estimate the efficiency of the cascade mechanism, we must compare the energy $\mathscr{E}$ given to the electron during the operation of the pulse with the ionization potential I_0. Assuming that the electron velocity is of the order of 10^8 cm/sec, and that the cross section for a collision between the electron and the molecule is of the order of 10^{-16} cm^2, we find that $\nu \sim 10^{10}$ sec^{-1} when $n \sim 10^{18}$ cm^{-3}. Suppose that the frequency ω_0 of the laser pulse corresponds to a 1.2-eV photon. In this situation, we have $\omega_0 \gg 1/\tau \gg \nu$, and elementary calculations show that $\mathscr{E} = e^2 E_0 v\tau / 4m\omega_0^2 \sim 3\times 10^{-3}$ eV, where e, m are, respectively, the charge and mass of the electron. The ionization potential I_0 of the HCN molecule is 13.9 eV, i.e., $\mathscr{E} \ll I_0$, so that the cascade does not succeed in developing during the operation of the pulse.

The field ionization probability can be estimated from the results reported by Keldysh.[4] Estimates show that the largest contribution is provided by multiphoton ionization through an intermediate level.

The probability of ionization during the pulse is of the order of[4]

$$10^{12}\tau[\mathrm{sec}]\cdot(6\cdot 10^{-15}Q[\mathrm{W/cm^2}])^{n_s-1},$$

where n_s is the number of photons in the energy interval between the ground and intermediate levels. Hence, it is clear that, for our values of τ and Q, the fraction of ionized molecules is negligible.

We note in conclusion that, since the above mechanism of producing overpopulation is not selective, it should, at least in principle, enable us to achieve generation simultaneously on a number of rotational transitions in a given molecule, or simultaneously on different molecules, when a gas mixture is employed.

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De-excitation of metastable nuclei during negative-muon capture

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A negative muon captured by a metastable nucleus can accelerate the de-excitation of the latter by several orders of magnitude. For a certain relationship between the nuclear and mesonic level spacing, this de-excitation is accompanied by the ejection of a meson, which can then participate in the de-excitation of other nuclei. When a specimen with sufficiently high density of metastable nuclei and a meson beam of sufficiently high intensity are used, this process leads to a rapid increase in the γ activity of the specimen, and can be used as a basis for a powerful source of monochromatic γ rays. The single-particle model is used in this paper to calculate the decay probability for different channels of metastable nuclear states in the presence of a meson. The conditions under which an experimental realization of the de-excitation acceleration effect may be possible are discussed.

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I. INTRODUCTION. FORMULATION OF THE PROBLEM

The possibility in principle of accumulating considerable quantities of metastable nuclei during the processes involved in nuclear technology, followed by concentration through chemical[1,2] and laser[3] methods, leads naturally to the question as to whether the rate of decay of such nuclei could be controlled. The possibility of controlling the rate of radiative decay of metastable nuclei through stimulated γ emission in a laser-type device (the current state of the γ laser problem is reviewed in[7]) was discussed in[4–6]. The possibility of influencing nuclear decay involving the participation of atomic-shell electrons (K capture and internal conversion) through ionization was considered in[8]. The possible acceleration of the de-excitation of a metastable nucleus through the transfer of some of its angular momentum to the atomic-shell electrons was recently considered in[9]. The influence of the electron shell turned out to be negligible because the ratio r_n/r_a of the nuclear to atomic radius was very small. In this respect, the mesonic atom is more attractive than the ordinary atom because the ratio r_n/r_a can then vary in a broad range of values, depending on the nuclear charge.

