B. Sabirov, V. Abazov, A. Demyanov, I. Falomkin, V. Gordeev[1],
K. Grama[2], S. Kutuzov, Do Khoang Kyong, M. Lewandowski[3],
I. Mitropolsky[1], G. Solyakin[1]

NUCLEAR PROCESSES INDUCED BY MUON DECAY
AT THE K-ORBIT OF MUONIC ATOM

[1] Nuclear Physics Institute, St. Petersburg, Russia

[2] University of Bucharest, Bucharest, Romania

[3] Institute of Physics, M. Curie-Sklodowska University, Lublin, Poland

Ядерные процессы, индуцированные распадом мюона на K-орбите мюонного атома

Представлены результаты экспериментального исследования процессов при остановке мюона в ядрах. Цель эксперимента — поиск возможности возбуждения ядра при распаде мюона на K-орбите мюонного атома. Уникальность этого процесса заключается в том, что ядро, находящееся в электромагнитном поле мюона, пребывающего на самой низкой атомной орбите с орбитальным моментом $\ell = 0$, при распаде мюона по схеме $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$ получает встряску и испытывает преимущественно монопольное возбуждение.

Основой эксперимента по поиску возбуждения ядра при распаде связанного мюона является регистрация совпадений электронов от μ-распада с γ-квантами ядерных переходов. Создана экспериментальная установка МЕГА, включающая систему сцинтилляционных счетчиков для выделения остановок мюонов в мишени обогащенной порошкообразной двуокиси самария Sm_2O_3, Ge(Li) γ-детектор с чувствительным объемом ~ 50 см^3 и черенковский счетчик, изготовленный из свинцового стекла ТФ-1. Эксперимент проводился на мюонном пучке фазотрона ЛЯП ОИЯИ. Суммарное число мюонов, остановившихся в мишени, позволило определить верхнюю границу вероятности $E0$-возбуждения ядра ^{152}Sm ($w(E0) < 1{,}5 \cdot 10^{-3}$), что не достигает уровня теоретической оценки ($\approx 3 \cdot 10^{-4}$). Измерен изомерный сдвиг уровня 121,78 кэВ в ядре в присутствии мюона на K-орбите мюонного атома: $\Delta E_{\mathrm{is}} = 820 \pm 40$ эВ.

Предполагается продолжение поиска монопольного возбуждения ядра при распаде связанного мюона на более совершенной аппаратуре и на более интенсивных мюонных пучках.

Nuclear Processes Induced by Muon Decay at the K-Orbit of Muonic Atom

Results are presented of an experimental study of processes taking place in the case of muons stopping in nuclei. The aim of the experiment consists in investigating the possibility of a nucleus being excited when a muon on the K-orbit decays. The uniqueness of this process is that the nucleus, happening to be in the electromagnetic field of the muon occupying the lowest atomic orbit of angular momentum $\ell = 0$, is jolted, when the muon decay $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$ occurs, and it mainly undergoes monopole excitation.

The experiment aimed at searching for nuclear excitation related to a bound muon is based on the registration of coincidences between electrons from μ decays and γ quanta from nuclear transitions. An experimental installation MEGA has been created, that involves a set of scintillation counters for identifying muons stopping in the target enriched with powder-like samarium dioxide Sm_2O_3, a Ge(Li) γ detector with a sensitive volume ~ 50 cm^3 and a Cherenkov counter made of TF-1 lead glass. The experiment was carried out with the muon beam in the low-background hall of the Phasotron of the JINR Laboratory of Nuclear Problems. The total number of muons that stopped in the target permitted to determine the upper limit for $E0$ excitation in the ^{152}Sm nucleus to be $w(E0) < 1.5 \cdot 10^{-3}$, which is inferior to the level of the theoretical estimate ($\approx 3 \cdot 10^{-4}$). The isomeric shift of the 121.78 keV level in the nucleus has been measured in the presence of a muon on the K-orbit of a muonic atom: $\Delta E_{\mathrm{is}} = 820 \pm 40$ eV.

The search for monopole excitation of a nucleus related to the decay of a bound muon is to be continued with the use of improved equipment and muon beams of higher intensity.

Investigation of the interaction of muons with complex nuclei yields important results on the properties of nuclei and on their electromagnetic interaction with muons happening to be in the Coulomb field of the nucleus [1, 2].

