# ıtensity of mesic x-ray transitions in lead, ıorium, and uranium

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The intensities of the principal transitions in muonic atoms of lead, thorium, and uranium were measured. The obtained intensities do not confirm the predictions of the cascade model.

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1. Knowledge of the intensities of mesic x-ray transition is of great impor-.nce for the study of the properties of muonic atoms. To normalize the yields ; different reaction, such as fission or neutron emission following the exci-.tion process, one must know the fraction of nonradiative muonic transitions .at excite the nucleus directly. For $2P-2S$ transitions this fraction can be de-ıed as the difference between the population of the $2P$ level and the intensity the radiative $2P-1S$ transitions. However, the determination of the intensi-əs of all the transitions at the $2P$ level encounters great experimental diffi-ılties, owing to the insufficient sensitivity of the detectors. In some udies[1,2] the fraction of the nonradiative transitions in actinide nuclei was erefore determined from the decrease of the intensity of the $2P-1S$ trans-ɔns in thorium, uranium, and plutonium in comparison with this transition lead. It was assumed here that the intensities of the higher radiative transi-ɔns in these nuclei should be equal. Otherwise, the missing part of the $\gamma$-ray tensity cannot be connected simply with nonradiative transitions. The pur-ɪse of the present experiment was to verify these assumptions by measuring e intensities of the principal mesic x-ray lines in lead, thorium, and ·anium.

The experiment was performed with the separated negative-muon beam from e synchrocyclotron of our institute ($E_p = 670$ MeV). The mesic x rays were :gistered with a coaxial Ge(Li) detector with a sensitive volume 45 cm$^3$, con-·cted for coincidence with the signal from the $\mu^-$ stopped in the target, which mes from a telescope connected in accordance with the $123\bar{4}$ scheme. The ne resolution $2\tau$ was 10 nsec, the energy resolution of the Ge(Li) detector ached 3 kV and 8 kV for $\gamma$ rays of energy 1 and 8 MeV, respectively. The unting rate reached 36 000, 11 000, 1300, and 200 per second for the coinci-nces "1, 2," "1, 2, 3," "1, 2, 3, $\bar{4}$," and ($123\bar{4}, \gamma$), respectively.

All the targets had the same dimensions, 60×77 mm, their weight was ap-oximately 50 g, the effective thickness amounted to ≈2 g/cm$^2$. Of great ıportance for the present experiment was a reliable determination of the effi-əncy of the registration of the $\gamma$ rays and of the number of stopped $\mu^-$ in the rget.

  

TABLE. Intensity of radiative muonic transitions.

| Transitions | Pb(nat) | | | $^{232}$Th | | $^{238}$U | |
|---|---|---|---|---|---|---|---|
| | E, keV | $I_{exp}$ | $I_{calc}$ ($\alpha = -0.14$) | E, keV | $I_{calc}$ | E, keV | $I_{exp}$ |
| $\Sigma$ 7i – 6h | | | | | | 166 – 182 | 0,367 ± 0,025 |
| 8j – 7i, 9i – 7h | | | | 181 – 191 | 0,034 ± 0,004 | 190 – 200 | 0,040 ± 0,004 |
| 8i – 6h | | | | | | 285 – 295 | 0,043 ± 0,007 |
| $\Sigma$ 6h – 5g | 230 – 237 | 0,436 ± 0,035 | 0,405 | 274 – 281 | 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 |
| $\Sigma$ 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 | 0,060 | 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 |
| $\Sigma$ 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<br>2792 – 2825<br>2892 – 2927 | 0,074 ± 0,012 | 2810 – 2850<br>2860 – 3035 | 0,142 ± 0,020 |
| $3d_{3/2} - 2p_{1/2}$ | 2642 | 0,176 ± 0,014 | 0,245 | 3086 – 3157 | 0,159 ± 0,013 | 3215 – 3242 | 0,185 ± 0,020 |
| $\Sigma$ 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 |
| $\Sigma$ 2p – 1s | | 0,595 ± 0,060 | 0,880 | | 0,460 ± 0,048 | | 0,550 ± 0,055 |

To decrease the errors connected with the possible instability of the beam, ten measurement cycles were performed. In each cycle, up to six measurements were made with four targets in the following sequence: Al, Pb, Al, Th, Al, U. This resulted in an effective averaging of the beam fluctuations. The Ge(Li) detector efficiency curve was normalized to absolute units from the known intensity of the $K_\alpha$ mesic x-ray line in aluminum.[3]

The number of $\mu^-$ stopped in the target was determined by the dependence o four quantities on the target thickness: the "1, 2, 3, 4" and ($12\overline{3}4$, $\gamma_t$) coincidences, and finally the intensity of the $K_\alpha$ series of mesic x rays in the case Al or the "6 → 5" and "5 → 4" transitions in case of heavy nuclei ($\gamma_t$ is the tota $\gamma$-photon count, and $\gamma_p$ is the count of the prompt $\gamma$ photons). The applicabilit of this method was verified by measuring the intensity of mesic x rays from target consisting of 16 alternating aluminum and lead foils, 50 and 60 mg/cm thick, respectively.

