff} and the calculated electromagnetic quadrupole constant $A_2(4f)=4.295$ keV in pionic ^{237}Np, the strong interaction quadrupole shift, $\epsilon_2(4f)=+0.49\pm0.08$ keV, is obtained (for the notation see ref. [14]). The formulae for calculating the quadrupole shift from experimental data for muonic and pionic atoms can be found in refs. [3,14]. In table 1 experimental values are also presented calculated from other experiments.

The agreement of $\epsilon_2(4f)$ with standard optical calculations, $\epsilon_2(4f)_{th}=0.0\pm0.1$, is rather poor. In addition, there is a change of sign for both the calculated and experimental values for the strong interaction quadrupole shift ϵ_2 as one goes from the 4f to the 3d level, whereas the monopole shift ϵ_0 remains positive (i.e. attractive). In the case of ^{237}Np we observe, for the first time, that the sign of the experimental value of $\epsilon_2(4f)$ is opposite to that of the calculated one and to that of the other elements in the same pionic shell (see table 1). This effect is very similar to the change of sign of the strong interaction monopole shift ϵ_0 observed in the pionic 2p level by Abela et al. [15]. The effect of changing sign in both cases can be ascribed to the increasing importance of the repulsive s-wave part in the strong interaction when the overlap between pion and nuclear wave functions becomes larger in deeper pionic orbits (see also the anomalous Γ_0 in 3d and 1s shells [2]). This change of sign is predicted to occur by theory for both ϵ_0 [1] and ϵ_2 [14] the experimental values are not repro-

Table 1
Strong interaction quadrupole shifts for the pionic 3d and 4f levels of some heavy deformed nuclei.

	Nucleus	$A_2^{\mathrm{eff}}(\mathrm{exp})$ (keV)	Re A_2 (keV)	$\epsilon_2^{\mathrm{exp}}$ (keV)	$\epsilon_2^{\mathrm{theory}}$ (keV)	Ref.
pionic 4f level	^{165}Ho	1.389 ± 0.027	1.336	-0.053 ± 0.027	-0.020	[16]
	^{165}Ho	1.419 ± 0.009	1.336	-0.083 ± 0.009	-0.020	[17]
	^{175}Lu	1.688 ± 0.032	1.609	-0.079 ± 0.032	-0.028	[16]
	^{181}Ta	1.724 ± 0.011	1.643	-0.081 ± 0.011	-0.031	[17]
	^{181}Ta	1.750 ± 0.016	1.643	-0.107 ± 0.016	-0.031	[4]
	Re	1.163 ± 0.010	1.117	-0.046 ± 0.010	-0.023	[4]
	^{209}Bi	-0.37 ± 0.05	-0.302	-0.07 ± 0.05	-0.009	[18]
	^{237}Np	3.80 ± 0.08	4.295	$+0.49 \pm 0.08$	-0.018	this paper
pionic 3d level	^{181}Ta	9.1 ± 0.5	9.610	$+0.5 \pm 0.5$	$+4.55$	[4]
	Re	5.4 ± 0.6	6.479	$+1.1 \pm 0.6$	$+3.24$	[4]

duced correctly, however.

The individual contributions to the $\epsilon_2(4\mathrm{f})$ in ^{237}Np for the pionic 4f state are calculated to be: $\epsilon_2(\mathrm{s}) = +0.901$ keV and $\epsilon_2(\mathrm{p}) = -0.919$ keV [‡1]. As pointed out by Koch and Scheck [14] the p-wave part is less important in ϵ_2 as compared to ϵ_0. Therefore, when going to heavier nuclei the pionic 4f level is more deeply bound and the repulsive s-wave interaction will become increasingly important, a change of sign in ϵ_2 is expected before it occurs in ϵ_0. A similar cancellation effect could also be the reason for the smaller theoretical values of $\epsilon_0(4\mathrm{f})$ in comparison with the experimental values for ^{238}U and ^{237}Np.

