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NONRADIATIVE TRANSITIONS IN HEAVY μ-MESIC ATOMS

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The spectra of mesic x-ray photons emitted by μ-mesic atoms of uranium and lead are studied with the aid of a scintillation spectrometer. It is shown that the 2P → 1S radiative transition rate per stopped muon is appreciably smaller in mesic uranium than in lead. Thus it is experimentally demonstrated that there exists a hitherto unobserved nonradiative transition mechanism in which the transition energy is transferred directly to the nucleus.

1. INTRODUCTION

TWO mechanisms for the fission of heavy nuclei by μ^-mesons were predicted by Wheeler[1]: "internal" fission, in which the energy necessary for fission is released when the nucleus captures a muon from a lower level of a mesic atom, and "external" fission, in which the muon does not disappear and the energy necessary for fission is released in a nonradiative mesic-atom transition to the 1S level.

Zaretskiĭ[2] calculated the nonradiative transition probability in mesic atoms of heavy nuclei, or more precisely the probability that the energy of the 2P → 1S transition is not released in the form of x rays, but is transferred directly to the nucleus.

In the work of Belovitskiĭ et al.[3] carried out with the aid of photographic film the conclusion was reached that the μ^--meson stoppages in U^{238} lead only to "internal" fission with a probability of 0.07 (nonradiative fission was not observed by these authors and has a probability of less than 1%). In the work of Diaz et al.[4]* carried out by means of electronic particle-counting methods, the conclusion is also reached that nonradiative fission, if it takes place, only amounts to a small fraction of the number of fission events.

Except for these experiments, which gave negative results the 1P → 1S nonradiative transition mechanism for mesic atoms proposed by Zaretskiĭ was not studied experimentally. Thus, until recently, only two 2P → 1S transition mechanisms were known in a mesic atom: (1) the emission of a mesic x-ray quantum, and (2) the Auger effect, which does not play a substantial part in heavy nuclei.

This paper is devoted to the study of nonradiative transitions.* The study of this phenomenon is not only of independent interest but could also provide valuable information on the properties of heavy nuclei.

2. EXPERIMENTAL SETUP

As was shown by Zaretskiĭ,[2] the probability of nonradiative transitions in the μ-mesic atom of uranium, in which the nuclear-level density is large, should be considerable. In the μ-mesic atom of lead, in which the nuclear-level density is small, this probability is practically zero. The fraction of nonradiative 2P → 1S transitions in mesic uranium was, therefore, determined by measuring the yield differences of the corresponding radiative x-ray transitions in uranium and lead. The fact that the transition energies of mesic uranium and mesic lead are similar (~6 Mev) facilitated the comparison of the photon yields, inasmuch as practically no corrections of the experimental spectra were required.

A beam of negative pions with a momentum of 270 Mev/c from the cyclotron of the Joint Institute for Nuclear Research was employed in our work. The schematic setup of the experiment is shown on Fig. 1. The muons which were stopped in the target were separated by a "telescope" consisting of three scintillation counters, connected according to a 1 + 2 − 3 scheme (coincidences of counters 1 and 2, in anticoincidence with counter 3).

The range curve obtained with a thin ($4 g/cm^2$ Pb) target is shown in Fig. 2. The measurements of the mesic x-ray photon emission spectra were carried out with thicker targets; the uranium (100 × 100 mm

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*We are grateful to Dr. Moyer who acquainted us with these results during the Kiev Conference.

*Preliminary results were published at the 9th International Conference on the Physics of High-Energy Particles in Kiev, 1959 (cf. paper by A. I. Alikhanov).