The measurements were performed in three stages. We first determined tl intensity of the $6h \to 5g$ and $5g \to 4f$ transitions in Pb, Th, and U; then we mea sured for a long time the mesic-x-ray spectra of all the targets in the range from 150 kV to 7 MeV, and determined the relative transition intensities. Th final results of these measurements are given in the table.

The errors of the results are due primarily to the uncertainty of the numbe of stoppings (5%). The uncertainty in the intensity of the mesic-x-ray $K_\alpha$ line of aluminum was approximately 2%. The statistical errors could be neglecte

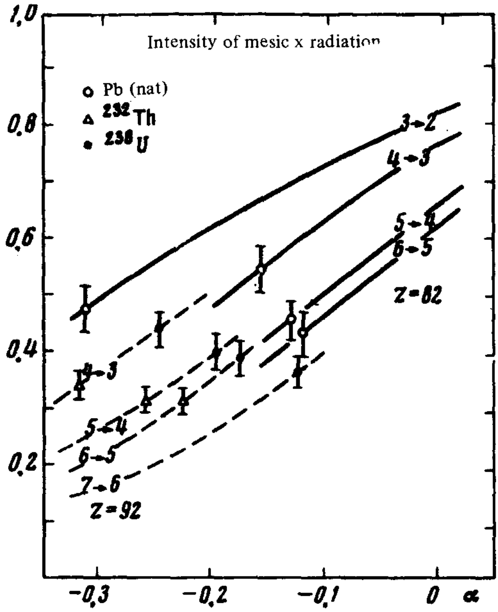


FIG. 1. Results of cascade calculation of the intensities of muonic transition per act of $\mu$ capture for $Z=82$ and $Z=92$. The dependence of the transition intensity on the parameter $\alpha$ of the initial distribution, $\rho \sim (2l+1) \times \exp(\alpha l)$, is shown. The figure shows also the measurement results.

the case of the higher transitions, and reached several percent in the case $K_\alpha$ transitions.

The curve of the relative efficiency of photopeak registration was determined ith the aid of known calibration sources and the reaction $^{35}Cl(n, \gamma)$. For a nctional representation of this curve by a fourth-degree polynomial in doubly-garithmic ($\log\epsilon_\gamma$, $\log E_\gamma$) coordinates, an error corridor with a relative width 5% was calculated.

The smooth dependence of the self-absorption coefficients on the $\gamma$-ray ener- was determined accurate to 3% by measuring the natural activity of a orium foil 0.05 mm thick.

The $\gamma$ spectra was reduced with the aid of the "SAMPO" program.[9]

The experimental results are compared in the figure with the predictions of e cascade calculations by the Hüfner program.[4] In the calculations we took to account the radiative $E1$ transitions and the Auger transitions, we included e conversion of the electrons on the $K$, $L$, and $M$ shells, and assumed that the itial population for $n=20$ is of the form $\rho \sim (2l+1)\exp(\alpha l)$. The experimental id theoretical values of the intensities of the transitions "6→5," "5→4," and →3" in lead coincide at $\alpha = -0.14$. For this value of the parameter $\alpha$, hower, the calculated values of the intensities of the transitions 3→2 and 2→1 e much larger than the experimental ones. Moreover, it can be seen from e figure that for uranium and thorium it is impossible to obtain agreement tween the calculated and experimental values for any value of $\alpha$. This seems indicate that the aforementioned cascade-calculation assumptions concerning e initial population in the muonic atoms are incorrect. Furthermore, it is t excluded that these calculations do not account for the observed intensity because they make no allowance for the connection between the nuclear and atomic motions.

The intensities of the $K_\alpha$ transitions were measured earlier only for $^{181}$Ta.[4] Our results for Pb agree with them. The results do contradict likewise the data of Anderson *et al.*,[5] but there is a noticeable discrepancy between intensities of the transitions 5→4 and 4→3 for thallium[7] and bismuth[8] and our measurements for lead.

On the basis of our measurements we can conclude that the intensity of the corresponding transitions for lead and the actinides differs significantly. Consequently, the decrease of the intensity of the mesic x rays cannot be attributed only to the fraction of nonradiative transitions. To determine reliably the fraction of the nonradiative transitions it is necessary to measure the difference between the probabilities of the population and radiative decay of the muonic states; this calls for a significant increase in the sensitivity of the measurement.

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