The Bohr orbit of a muon is ~ 207 times closer to the nucleus than that of an electron, the nucleus is transparent-like to it, and it spends a large part of its time inside the nucleus, especially in the case of medium and heavy nuclei. For this reason, the muon serves as a unique instrument in studies of the charge distribution and of other properties of nuclei. The following are processes which yield information relevant to the properties of nuclei.

1. Hyperfine interactions that are responsible for dynamic effects of virtual excitation of the nucleus, due to the perturbative electromagnetic field of the muon, and result in corrections to the wave functions and energy levels of the muonic atom. They are essential for the lower states of the muonic atom, when the muon can spend a significant part of time inside the nucleus. Hyperfine interactions may be magnetic and electric quadrupole interactions. The magnetic interaction is due to interaction of the total angular momentum of the nucleus $F = I + J$ with the magnetic field created by the muon in the nucleus. The magnetic hyperfine structure constant for medium and heavy muonic nuclei is of the order of magnitude of several keV [3], which is significantly lower than corrections due to the «dynamic hyperfine splitting» caused by the muon–nucleus electric quadrupole interaction [4]. Enhancement of the deformation of the nucleus is accompanied by a decrease in the absolute excitation energy of the nucleus and an enhancement in its quadrupole angular momentum and in the $E2$ transition probabilities, which results in favourable conditions for resonance-like interaction between the muon and the nucleus. Investigation of dynamic hyperfine structure in the X-ray spectra of muonic atoms of deformed nuclei can yield information on the quadrupole angular momenta of excited nuclear states and on $E2$ excitation probabilities.

If the excitation energy of a certain state of a nucleus exhibiting the same spin and parity as its ground state nearly coincides with its $2S \to 1S$ transition energy, then dynamic monopole excitation of the nucleus will occur [5]. This effect occurs in nuclei within a limited range, since an increase in A is accompanied by a decrease in the nuclear vibrational energy, while the $2S \to 1S$ transition energy increases. Dynamic $E0$ excitation has not yet been observed [6].

2. Radiationless excitation of the nucleus to the continuous spectrum was first predicted by D. F. Zaretsky [7] and, then, observed in Dubna [8]. Energy

conservation allows this process only in the most heavy muonic atoms. If radiationless capture occurs, then nuclear decay via various channels is much more rapid than nuclear capture of the muon. Fission represents one of the main transition channels to the continuous spectrum, and after fission the muon can be captured by one of the fission fragments and form a new muonic atom in an excited state [9]. Muonic X-ray emission from a fragment was observed in radiationless fission of the ^{238}U nucleus [10].

When the muon reaches the $1S$ state, its further destiny depends on two competing processes: 3 — on nuclear capture and 4 — on the $\mu^- \rightarrow e^- + \nu_\mu + \tilde{\nu}_e$ decay.

3. Nuclear capture of the muon is a weak semileptonic process. Intense studies of muon capture by complex nuclei aimed at testing weak interaction theory have revealed that issues related to nuclear structure are of great importance [2]. All aspects of muon capture in nuclei have been dealt with in detail and a thorough analysis of experimental data is presented in the paper by V. V. Balashov et al. [2].

4. The decay of a bound muon on the K-orbit of a mesonic atom is a process that competes with nuclear capture. If τ_0 is the lifetime of the muon on the K-orbit, then the rate of this process $\lambda_0 = 1/\tau_0 = \lambda_c + Q\lambda_d$, where λ_c is the nuclear capture rate and λ_d is the decay rate, Q is the Huff parameter [11]. The relationship between λ_c and λ_d changes drastically as Z increases [12]: while in the case of small Z muon decay is the dominant process, at $Z = 11(\text{Na})$ the two processes become equal, and when $Z \sim 25-30$, about 90% of the muons are captured (see Fig. 1 and the paper by S. Charalambus [2]).

The Huff parameter Q determines the decrease in the decay rate of a bound muon with respect to the decay of a free muon and depends on three factors:
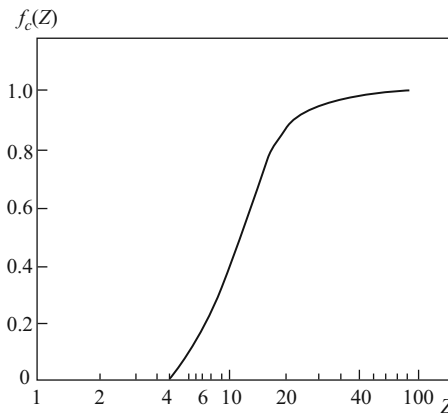

Fig. 1. Dependence of relational muon capture velocity vs. nuclear charge Z

2

the system (i.e., in the centre-of-mass system of the nucleus), and Coulomb interaction of the muon and electron with the nucleus. The parameter Q is particularly significant in the case of heavy nuclei.