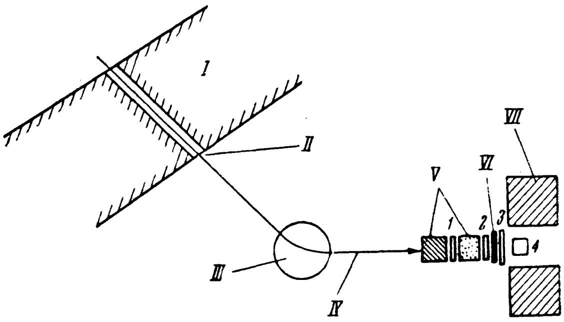

FIG. 1. Experimental setup (schematic): I – concrete shield, II – collimator (100 mm diameter), III – deflecting magnet, IV – negative-pion beam, V – absorber (75 g/cm² Cu + 32 g/cm² B_4C), VI – target, VII – shielding of counter 4 (20 cm Pb); 1, 2 – plastic scintillators, 100 mm diameter and 10 mm thickness; 3 – the same, 125 mm diameter and 12 mm thickness; 4 – NaI(Tl) crystal, 30 mm diameter and 10 mm thickness.

× 10.7 g/cm²) and lead (100 × 100 mm × 10.3 g/cm²) targets were equivalent with regard to the ionization losses.

A scintillation counter 4, consisting of an NaI(Tl) crystal of 30 mm diameter and 35 mm high, and of a FÉU-33 photomultiplier, was used to detect the gamma rays. The gamma-counter pulse was fed to a 64-channel pulse-height analyzer which was monitored by the signal of the coincidence scheme (1 + 2 – 3) + (2 + 4). The background of accidental coincidences amounted to about 1/20 of the total count.

A Na^{24} source with γ-ray energies of 1.38 and 2.76 Mev was employed for energy calibration and to check the linearity of the whole system.

During the measurements the uranium and lead targets were periodically exchanged. All the obtained spectra had the same shape and were shifted relative to each other.

3. MEASUREMENT RESULTS AND THEIR DISCUSSION

Figure 3 shows the photon spectra for mesic uranium and lead in the 3- to 8-Mev energy region. The spectra are normalized for equal numbers of μ^- mesons stopped in the target. In the lead spectrum we see clearly the peak with an energy of ~5.3 Mev. In view of the small dimensions of the NaI(Tl) crystal this peak is due to three values of energy lost by the photons in the crystal: (1) E_γ, (2) E_γ – 0.51 Mev, and (3) E_γ – 1.02 Mev, where E_γ = 6.02 Mev (reference 5) is the photon energy of the 2P → 1S transition in mesic lead. Uranium gives fewer counts in the 5- to 5.5-Mev energy region, and practically the same number as lead in regions sufficiently far from 5.5 Mev. The mean energy of the peak, corresponding to the 2P → 1S transition is larger in uranium than in lead by about 200 kev.

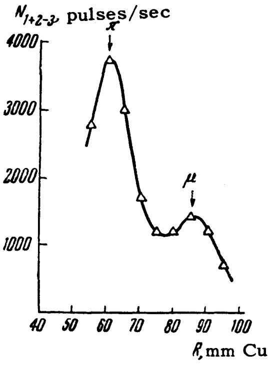

FIG. 2. Range curve (R is the absorber thickness, N – the number of coincidences in arbitrary units).

The difference in the intensity of the photons with an energy of ~6 Mev in mesic uranium and mesic lead for identical geometries and close emission energies indicates that here the effect of the nonradiative μ^-meson transition to the 1S level of mesic uranium has indeed been observed. A quantitative estimate of the probability of this process seems to us to be difficult. In order to determine the ratio of intensities of the radiative 2P → 1S transitions in mesic uranium and mesic lead, it is necessary to know the number of counts in each analyzer channel which are really due to photons from the 2P → 1S transition. In other words, it is necessary to know the contribution of "background" counts, that is of counts which are not connected with the 2P → 1S transition. The "background" counts are due to other transitions in the mesic atom, and also to the presence of electrons in the primary beam.

The determination of the background is a rather complex problem, and new studies will be devoted to its solution. At present, we can only indicate rather rough limits for this background. We know, from measurements with a Cerenkov gas counter, that the "background" counts in the photon energy region $E_\gamma > 4$ Mev are both for uranium and for lead mainly due to the electron background. This background depends weakly on the target material and on the channel number of the analyzer. Clearly, the counting rates in uranium and lead at ~8 Mev are the lower limits of the background levels in uranium and lead in the energy region ~5 Mev of interest to us (Fig. 3). The upper limit of the background will obviously be the curve obtained by smooth interpolation of the uranium and lead spectra for energy ranges with $E_\gamma < 5$ Mev and $E_\gamma > 5$ Mev (Fig. 3).

