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E4-82-694

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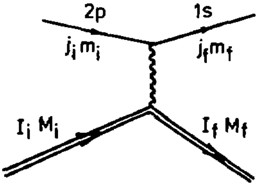
THE NONRADIATIVE EXCITATION OF THE MUONIC ATOM ^{238}U AS AN INVERSE CONVERSION PROCESS

1982

Nonradiative excitation (NE) of nuclei[1,2] is an inverse muonic conversion process with nuclear excitation when a muon transfers to the 1s-state in the muonic atom. The Feynman graph for the muon transition 2p→1s is shown in the figure. It is known from the experiment that the NE probability is 0.2-0.4 for the nuclei of the transuranium region[3]. The research of NE process allows one to investigate the giant resonances and other modes of nuclear excitation by "monoenergetic" γ-quanta of rigorously defined multipolarity (the width of the mesoatomic γ-lines is approximately 1 keV). As a result one can obtain information with high energy resolution on the nuclear structure. The study of NE enables also the data on the fission barrier to be defined more accurately[4].



Feynman graph of the nonradiative nuclear excitation in the μ-mesoatomic 2p→1s transition. The double line denotes the nuclear transition, the single one—the muonic transition

At present these problems become actual in view of the experiments[5,6] aimed at determining the relative role of transitions of different energy and multipolarity in NE. Johansson et al.[5] have made a conclusion that the main role in the case of ^{238}U belongs to the E2 transitions 3d→1s. A considerable contribution of the transitions 3→1 has been observed/6/ for ^{235,238}U, though in this experiment the role of the transitions 3→1 turned out to be less than that of 2→1.

The first theoretical calculations of the NE probability were performed in/1,2/ for the dipole 2p→1s and 3p→1s transitions and in/7/ for the quadrupole 3d→1s transitions. They used the experimental photoexcitation cross section, whereas Teller and Weiss/4/ used the data on giant resonances. However, to calculate the amplitude of NE one should take a double integral over the muon and nuclear variables. To correctly calculate this integral, one should know apart from the muon wave functions and matrix elements of the nucleus - γ-ray interaction the concrete form of the nuclear transition current. This is just the so-called dynamic effect of nuclear size/8/. Its inclusion is especially important for the uranium muonic atom, in which the Bohr radius of the K-orbit (allowing for finite nuclear size) is twice as small as the nuclear one.

In the present paper we have used the muon conversion coefficients/8,9/ to calculate the NE probability. In/8,10/ it has been shown that for the calculation of the muon conversion coefficients the models of surface or volume transition currents may be successfully used. We performed the calculations in both these models to find the possible error arising in the model calculation of the muon conversion coefficients.

The width of the nonradiative transition can be expressed as

$$\Gamma_{NE} = \alpha_\mu^{(d)}(i \to f)\,\frac{8\pi(L+1)}{L[(2L+1)!!]^2}\,\frac{\omega_f^{2L+1}}{(\hbar c)^{2L}}\,B(EL;0\to\omega_f). \qquad (1)$$

Here $\alpha_\mu^{(d)}(i\to f)$ is the muon conversion coefficient for the muon transition from the discrete state i (the notation is given in fig.1) to the discrete state f. Karpeshin and Zaretsky/9/ have considered the resonance promotion of the muon in the K-orbit during a nuclear de-excitation with the subsequent emission of a mesoatomic X-ray. The $\alpha_\mu^{(d)}(i\to f)$ value is related to the conversion coefficient $\alpha_d \equiv \alpha_\mu^{(d)}(f\to i)$ of the inverse transition $f\to i$ which is determined in/9/ by

$$\alpha_\mu^{(d)}(i\to f) = \frac{2j_f+1}{2j_i+1}\,\alpha_\mu^{(d)}(f\to i). \qquad (2)$$