The decay of a muon on the K-orbit can be interpreted as a sharp switch off of the spherical Coulomb field created around the nucleus by the muon on the orbit of angular momentum $\ell = 0$ resulting in an electric shake up of the nucleus. The energy released in this process significantly exceeds the energies of low-lying nuclear excitations in medium and heavy deformed nuclei. A feature peculiar to this process is that monopole excitation of the nucleus should dominate. This phenomenon was first noticed by I. S. Batkin [13]. He calculated the excitation probabilities for the first 0^+ states in several rare-earth nuclei applying the Davydov–Chaban droplet model and obtained $\omega(E0) \sim 10^{-2}$ per decay event. Calculations performed by I. A. Mitropolsky utilizing the microscopic model of the nucleus yielded results by 1–2 orders of magnitude lower [14].

The upper limit obtained in the first experiment on search of monopole excitation in the ^{152}Sm yielded the following value for the excitation probability of the 0^+ state: $w(E0) < 5 \cdot 10^{-3}$ [15]. The present work continues the investigation of the γ radiation of a ^{152}Sm nucleus, in which a muon has stopped. The choice of the ^{152}Sm nucleus as a target is due to the following: a) This is a rare-earth transitional nucleus with noticeable deformation, and, consequently, the energy of the first excited 0_2^+ state is low (685 keV). The transition energy is present in the denominator of the corresponding matrix element [14]. b) The ratio between the probability of conversion deexcitation of the 0^+ level, w_e, and the probability of radiation transition, w_γ, is 0.02 [15].

The measurement was performed in the low-background hall of the JINR Laboratory of Nuclear Problems. The beam intensity was $\approx 4 \cdot 10^4 \mu$/s, the number of muon-stops in the target weighing 117 g amounted to $(7 \div 10) \cdot 10^3$ s^{-1}. A powder of samarium dioxide Sm_2O_3 enriched up to 98% was used. The target was made in the form of an upside-down letter V permitting enhancement of the thickness of the material in the path of the muons and decreasing the path for γ quanta (the Ge(Li) detector was situated under the target). The sketch of the layout of MEGA experimental installation is shown in Fig. 2. Its construction and operation principle are described in [15, 16].

Energy calibration of the spectrometric system involving a Ge(Li) detector with a sensitive volume ~ 50 cm^3 permitted determination of the energy of statistically reliable lines with a precision of 2–3 tens of eV. Fully calibrated ^{182}Ta, ^{152}Eu, ^{192}Ir, ^{133}Ba, ^{110}Ag, and ^{56}Co γ sources were used for calibration with respect to absolute efficiency. For eliminating corrections due to the complicated geometry of the extended target, each source was placed successively in 12 zones into which the planes of the support for the target were divided.

After calculating the absolute intensity for each isotope taking into account its certification time, its halflife and the target irradiation time, all the obtained points
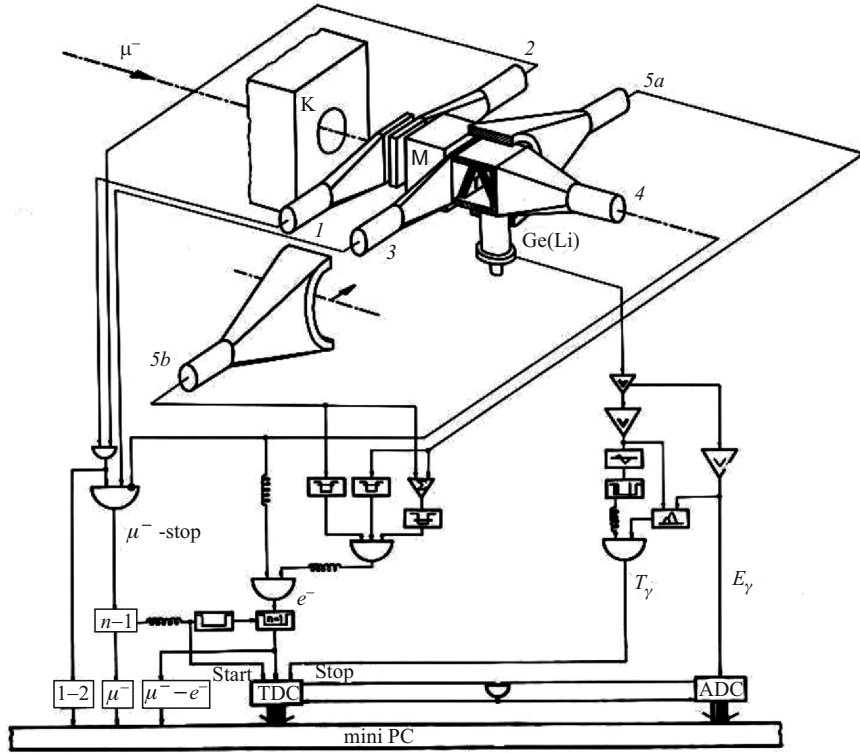
3