Assuming that the probability for nonradiative transition in lead W_n is negligibly small by comparison with the probability of photon emission

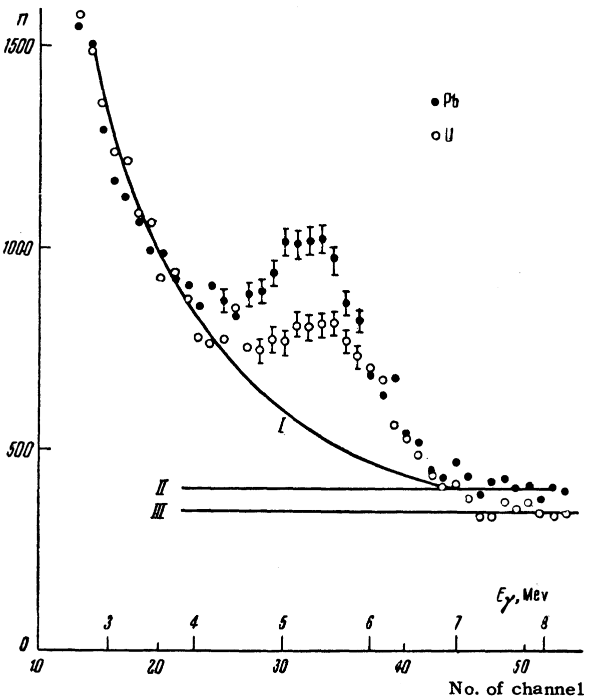

FIG. 3. Photon spectra from mesic lead and mesic uranium: I – the upper limit of the background, II – the lower limit of the background in lead, III – the lower limit of the background in uranium (n is the number of counts per analyzer channel).

W_γ, and taking into consideration the above-mentioned background limits, we obtain

$$0.1 < (W_n / W_\gamma)_{U^{238}} < 1. \qquad (1)$$

Another, also rough, estimate of the background can be obtained from the condition that the width of the uranium and lead peaks must be equal. From this estimate we obtain $(W_n/W_\gamma)_{U^{238}} \sim 0.2$, that is a value close to the lower limit of inequality (1).

On the above grounds it is possible to conclude that the probabilities of radiative and nonradiative transitions in U^{238} are comparable,* while radiative transitions apparently predominate.

Preliminary experiments indicate that nonradiative transitions take place in Th^{232}.

A value of ~5 to 20 was predicted in Zaretskiĭ's work for the ratio $(W_n/W_{h\nu})_{U^{238}}$. This result contradicts inequality (1). However, in Zaretskiĭ's estimate it was assumed that in the uranium nucleus $\rho\Gamma_{nuc} \gg 1$, where ρ is the mean density of uranium levels excited by 2P → 1S transitions and Γ_{nuc} is their mean nuclear width. In this case it is possible to neglect processes in which the excited nucleus with the muon in the 1S state returns to the ground state with the muon in the 2P state. As was noted by Zaretskiĭ during the discussion of our results, the hypothesis that $\rho\Gamma_{nuc} \gg 1$ is actually unfounded. If $\rho\Gamma_{nuc} \ll 1$, then the oscillation processes of the muon between the 2P and 1S state with the simultaneous oscillation of the nucleus between the excited and ground level cannot be neglected, and therefore the ratio W_n/W_γ decreases considerably.[6]

At present, more precise measurements of the W_n/W_γ ratio for various mesic atoms are being carried out.

The authors sincerely thank A. I. Alikhanov for his continuous interest in their work, and D. F. Zaretskiĭ who acquainted them with his work before its publication.

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*Our preliminary communication at the Kiev Conference (in 1959) that the radiative and nonradiative 2P → 1S transition probabilities in U^{238} are "approximately equal" was not sufficiently grounded.

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