EXCITATION OF NUCLEAR ROTATIONAL LEVELS IN μ-MESIC ATOMIC TRANSITIONS

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The occurrence of Coulomb excitation of nuclear rotational levels in the U^{238} nucleus accompanying μ^--mesic atomic transitions is established by means of the thick nuclear emulsion technique. The probability of this process has turned out to be ~ 0.5 in satisfactory agreement with the theoretically expected value.

SLOW μ^- mesons brought to rest in a medium are captured by atoms forming a bound system consisting of a μ-mesic atom in a highly excited state. Transition to the 1s ground state takes place by means of a cascade process. The energy of the μ-mesic atomic transitions is expended in the emission of Auger electrons and of x rays.

In the case of μ-mesis atomic transitions to the 2p state in mesic atoms with highly deformed nuclei ($155 < A < 185$ and $A > 225$) there exists an additional interaction of the μ^- meson with the quadrupole moment of the nucleus. As a result of this, in the case of such transitions the probability for the excitation of low lying nuclear rotational levels[1,2] is high (~ 0.5). There exists a low probability (~ 0.05) for the excitation of rotational levels also in the case of transitions to the 3d state, but such excitation does not take place at all in the case of transitions to the 1s state.[1]

The lifetime of the first excited level of a heavy nucleus ($\leq 10^{-9}$ sec) is considerably shorter than the lifetime of a μ^- meson in its K shell prior to its capture ($\sim 10^{-7}$ sec). Therefore, the nucleus has time to make the transition to its ground state before the μ^- meson is captured by the nucleus. A measurement of the number of corresponding γ quanta and conversion electrons normalized per μ^--meson capture yields directly the probability of Coulomb excitation of the nucleus W_μ.

The probability W_μ depends both on the magnitude and on the sign of the intrinsic quadrupole moment of the nucleus Q_0. Therefore, a measurement of W_μ enables us, in principle, to determine one of these two quantities, for example, the sign of the quadrupole moment Q_0, if its absolute value is known. In nuclei for which the first excited state is not a purely rotational state, W_μ also depends on the quadrupole moment of the excited state.

Another possible method of determining all the characteristics of the quadrupole moment consists of measuring the hyperfine structure of the $2p \to 1s$ γ transitions due to the splitting of the fine structure of the 2p level caused by the interaction of the μ^- meson with the quadrupole moment of the nucleus. As a result of the stringent requirements on the degree of accuracy in the measurement of the energy of the γ quanta (1%) such experiments also have not been performed to date. Both types of experiments are of considerable interest, since no other methods of determining the sign of Q_0 are known at the present in the case of even-even nuclei.

1. EXPERIMENTAL PROCEDURE AND RESULTS

In the present work an experimental attempt is made for the first time to observe the Coulomb excitation of rotational levels of U^{238} nuclei accompanying μ^--mesic atomic transitions. The energy of the first rotational level (2^+) in U^{238} is 45 kev. Transitions to the ground state occur entirely by means of conversion. Conversion is possible only from L and higher shells. The energy of conversion electrons from the L shell amounted to 25 — 28 kev, and from the M shell amounted to 40 kev.

The effect under investigation was studied by observing conversion electrons. Photoplates NIKFI-R of 200 μ thickness were used to record the electrons. To achieve more reliable recording and greater accuracy in the measurement of the ranges of slow electrons the plates were first treated with a solution of triethanolamine which produced a grain density in relativistic electron tracks up to 50 per 100 μ. Then photoplates doped with uranyl acetate[3] were irradiated by the beam of slow μ^- mesons produced by the synchrocyclotron of the Joint Institute for Nuclear Research.[4]

The capture of a μ^- meson in uranium was identified by means of the fission of the uranium nucleus to which it gives rise. Emission of one or more electrons from the point at which fission occurred was frequently observed.

The energy of the electrons was determined from their range. The range-energy curve was calibrated at one point (~ 30 kev) by means of conversion electrons accompanying the α decay of uranium isotopes as observed in the same photoplates. The accuracy of energy determination is 15%. The efficiency for recording electrons of the given energy has turned out to be close to 100%.

We have analyzed 220 cases of fission of uranium nuclei by μ^- mesons and we have determined the energy of all the electrons emitted from the point at which fission occurs. We have selected only electrons of energy > 20 kev. This has enabled us to exclude the Auger electrons emitted as a result of filling a vacancy in the L and higher shells.