Fig. 2. Layout of MEGA installation and scheme for registration of γ rays due to rest of muons at ^{152}Sm: *1–4* — plastic counters, $5a + 5b$ — Cherenkov lead glass counter, M — muon beam degrader, T — Sm_2O_3 target, Ge(Li) — semiconductor γ detector, K — beam collimator

for all the sources were approximated by the following logarithmic four-parameter function [17]:

$$U = \alpha_1 + \alpha_2 \ell nt + \alpha_3 t + \alpha_4 \Theta(t-1) t \ell nt,$$

where $t = E/E_0 (E_0 = m_e c^2)$.

The calibration points scaled to the respective calculated absolute efficiencies are shown in Fig. 3 for the utilized γ sources. The measurement errors were within the sizes of the points. Unlike the plastic counter used for detection of electrons and described in [15], a Cherenkov counter utilizing TF-1 lead glass and a FEU-143 photomultiplier operating in the single-electron mode were utilized in the present experiment. The TF-1 refraction coefficient was $n_D = 1.65$, i.e., the
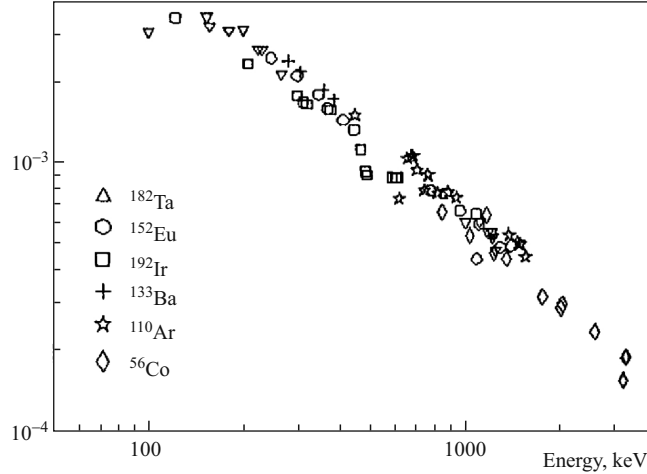
4

Fig. 3. Absolute efficiency of the Ge(Li) detector versus the γ energy

amount of photons, emitted by a $\beta = 0.99$ electron in the 40–70 nm range, was $N_{ph} \approx 330$ ph/cm [23].

The transmission coefficient of TF-1 is for visible light ~ 0.9 [18]. Therefore, if our counter is 5 cm thick, its efficiency can be considered to be in the vicinity of 0.9.

The detection threshold for the γ spectra was set at a level of 85–90 keV. The measured mesonic X-ray spectra coincide with the data presented in [19]. Selection of the gamma spectrum related to electrons was performed by coincidence of a time signal from the Ge(Li) detector inside a 1 μs gate initiated by the stop of a muon and the signal from the Cherenkov counter, also inside the gate from the μ-stop [16] (Fig. 4).