In this paper, we consider the possibility of de-excitation of metastable nuclei by negative-muon bombardment. We shall not consider muon capture as such, since it has been discussed in detail in the fundamental papers.[10–12] The γ-ray spectrum emitted during cap-

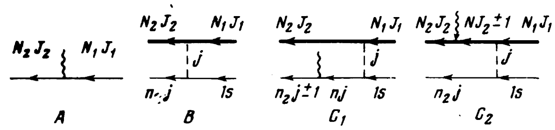

FIG. 1. Feynman diagrams corresponding to different decay channels for the the excited states of a mesic atom.

ture will not be discussed either. We shall merely assume that the nucleus does not change its state during meson capture, and will take the initial state to consist of an excited nucleus and the meson in the $1s$ state. Different radiative and radiationless processes can occur in this system, depending on the relationship between the nuclear and mesonic level spacings. The main aim of the present work was to determine a situation in which the principal reaction channel is the de-excitation of the nucleus, accompanied by γ emission and subsequent conversion of the meson which initiated this de-excitation. Under these conditions, a single meson can participate in the de-excitation of several nuclei during its lifetime (approximately 10^{-6} sec). A fraction of the nuclear excitation energy is then expended in ejecting the meson, and this energy is subsequently released during the capture of the meson by another nucleus. When the specimen contains a sufficiently high density of metastable nuclei, and the meson source has sufficient intensity, this process can be used as a basis for a powerful source of monochromatic γ rays.

2. MODEL AND PROCESSES TAKEN INTO ACCOUNT

To simplify our analysis, we shall confine our attention to a simple single-particle model of the nucleus, and will assume that the system under investigation consists of a doubly-magic hard core with one proton and one meson moving in the field of the core. The proton and the meson have a Coulomb interaction with one another, which will be taken into account in the first order of perturbation theory. In addition to the Coulomb interaction, we have also considered in[9] the dynamic interaction between the two particles through a third particle (core), which takes into account the finite mass of the core. However, this interaction can reduce the multipole order of the nuclear transition only by unity, whereas we are interested in highly forbidden transitions of high multipole order. Of course, most of the nuclear states which are known and are of interest have a multiparticle character, and the structure of their energy states cannot be predicted, even very approximately, by the single-particle model. However, the meson-proton effects, in which we are interested here, are unrelated to the single-particle character of the model.

We shall calculate the probabilities of decay along different channels of a system consisting of a proton in an excited state $\varphi_{N_1J_1}$ and a meson in the ground state ψ_{1s}. Three channels will be taken into account: (1) radiative and purely nuclear 2^j-pole transition (probability P_1), (2) radiationless transition in which the proton goes down to the ground state and the meson leaves the nucleus with energy $E = \Delta E^p_{N_1J_1} - E^i_\mu$, where $\Delta E^p_{N_1J_1}$ is the energy of the nuclear transition and E^i_μ is the meson binding energy in the $1s$ state (probability P_2), and (3) transition of the proton to the ground state, accompanied by the excitation of the meson and the emission of a γ ray of energy $\hbar\omega = \Delta E^p_{N_1J_1} - \Delta E^\mu_{nl}$ (probability P_3). These channels are described by the Feynman diagrams shown in Fig. 1.

The first channel is represented by diagram A, the second channel by diagram B, and the third by diagrams C_1 and C_2. The thin line in these diagrams represents the mesonic state and the thick line the proton state. The symbols at the ends of the lines represent the initial and final states of the proton and meson. The broken line with the symbol j represents the Coulomb interaction between the meson and proton, which involves the exchange of a 2^j-pole photon, and the wavy line represents the dipole radiative-transition operator. This transition is possible in the system because of the meson-proton interaction. Since angular momentum must be conserved, it follows that $j \geq \Delta J$ for diagrams B and C_1, and $j \geq \Delta J - 1$ for diagram C_2. In the case of decay along the third channel, the radiative transition proper can be executed either by the meson or by the proton from the virtual state nj or $NJ_2 \pm 1$. Diagrams C_1 and C_2 correspond to these two possibilities. Diagram A is of zero order in the meson-proton interaction, and the remaining diagrams are of the first order in this interaction. Diagrams C_1 and C_2 include the effects of the interaction between the particles on the initial state. There are also other versions of these diagrams, and take into account the effect of the interaction on the final states. However, calculations show that their contribution to the probability of these transitions is less than the contribution of diagrams C_1 and C_2.