Electrons of energy > 20 kev can be produced in three ways: excitation of rotational levels, mesic atomic transitions and nuclear fission. The existing theories of the Auger effect in mesic atoms do not allow us to calculate exactly the number of electrons emitted in a mesic atomic transition in an atom of given Z. Therefore, electrons arising in μ^--mesic atomic transitions in uranium were eliminated by means of comparison with the number of electrons per π^- meson stopped in uranium ($\overline{N}_\pi$). Even if π^- mesons do give rise to excitation of rotational levels in a uranium nucleus this process cannot be observed since nuclear capture of a π^- meson occurs in a time which is much shorter than the lifetime of the 2^+ excited level. But the nature of mesic atomic transitions does not depend on the nuclear properties of the mesons and must be the same both for μ^- and π^- mesons.

The number of electrons per π^- meson stopped in uranium was determined in the same manner as in the case of μ^- mesons. On plates irradiated by a beam of slow π^- mesons we have analyzed 132 cases of fission of a uranium nucleus by π^- mesons, and we have determined the energy of all the electrons emitted from points at which fission has occurred.

The fission of uranium nuclei is accompanied by a rearrangement of the electronic shell structure and by other processes as a result of which electrons can be emitted from the point at which fission occurs. In order to determine the number of such "parasitic" electrons control experiments were carried out involving the fission of U^{238} nuclei by 14-Mev neutrons and of U^{235} nuclei by thermal neutrons.

In the case of neutron-induced fission of uranium nuclei it is impossible to determine the point at which fission occurs. However, it is known [5] that the ratio of the ranges l_l of the light and l_h of the heavy fragments satisfies $l_l/l_h \leq 2$. Therefore, it was assumed that fission is accompanied by the emission of an electron if the ratio of the ranges measured for a point from which the emission of an electron is observed satisfies the condition $l_l/l_h \leq 2$. It turned out that fission brought about both by thermal neutrons (600 cases) and by 14-Mev neutrons (500 cases) is accompanied in $\sim 3\%$ of the cases by the emission of 20 — 50 kev electrons (50 kev electrons were observed in 1% of the cases). This is approximately 10 times less than the number of electrons observed when the fission of uranium nuclei is induced by μ^- and π^- mesons. This result was used in evaluating the true number of electrons per μ^- meson and per π^- meson stopped in uranium.

Control experiments were also carried out with Ag and Br nuclei.

In the slightly deformed Ag and Br nuclei the value of Q_0 is approximately 10 times smaller than in uranium, and this, taken together with a number of other factors, leads to a low probability for Coulomb excitation to accompany μ^--mesic atomic transitions. It follows from general considerations that in such nuclei the number of observed electrons emitted in mesic atomic transitions increases with increasing meson mass. This had been previously demonstrated in experiments involving π^- and K^- mesons. [6]

Below we exhibit results obtained by us for μ^- and π^- mesons. In the same photoplates in which we have observed the fission of uranium nuclei by μ^- and π^- mesons, we have also found and analyzed 1,000 μ^- mesons brought to rest and 850 stars with one or more prongs due to π^- mesons.

Capture of μ^- mesons by AgBr nuclei was inferred from the absence of the electron arising from $\mu \rightarrow e$ decay as was done, for example, in Fry's paper. [7] It turned out that 60% of the mesons are captured by AgBr nuclei. According to the data of Brown and Hughes, [8] 56% of the stars with one or more prongs, induced by π^- mesons, come from AgBr nuclei. An analysis of stars accompanied by the emission of Auger electrons of mesic atomic origin has shown that with rare exceptions they all come from AgBr nuclei. This last result is in good agreement with the results of other papers, for example [9].

Nucleus	Kind of meson	20–50 kev	> 50 kev	$\overline{N}_\mu/\overline{N}_\pi$ (for 20–50 kev electrons) experimental value	calculated value
U	μ^-	0.65±0.08	0.22±0.04	2.3 ±0.7	~0.8
	π^-	0.28±0.06	0.15±0.04		
AgBr	μ^-	0.15±0.02	0.14±0.02	0.58±0.14	~0.75
	π^-	0.26±0.03	0.19±0.02		

The table shows experimental data on the average number $\overline{N}$ of electrons of 20 — 50 kev and > 50 kev energy evaluated per μ^- meson and per π^- meson stopped by AgBr and by uranium nuclei (after the background due to the "parasitic" electrons has been subtracted). The table also gives experimental and theoretical values of $\overline{N}_\mu/\overline{N}_\pi$ for uranium and for AgBr (for 20 — 50 kev electrons).