The two-dimensional time distribution of $\gamma - e$ coincidences is shown in Fig. 5. An enhanced concentration of events is to be noted in the lower right-hand part of the distribution. These are $\gamma - e$ events corresponding to the time after departure of the electron. One tends to think of possible interaction in the final state. But this is difficult to imagine, since the propagation time of the electron in the space occupied by a nucleus of radius R is $\tau_1 \sim R/c \sim 10^{-23}$ s, while the characteristic time of nuclear oscillations $\tau_2 \sim \hbar/E \sim 10^{-21}$ s, i.e., $\tau_1 \ll \tau_2$ [13]. But the energy spectra corresponding to the lower part to the right of the «trail» and to the upper part to the left of the «trail», respectively, *slightly differ*. Therefore this phenomenon deserves special investigation. The frame indicating an exponential segment along the «trail» of $\gamma - e$ coincidences corresponds to the lifetime of a muon on the K-orbit of the ^{152}Sm muonic atom (window *3* of Fig. 4).
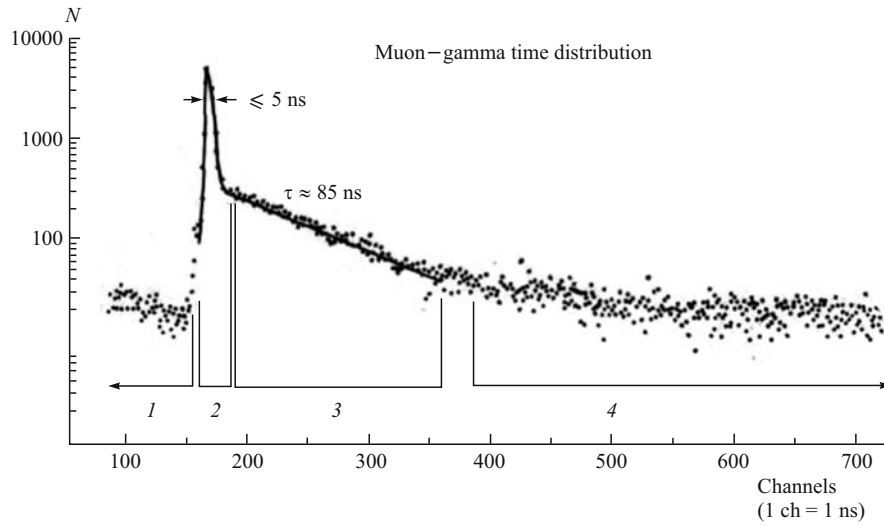
5

Fig. 4. T — spectrum of γ at rest muon in ^{152}Sm. Windows: *1* — background before μ-stop; *2* — prompt muonic X-ray; *3* — delay nuclear γ ray due to μ capture; *4* — background after μ capture
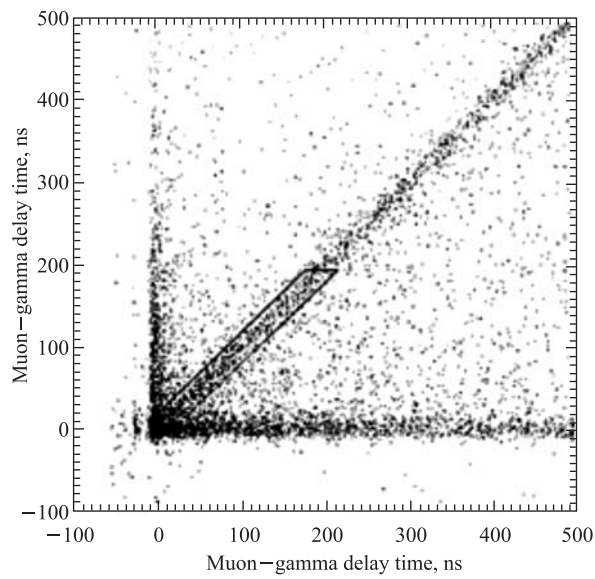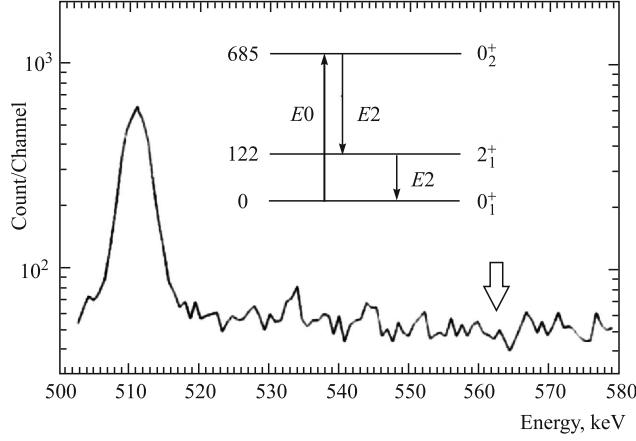

Fig. 5. Spectrum of $\gamma - e$ coincidence

Fig. 6. The γ spectrum in the energy region of the $0_2^+ \to 2_1^+$ transition for events indicated by the frame in this figure

It is essential to find the optimum position of the starting point of the time window for delayed events to make the contribution to these events from prompt events having a Gaussian distribution as small as possible, so as to reduce to a minimum the loss due to the area of the exponential. By appropriate selection such a position was found, for which the area under the exponential in this window amounted $\sim 78\%$ of the total area.

