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Интенсивности мезорентгеновских переходов в свинце, тории и уране

Измерены абсолютные интенсивности основных переходов в мюонных атомах естественных элементов свинца, тория и урана. Полученные абсолютные интенсивности не подтверждают предсказания каскадной модели.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Intensities of Muonic X-Rays in Lead, Thorium and Uranium

The absolute intensities of the principal transitions in muonic atoms of natural lead, thorium and uranium have been measured. The predictions of the cascade calculations are in disagreement with the observed intensities.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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Knowledge of the intensities of muonic transitions is of essential importance for the study of muonic atom properties as well as for the investigation of the interaction between a muon and a nucleus. In the latter case the fraction of nonradiative muonic transitions directly exciting the nucleus should be known to normalize the yields of various reactions, like fission or neutron emission, following this excitation. This fraction of $2p-1s$ transition may be defined as the difference between the population of $2p$ levels and the intensity of $2p-1s$ radiative transitions. But because of the limitations of sensitivity it is experimentally very difficult at present to measure the intensities of all transitions leading to $2p$ levels. Therefore, in a few papers dealing with this problem [1,2], the lack of the intensity of $2p-1s$ transitions in thorium, uranium and plutonium elements with respect to the intensity of this transition in lead was interpreted as a fraction of radiationless transitions in the actinide nuclei. But there is one important assumption made that the intensities of the higher radiative transitions are the same for the nuclei under consideration. Otherwise, the fraction of missing X-rays cannot be simply related to that of radiationless transitions.

In the present experiment we attempt to check this assumption measuring the absolute intensities of the main muonic X-rays in natural lead, thorium and uranium.

The experiment has been performed using the separated negative muon beam of the 680 *MeV* synchrocyclotron, Dubna. The muonic X-rays were detected with a true-coaxial Ge(Li) diode of a 45 *ccm* volume, in prompt coincidences with the μ-stop signal developed by a conventional 123$\bar{4}$-counter telescope. The time resolution was $2\tau = 10$ *nsec* and the energy resolution was 3 *keV* and 8 *keV* for 1 *MeV* and 8 *MeV* energy of gamma-ray, respectively. The typical rates were as follows: 36000, 11000, 1300 and 200 per second for "1,2", "1,2,3", "1,2,3,$\bar{4}$" and (μ,γ) coincidences, respectively.

The targets were of identical dimensions, 60x77 mm^2, weighing about 50 *g* each and with the effective thickness of about 2 g/cm^2.

The reliable determination of the efficiency of X-ray detection and of the true number of μ-stops in targets was of major importance in these measurements.

To be free of beam stability problems, ten cycles of measurements were accomplished. In every cycle six runs were performed with all four targets in the order as follows: Al, Pb, Al, Th, Al, U. Thus, reasonable averaging over the fluctuations of beam conditions could be achieved. Moreover, the efficiency curve of the Ge(Li) diode was normalized to the absolute units using the well-known value of the intensity of K_α muonic transition in aluminium /3/.

The true number of μ-stops was determined comparing the dependence of four quantities on the target thickness, which were the number of μ-stops, $(\mu_{stop}, \gamma_{total})$ and $(\mu_{stop}, \gamma_{prompt})$ coincidences, and the yields of K_α muonic X-ray in Al and "6→5" and "5→4" transitions in heavy targets.

The method was checked by measuring the yields of muonic X-rays from the sandwich target composed of sixteen aluminium and lead foils 50 mg/cm^2 and 60 mg/cm^2 thick, respectively.

The experiment was carried out in two steps. Firstly, the absolute intensities of $6h \to 5g$ and $5g \to 4f$ transitions in lead, thorium and uranium were found applying the above mentioned repetitive measurements. Then in runs of longer duration the muonic X-ray spectra of all targets were measured from 150 *keV* to 7 *MeV*, and the relative intensities of transitions were established. Combining both data we obtained the final results presented in the Table.