In conclusion the muonic X-ray spectrum of ^{237}Np provided us with a model independent nuclear structure information regarding $B(\mathrm{E2})\downarrow$-values and the nuclear spectroscopic quadrupole moment $Q = 3.886 \pm 0.006$ b, which could be determined from the hfs of the muonic 5g→4f complexes to an accuracy of about 0.2%. The intrinsic quadrupole moments of the nuclear ground states show a smooth systematic increase with increasing atomic mass in the heavy actinides and the present result fits well into this regular trend [19]. The present value for the intrinsic quadrupole moment, $Q_0 = 10.88 \pm 0.02$ b, is also in good agreement with theoretical calculations [20]. The pionic X-ray spectrum provided values for the strong interaction monopole width and shift of the pionic 4f level. For the first time a change of sign for the strong interaction quadrupole shift $\epsilon_2(4\mathrm{f})$ was observed. The standard optical model calculations are in disagreement with the experimental value for $\epsilon_2(4\mathrm{f})$, while the strong interaction monopole parameters $\Gamma_0(4\mathrm{f})$ and $\epsilon_0(4\mathrm{f})$ agree reasonably well with these calculations.

This work is part of the research programme of NIKHEF-K at Amsterdam, made possible by financial support from the Foundation for Fundamental Research on Matter (FOM) and the Netherlands' Organization for the Advancement of Pure Research (ZWO). It was also supported in part by the Swiss National Foundation and by the Bundesministerium für Forschung und Technologie of the Federal Republic of Germany and by the University of Warsaw. For preparing the target we thank Mr.K. Richter and his coworkers at the European Institute for Transuranium Elements, JRC Karlsruhe, Fed. Rep. Germany.

References

[1] M. Ericson and T.E.O. Ericson, Ann. Phys. 36 (1966) 323.
[2] C.T.A.M. de Laat et al., Phys. Lett. B 162 (1985) 81.
[3] W. Dey et al., Nucl. Phys. A 326 (1979) 418.
[4] J. Konijn et al., Nucl. Phys. A 360 (1981) 187.
[5] A. Veyssière et al., Nucl. Phys. A 199 (1973) 45.

[‡1] Unfortunately the sign definition [14] of the strong interaction quadrupole shift ϵ_2, $A_2^{\mathrm{eff}} = A_2 - \epsilon_2$, yields a negative value of ϵ_2 for an attractive interaction (p-wave), opposite to the definition of the monopole shift ϵ_0.

[6] J.O. Newton, Nucl. Phys. 5 (1958) 218.

[7] Y.A. Ellis, Nuclear Data Sheets 23 (1978) 71.

[8] B.D. Dunlap and G.M. Kalvius, Phys. Rev. 186 (1969) 1296.

[9] B.D. Dunlap et al., Phys. Rev. 171 (1968) 316;
J.A. Stone and W.L. Phillinger, Symp. Faraday Soc. 1 (1967) 77.

[10] M.W. Johnson et al., Phys. Lett. B 161 (1985) 75.

[11] L. Tauscher, Proc. Intern. Seminar on π-meson nucleus interaction (Strasbourg, 1971), Report CNRS-Strasbourg, p. 45.

[12] C.J. Batty et al., Nucl. Phys. A 402 (1983) 411.

[13] R. Seki and K. Masutani, Phys. Rev. C 27 (1983) 2799.

[14] J.H. Koch and F. Scheck, Nucl. Phys. A 340 (1980) 221.

[15] R. Abela et al., Z. Phys. A 282 (1977) 93.

[16] P. Ebersold et al., Nucl. Phys. A 296 (1974) 493.

[17] C.J. Batty et al., Nucl. Phys. A 355 (1981) 383.

[18] R. Beetz et al., Z. Phys. A 286 (1978) 215.

[19] J.D. Zumbro et al., Phys. Lett. B 167 (1986) 383.

[20] M. Brack et al., Nucl. Phys. A 234 (1974) 185;
J. Libert and P. Quentin, Phys. Rev. C 25 (1982) 571.