The main goal of the search was the $E2$ γ transition ($E_\gamma = 563.2$ keV) between the 0_2^+ and 2_1^+ levels (Fig. 6) in coincidence with the decay electron. A segment of such a spectrum in the $\sim 500-600$ keV range is shown in Fig. 6. The arrow indicates the position of the 563 keV peak. The average background at this point is $N_{\mathrm{bgrd}} \approx 40$.

The counting rate expected at the 563 keV peak is determined by the following expression:

$$N = N_\mu w_{\mathrm{ac}} a w_{\mathrm{d}} w(0^+) B \Omega_e \varepsilon_e \varepsilon_\gamma T A,$$

where N_μ is the whole number of μ-stops ($\approx 2 \cdot 10^9$); w_{ac} — the probability of atomic capture by Sm ($= 0.76$ [22]); a — the isotopic enrichment with ^{152}Sm ($= 0.98$); w_{d} — the decay probability of a muon on the K-orbit of ^{152}Sm ($\approx 3.83 \cdot 10^{-2}$); $w(0^+)$ — the excitation probability of the 0^+ level in ^{152}Sm per decay event ($3 \cdot 10^{-4}$); B — the 0^+ deexcitation branching via the $E2$ γ transition (≈ 0.98); Ω_e — the solid angle covered by the electron counter (≈ 0.42); ε_e — the electron detection efficiency (≈ 0.9); ε_γ — the absolute efficiency of the γ spectrometer ($\varepsilon_\gamma \approx 10^{-3}$ for $E_\gamma = 563$ keV); T — a coefficient taking into

7

account the overlapping of the exponential and the Gaussian distribution (~ 0.78); A — the absorption coefficient of the target for γ quanta with $E_\gamma = 563$ keV (≈ 0.8).

Thus, $N \approx 4.7$, which at a 90% confidence level yields for the experimental quantity $w(E0)$ an upper limit $< 1.5 \cdot 10^{-3}$. This is 3.3 times lower than our previous result ($< 5 \cdot 10^{-3}$), but still does not reach the theoretical estimation ($\approx 3 \cdot 10^{-4}$).

Above it was mentioned that dynamic $E2$ muon–nucleus interaction inside the nucleus may result in excitation of low-lying rotational levels. The probability for the ^{152}Sm nucleus to remain in the 2_1^+ state after completion of the muonic cascade is 0.30 [20]. The deexcitation time of the 2_1^+ nuclear level ($E_\gamma = 121.78$ keV) is about $= 1.44 \cdot 10^{-9}$ s, the lifetime of the muon on the K-orbit is $\approx 8 \cdot 10^{-8}$ s. This means that the $2_1^+ \to 0_1^+$ nuclear transition takes place when the muon is present on the K-orbit of the muonic atom. The perturbation introduced by the muon alters the radius of the excited nucleus. The change occurring in the nuclear potential has been termed the «isomeric shift». Experimentally observed isomeric shifts in various nuclei have been reported in [19, 20, 21]. The results are spread out in the range from 350 eV up to $\geqslant 1$ keV. Measurements of the isomeric shift in the 2_1^+ level of ^{152}Sm have yielded the following values: $\Delta E_{\text{is}} = 1.03 \pm 0.15$ keV, 560 ± 60 eV and 550 ± 70 eV [20, 21]. Our measurement gave $\Delta E_{\text{is}} = 820 \pm 40$ eV. Thus, in the present work, a new upper limit has been obtained for the probability of monopole excitation of the ^{152}Sm nucleus due to the decay of a bound muon on the K-orbit of a muonic atom: $w(E0) < 1.5 \cdot 10^{-3}$. The isomeric shift for the $2j$ level (121.78 keV) has been measured to be $\Delta E_{\text{is}} = 820 \pm 40$ eV (preliminary result).