Table 1

Intensities of radiative muonic transitions

Transitions	Pb(nat) E(keV)	Pb(nat) I_{exp}	Pb(nat) I_{calc} ($\alpha = -0.14$)	^{232}Th E(keV)	^{232}Th I_{exp}	^{238}U E(keV)	^{238}U I_{exp}
Σ 7i – 6h						166–182	0.367 ± 0.025
9j – 7i, 9i – 7h				181–191	0.034 ± 0.004	190–200	0.040 ± 0.004
8i – 6h						285–295	0.043 ± 0.007
Σ 6h – 5g	230–237	0.436 ± 0.035	0.405	274–291	0.315 ± 0.022	285–304	0.391 ± 0.027
7h – 5g	370–375	0.060 ± 0.005	0.075	443–456	0.035 ± 0.003	464–477	0.050 ± 0.006
$5g_{9/2} - 4f_{7/2}$	429–432	0.265 ± 0.016	0.239		0.176 ± 0.014		0.228 ± 0.016
$5g_{7/2} - 4f_{5/2}$	437–441	0.192 ± 0.013	0.211		0.139 ± 0.009		0.173 ± 0.010
Σ 5g – 4f	429–441	0.457 ± 0.032	0.450	514–535	0.315 ± 0.022	537–560	0.401 ± 0.026
6g – 4f	662–673	0.055 ± 0.005	0.080	794–816	0.033 ± 0.004	831–854	0.048 ± 0.005
$4f_{5/2} - 3d_{5/2}$	929	0.024 ± 0.003	0.016				
$4f_{7/2} - 3d_{5/2}$	938	0.298 ± 0.021	0.320	1115–1151	0.205 ± 0.015	1170–1210	0.260 ± 0.020
$4f_{5/2} - 3d_{3/2}$	965–972	0.224 ± 0.016	0.284	1174–1193	0.135 ± 0.010	1230–1260	0.180 ± 0.012
Σ 4f – 3d		0.546 ± 0.040	0.570		0.340 ± 0.025		0.440 ± 0.032
$3d_{5/2} - 2p_{3/2}$	2501	0.298 ± 0.022	0.435	2730–2740 2792–2825 2892–2927	0.074 ± 0.012	2810–2850 2860–3035	0.142 ± 0.020
$3d_{3/2} - 2p_{1/2}$	2642	0.176 ± 0.014	0.245	3088–3157	0.159 ± 0.013	3215–3242	0.185 ± 0.020
Σ 3d – 2p		0.474 ± 0.038	0.680		0.233 ± 0.025		0.327 ± 0.040
$2p_{1/2} - 1s_{1/2}$	5781	0.259 ± 0.026	0.295	6000–6120	0.230 ± 0.024	6050–6200	0.312 ± 0.030
$2p_{3/2} - 1s_{1/2}$	5967	0.336 ± 0.029	0.585	6280–6470	0.230 ± 0.024	6380–6580	0.237 ± 0.024
Σ 2p – 1s		0.595 ± 0.060	0.880		0.460 ± 0.048		0.550 ± 0.055

The quoted errors are determined first of all by the uncertainty of about 5% in the estimation of the μ -stop number. The error in the value of μ Ar K_α - transition intensity contribute in a 2% amount. The statistical errors are negligible for higher transitions and they amount to several per cent for K_α transitions.

The relative efficiency curve for photopeak detection was measured, extending the calibration by means of radioactive isotopes with the $^{35}Cl(n, \gamma)$ reaction. The corridor of errors of a 0.5% relative width was obtained for the functional representation of efficiency data by the polynomial of the fourth degree in the doubly logarithmic coordinates (log ϵ_r versus log E_γ).

The smooth dependence of self-absorption coefficients in the function of gamma-ray energy was determined with the inaccuracy of 3% by measuring the natural activity of the thorium target and thorium foil 0.05 *mm* thick.

The off-line analysis of the spectra was made using the computer code SAMPO /9/. The comparison of experimental results and the predictions of the cascade calculations based on the code developed by Hüfner /4/ is shown in *Fig. 1*. In the calculation only radiative E1 transitions and Auger transitions were allowed, the electronic K–, L– and M-shell conversion was included and the initial population distribution at $n = 20$: $\rho \sim (2\ell+1)e^{a\ell}$, was assumed. The intensities of $6 \to 5$, $5 \to 4$, and $4 \to 3$ transitions in lead may be reproduced by using $a = -0.14$. But for this value of the "a" parameter the calculated intensities of $3 \to 2$ and $2 \to 1$ transitions are much larger than those found experimentally. Moreover, as we can see from *Fig. 1.*, there is no value of the "a" parameter with which the intensities of muonic transitions in thorium or uranium could be reproduced. Therefore, the basic assumption of the cascade calculations referring to the initial population distribution seem to be not adequate. The theoretical predictions may also fail to reproduce the observed intensities because the effective coupling between nuclear and atomic motions is not considered at all in the used cascade calculations.