By $\mathcal{B}(EL;0\to\omega_f)$ we have denoted in (1) the strength function of the reduced EL transition probability, which has the form

$$\mathcal{B}(EL;0\to\omega_f)=\sum_g B(EL;g.s.\to\omega_g)\frac{\Delta}{2\pi}\frac{1}{(\omega_f-\omega_g)^2+(\Delta/2)^2},$$

where ω_g is the energy of the one-phonon state g , Δ is the averaging parameter. The quantity $\mathcal{B}(EL;0\to\omega_f)$ has been calculated in the RPA within the quasiparticle-phonon nuclear model/11/ which is valid for the investigation of low-lying states and giant resonances in complex nuclei. We have used in the calculations the value Δ = 300-500 keV. At the excitation energy 6-10 MeV the density of the one-phonon states with given L is about 10^2 per 1 MeV. The used values of Δ are fairly large to smooth away fluctuations in $\mathcal{B}(EL;0\to\omega_f)$ produced by concrete highly excited states ω_g. On the other hand, such values of Δ are fairly small so as not to distort the average value of $\mathcal{B}(EL;0\to\omega_f)$ at the given excitation energy.

The probability of the nonradiative transition is defined by the branching ratio

$$W_{NE}=\Gamma_{NE}/(\Gamma_{NE}+\Gamma_\gamma^{(a)}),$$

where $\Gamma_\gamma^{(a)}$ is the radiative width of the mesoatomic level $j_i m_i$. To calculate $\alpha_\mu^{(d)}$ and $\Gamma_\gamma^{(a)}$ a number of programs from the set RAINE/12/ were used.

The results of the calculation of W_{NE}, averaged statistically over the states with the same ℓ_i , but different j_i, are presented in the table. The accuracy of the results for W_{NE} is mainly determined by that of the model/11/. The total probability of NE per μ-atom proves to be some larger than the experimental value equal to (20-30)%/3/. For 3p→1s transitions the given in the table values must be multiplied by the population probability of the 3d-state, which is known to be (5-10)% (see, for example/4/). Consequently, their role in NE turns out to be by several times less. A rather large NE probability of E3 transition 3d→2p is of great interest. This is caused by low energy giant octupole resonance. The NE probabilities for transitions 4→1 (E1, E2, E3) turned out to be less than 0.01.

For comparison with the experimental data/5,6/ one should calculate the probability of prompt fission per muonic atom

$$W_{pf}(i\to f)=Q_{pop}(i)\,W_{NE}(i\to f)\,P_f(i\to f), \qquad (3)$$

Table. Probabilities of the nonradiative transitions W_{NE} in the muonic atom ^{238}U, calculated using strength functions $B(EL;0\to\omega_f)$

The transition	Energy MeV	$\alpha_\mu^{(d)}(i\to f)$ MeV		$B(EL;0\to\omega_f)$ spu/MeV	$\Gamma_\gamma^{(a)}$ keV	W_{NE}	
		surf.cur.	vol.cur.			surf. cur.	vol. cur.
2p→1s, E1	6.4	1.2	1.7	0.07	1.4	0.11	0.15
3p→1s, E1	9.6	0.08	0.13	0.6	0.36	0.48	0.60
3d→1s, E2	9.5	0.9	1.3	7.5	0.55	0.25	0.33
3d→2p, E3	3.2	$1.9\cdot10^5$	$2.7\cdot10^5$	7.7	0.55	0.08	0.10

where $Q_{pop}(i)$ is the probability of the population of the i-th level in the mesoatomic cascade, $P_f(i\to f)=\Gamma_f/(\Gamma_f+\Gamma_n)$ is the branching ratio for fission of the nucleus excited in the nonradiative muon transition $i\to f$. The presence of a muon in the K-orbit reduces by several times the value of P_f due to the increase of the fission barrier by 0.6 MeV/2,14/. Assuming that the observed value $W_{pf}^{(exp)}(3\to1)=0.0026\pm0.0008$/6/ is caused only by the transitions 3p→1s or 3d→1s and using the values of $Q_{pop}(3p)\simeq0.1$, $Q_{pop}(3d)\simeq1$, (see, for instance,/4/) we get from (3) the upper bounds for P_f in the presence of a muon: $P_f\simeq0.1$ and 0.01 for the 3p→1s and 3d→1s transitions, respectively. The second value is in better agreement with the experiment/15/ ($\Gamma_n/\Gamma_f\simeq83$), but in both cases P_f value turns out to be less or of the same order of magnitude as for the experimental photoexcitation value (0.2 for E1-transition/13/ and about few percents for E2-transition/16/). Therefore, the observed prompt fission probability for 3→1 transitions can be attributed in general to dipole as well as quadrupole transitions.