This work is the first (and unique) investigation of the dynamic $E0$ excitation of nucleus at μ^- decay on the K-orbit of muonic atom. This excitation mechanism permits one to get per se nuclear monopole excitation. Study of nuclear excitation by the decay of the bound muon is of independent interest — the discovery of a new process and validation of ideas about it in the future can provide a new complementary method for studying nuclear monopole states [24]. Thus and so a search of this process should be in progress with more perfect equipment and at more intensive muon beam.

Studying the process $\mu^- \to e^- \nu_\mu \tilde{\nu}_e$ becomes important in relation to the planned experiment in search of $\mu^- \to e^-$ conversion to be carried out at leading world scientific centers and owing to the enormous interest shown by the scientific community. The double-neutrino decay of a muon on the K-orbit is the main background process, and the possible application of monopole excitation of the nucleus as a trigger of muon conversion would render significant aid in the selection of useful events.

REFERENCES

1. *Fermi E., Teller E.* // Phys. Rev. 1947. V. 72. P. 399.

2. *Kim Y. N.* Mesic Atoms and Nuclear Structure. Amsterdam: N.-Holland, 1971;
   Balashov V. V. et al. Absorption of Mesons by Atomic Nuclei. M.: Atomizdat, 1978. P. 170;
   Charalambus S. // Nucl. Phys. A. 1971. V. 166. P. 145.

3. *Delyagin N. P. et al.* Hyperfine Interactions and Nuclear Radiations. M.: Moscow University Publ. House, 1985.

4. *Wilets L.* // Mat. Fys. Med. 1954. V. 29. No. 3;
   Jacobsohn B. A. // Phys. Rev. 1954. V. 96. P. 1637.

5. *Henley E. M., Wilets L.* // Phys. Rev. Lett. 1968. V. 20. P. 1389.

6. *Abela R. et al.* // Phys. Lett. B. 1980. V. 94. P. 331.

7. *Zaretsky D. F.* // Proc. of the II United Nations Intern. Conf. on the Peaceful Uses of Atomic Energy, Geneva, Sept. 1–13, 1958.

8. *Balats M. Ja. et al.* // JETPh. 1960. V. 3–8. P. 1715.

9. *Zaretsky D. F., Karpeshin F. F.* // J. Nucl. Phys. 1979. V. 29. P. 151.

10. *Rösel Ch. et al.* // Z. Phys. A. 1993. V. 345. P. 425.

11. *Huff R. W.* // Ann. Phys. 1961. V. 16. P. 288.

12. *Charalambus S.* // Nucl. Phys. A. 1971. V. 166. P. 145.

13. *Batkin I. S.* // J. Nucl. Phys. 1976. V. 24. P. 254.

14. *Mitropolsky I. A.* // J. Nucl. Phys. 1981. V. 33. P. 1158.

15. *Abazov V. M. et al.* // Izvestiya AN SSSR, Ser. Fiz. 1988. V. 52. P. 1008;
    Sabirov B. M. et al. // Proc. of the II Intern. Symposium «Muons and Pions in Matter», 30 June – 4 July 1987, Dubna. P. 393.

16. *Sabirov B. M. et al.* JINR Commun. P15-87-641. Dubna, 1987.

17. *Shil'nikov O. V. et al.* // Abstracts of XXXIX Workshop on Nuclear Spectroscopy and Nuclear Structure, 18–21 April 1989, Tashkent.

18. *Kobayashi M. et al.* // Nucl. Instr. Meth. A. 1994. V. 345. P. 210.

19. *Backe H. et al.* // Nucl. Phys. A. 1974. V. 234. P. 469;
    Yamazaki Y. et al. // Phys. Rev. C. 1978. V. 18. P. 474;
    Powers R. J. et al. // Nucl. Phys. A. 1979. V. 316. P. 295.

20. *Wu C. S.* Hyperfine Structure and Nuclear Radiations. Amsterdam: N.-Holland, 1968.

21. *Bernow S. et al.* // Phys. Rev. Lett. 1967. V. 8. P. 787;
    Phys. Rev. Lett. 1968. V. 21. P. 457.

22. *Zinov V. G. et al.* // J. Nucl. Phys. 1965. V. 2. P. 859.

23. *Zrelov V. P.* Vavilov–Cherenkov Radiation and Its Application in High Energy Physics. Part 2. M.: Atomizdat, 1968.

24. *Voinova-Eliseeva N. A., Mitropolsky I. A.* // PEPAN. 1986. V. 17. P. 1173.

Корректор *Т. Е. Попеко*