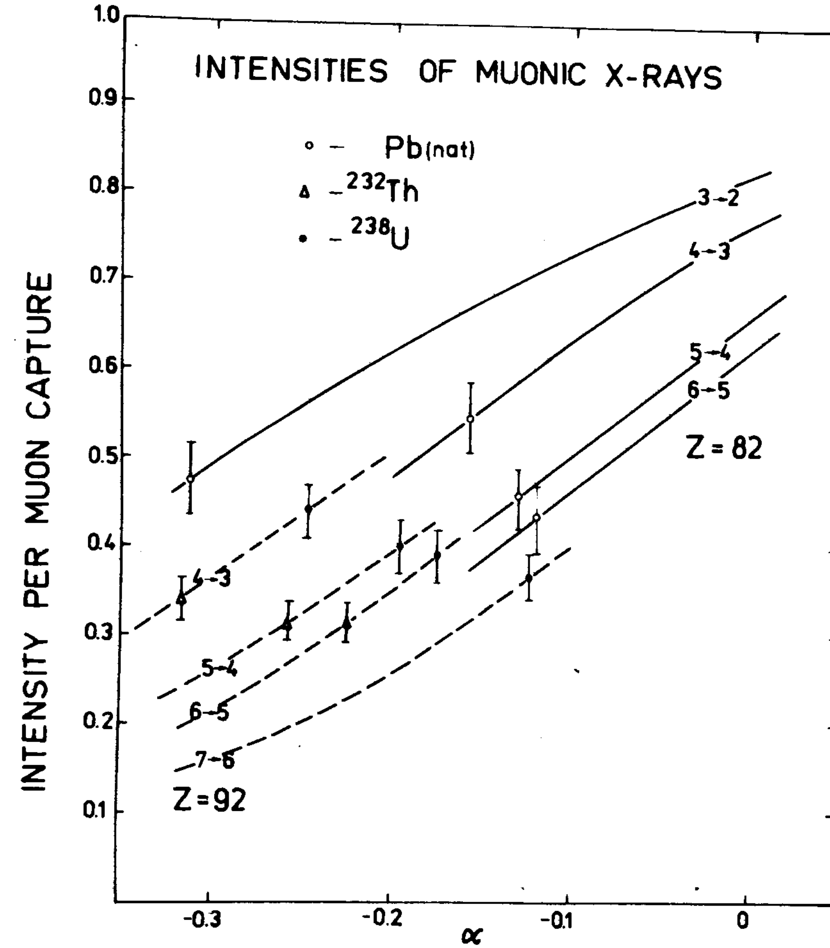

Fig. 1. Results of the cascade calculations of muonic transition intensities per μ-capture for Z =82 and Z =92, plotted against the "a" parameter of the initial population distribution: $\rho \sim (2\ell+1)\exp(a\ell)$. The measured intensities are quoted alongside.

The absolute intensity of K_α muonic transition has been measured only in the case of ^{181}Ta by Bleser et al. /5/ and our result for Pb_{nat} is in very good agreement with it. Our results are not in contradiction with Anderson's et al.[6] relative measurements but there is a meaningful difference between the intensities of both $5 \to 4$ and $4 \to 3$ transitions as measured for natural thallium[7] or bismuth[8] and as measured for natural lead by us.

One may conclude that the intensities of all corresponding transitions are different for lead and actinide muonic atoms. Therefore, the fraction of missing X-rays cannot be simply related to the fraction of radiationless transitions, and only improving considerably the sensitivity of the measurements of muonic X-ray intensities and searching for the difference between the population and the radiative decay rates of muonic states one might be able to infer reliably the fraction of radioationless transitions.

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