For the transition 2p→1s the energy is considerably less than that of the giant E1 resonance, and the strength function $B(E1;0\to\omega_f)$ is calculated with less accuracy than for 3→1. Therefore, for the transition 2p→1s it is advisable to calculate W_{NE} using the experimental photoexcitation cross section/13/. As a result we have obtained $W_{NE}(2\to1)=(30-40)\%$, that is three times as large as W_{NE}(2p→1s) in the table. To get the experimental value $W_{pf}^{(exp)}=0.0038\pm0.0009$ /6/, one should take $P_f\simeq0.01$ in accordance with the experiment/15/. This value of P_f is less by approximately 20 times than that for photoexcitation/13/. This can be attributed to the greater influence of the increase of the fission barrier in this case in comparison with 3→1 transitions, whose energy exceeds the fission barrier by 3 MeV.

It should be noted, that had the dynamic effect of nuclear size be neglected (corresponding to the so-called model "without penetration", which is widely used in the theory of electron conversion, but is not adequate in the muon case/8/), the values of $\alpha_\mu^{(d)}$ and consequently Γ_{NE} *would increase by more than* three times in comparison with the model of surface transition currents.

Acknowledgements

The authors are deeply indebted to prof. D.F.Zaretsky, prof. V.G.Soloviev and L.A.Malov for fruitful discussions.

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Received by Publishing Department
on September 29 1982.

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Карпешин Ф.Ф., Нестеренко В.О.   E4-82-694

Безрадиационное возбуждение ядра ^{238}U в мезоатоме
как обратная конверсия

Вычислены вероятности безрадиационного возбуждения /БРВ/ ядра для разных переходов мюона в мезоатоме ^{238}U. При этом использован аппарат коэффициентов мюонной конверсии, а также микроскопические ядерные волновые функции, полученные в рамках квазичастично-фононной модели. Показано, что вероятность БРВ для мюонных переходов 2p → 1s и 3p → 1s равна 0,3, а в случае безрадиационных E3-переходов 3d → 2p - 0,08÷0,10. Рассмотрено влияние динамического эффекта ядерной структуры на БРВ. Сделаны оценки делимости ядра ^{238}U при безрадиационных переходах.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1982

Karpeshin F.F., Nesterenko V.O.   E4-82-694

The Nonradiative Excitation of the Muonic Atom ^{238}U
as an Inverse Conversion Process

The probabilities of nonradiation nuclear excitation are calculated for different muon transitions in the muonic atom ^{238}U. Microscopic nuclear wave functions, obtained within the quasiparticle-phonon nuclear model and the muonic conversion coefficients have been used. The probability of nonradiation nuclear excitation for the muonic transitions 2p → 1s and 3p → 1s has been found to be equal to 0.3. It is predicted that nonradiative E3 transitions 3d → 2p can take place with the probability 0.08-0.10. The dynamic effect of nuclear structure on the probability of nonradiative nuclear excitation is taken into account. The estimates of fission branching ratio $\Gamma_f/(\Gamma_f+\Gamma_n)$ are also obtained.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1982

Редактор Э.В.Ивашкевич.   Макет Р.Д.Фоминой.

Подписано в печать 6.10.82.
Формат 60x90/16. Офсетная печать. Уч.-изд.листов 0,63.
Тираж 500. Заказ 31908.
дательский отдел Объединенного института ядерных исследований.
Дубна Московской области.