The calculation of $\overline{N}_\mu/\overline{N}_\pi$ was carried out in the following manner. The energy levels for μ^- and π^- mesons in mesic atoms of Ag, Br, and uranium, and also the energies of the mesic atomic transitions were calculated on the assumption that $\Delta n = \Delta l = 1$, where n and l are the principal and the orbital quantum numbers. In evaluating the internal-conversion coefficients for each transition theoretical results on mesic atomic transitions were utilized.[10,11]

2. DISCUSSION OF RESULTS

From the table it can be seen that for uranium $\overline{N}_\mu > \overline{N}_\pi$, while for AgBr, as should have been expected, $\overline{N}_\mu < \overline{N}_\pi$. The values of $\overline{N}_\pi$ for uranium and for AgBr have turned out to be close to each other, and this is due to the weak dependence of the Auger effect on Z.

The value of $\overline{N}_\mu$ for uranium for 20 — 50 kev electrons is approximately four times larger than for AgBr. This difference can be due to: a) Coulomb excitation of nuclear rotational levels in uranium, b) excitation of the nucleus as a result of direct transfer to the nucleus of the energy of the 2p → 1s mesic atomic transition.

The latter process was discussed in the theoretical paper of Zaretskii.[12] Its probability in U^{238} was measured in the paper by Balats, Kondrat'ev, et al.[13] and has turned out to be equal to (0.23 ± 0.04). In the case of such excitation the energy transferred to the nucleus is 6.3 Mev and this can be expended in the emission of a neutron, γ rays and conversion electrons. The latter are, perhaps, responsible for the slight excess in uranium of the number $\overline{N}_\pi$ over $\overline{N}_\mu$ for electrons of energy > 50 kev (in AgBr in the case of electrons of energy > 50 kev the opposite inequality $\overline{N}_\mu < \overline{N}_\pi$ holds).

For the experimentally observed probability of excitation of rotational levels we obtain the value

$$(W_\mu)_{\text{obs}} = (\overline{N}_\mu)_U - \left(\frac{\overline{N}_\mu}{\overline{N}_\pi}\right)_{\text{AgBr}} (\overline{N}_\pi)_U = 0.5 \pm 0.1. \quad (1)$$

The true value of the probability W_μ can be obtained from $(W_\mu)_{\text{obs}}$ in the following manner:

$$(W_\mu)_{\text{obs}} = W_\mu (1 - 0.23) + 0.23\,\alpha, \quad (2)$$

where α is the probability that the transition from the excited (6.3 Mev) to the ground level will take place via the first excited level of the U^{238} or U^{237} nucleus. On substituting into (2) the value $(W_\mu)_{\text{obs}}$ we obtain

$$W_\mu = 0.65 - 0.3\,\alpha,$$

and since $0 < \alpha < 1$, then $0.35 < W_\mu < 0.65$. The spin and parity of the excited (as a result of the 2p → 1s transition) U^{238} nucleus are given by 1^-. If a neutron is not emitted by the nucleus then transitions to the ground state (0^+) or to the first excited state (2^+) will apparently be equally probable. From this it follows that $\alpha = 0.5$. However, if a neutron is emitted then U^{237} is formed for which the value of the spin in the excited state is unknown.

Apparently, we can assume without gross error that $\alpha = 0.5$ in all cases, so that $W_\mu = 0.5 \pm 0.1$. Thus, it is quite probable that the excitation of the nucleus as a result of the 2p → 1s transition does not appreciably alter the value of W_μ.

The theoretical values[1] of W_μ for $Q_0 > 0$ and $Q_0 < 0$ are respectively equal to 0.5 and 0.4. Therefore, in order to obtain a definitive solution of the problem of the sign of Q_0 it is necessary to increase the experimental accuracy of the determination of W_μ and to eliminate reliably the influence of side effects. Moreover, it is desirable to know more accurately the theoretical value of the probability of excitation of rotational levels from the 3d state.

The high value of W_μ (~ 0.5) makes experiments of such type for the determination of the sign of Q_0 appropriate in the case of even-even nuclei. These experiments can also be carried out using pure samples of the elements in a Wilson cloud chamber or in a diffusion chamber, utilizing thin solid or gaseous targets.

The excitation of rotational levels in μ^--mesic atomic transitions leads to another effect discussed in the theoretical paper of Zaretskii and Novikov.[14] This effect consists of the fact that in deformed even-even nuclei as a result of the excitation of rotational levels the spin of the excited level turns out to be different from zero with a probability of ~ 0.5. This results in additional depolarization of μ^- mesons in transitions to the 1s state due to the hyperfine splitting of the 1s level.

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16