In practice, one can also have processes involving the participation of electrons, which are analogous to the above processes involving the meson. However, in the region of transferred energies in which we are interested (ΔE^p of the order of $E^i_\mu \gtrsim 1$ MeV), the probability of these processes is small even in comparison with the probability of purely radiative nuclear transitions (see table). The only exception is the case of zero–zero transitions.

An approximate calculation is given below of the probabilities of the different transitions, using the Coulomb meson functions and the assumption that $r_n \ll r_\mu$ (r_μ is the radius of the meson orbital), which is valid for light nuclei. This is followed by an accurate numerical calculation for a particular state of ${}^{49}_{29}Sc_{28}$, using a model nuclear potential.

TABLE 1. Probability of radiative 2^j-pole nuclear transitions (P_1), meson conversion (P_2^μ), and electron conversion (P_2^e) for $\Delta E^p \approx E^i_\mu$.

j	P_1	P_2^μ	P_2^e	j	P_1	P_2^μ	P_2^e
	sec^{-1}				sec^{-1}		
0	–	$7.7\cdot10^{18}$	$9.1\cdot10^{13}E^{-1.5}$				
1	$4.0\cdot10^{14}E^3$	$1.0\cdot10^{16}$	$1.3\cdot10^{10}E^{-0.5}$	4	$2.0\cdot10^{-1}E^9$	$4.2\cdot10^{14}$	$7.6\cdot10^{-5}E^{2.5}$
2	$4.8\cdot10^9E^5$	$1.4\cdot10^{16}$	$5.0\cdot10^5E^{0.5}$	5	$3.8\cdot10^{-7}E^{11}$	$5.1\cdot10^{13}$	$4.7\cdot10^{-10}E^{3.5}$
3	$3.4\cdot10^4E^7$	$2.8\cdot10^{15}$	$8.3\cdot10^0E^{1.5}$	6	$2.2\cdot10^{-12}E^{13}$	$5.1\cdot10^{12}$	$1.9\cdot10^{-15}E^{4.5}$

Note. Energies in MeV, $Z=20$.

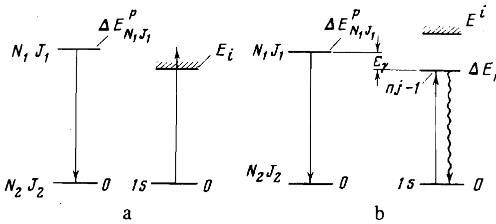

FIG. 2. Proton and meson level schemes (left and right, respectively) in a hypothetic nucleus. In case a ($\Delta E^p > E^i_\mu$), the main decay channel is the radiationless ejection of the meson, and in case b ($E^i_\mu > \Delta E^p_{N_1J_1} > \Delta E^\mu_{nj-1}$), the de-excitation of the nucleus is accompanied by the excitation of the meson and the emission of γ ray with energy $\hbar\omega = \Delta E^p_{N_1J_1} - \Delta E^\mu_{nj-1}$. The wavy line represents radiative transition of the meson to the ground state, which may be a cascade transition.

3. CASE WHERE $\Delta E^p_{N_1J_1} > E^i_\mu$. AUTOIONIZATION

The probability of a purely radiative nuclear 2^j-pole transition can be estimated from a well-known formula (see, for example, [13]). For $r_n = 5\times10^{-13}$ cm, we have

$$P_1=2\cdot10^{20}\frac{j+1}{j[(2j+1)!!]^2}\left(\frac{3}{j+3}\right)^2\left(\frac{\Delta E^p\,[\mathrm{MeV}]}{40}\right)^{2j+1}. \tag{1}$$

Consider the case where the nuclear excitation energy exceeds the ionization energy E^i_μ of the mesic atom. The energy-level scheme corresponding to this case is shown in Fig. 2a. It is clear that, under these conditions, $P_3 \ll P_2$ because P_3 contains an additional parameter connected with the fact that the interaction between the particles and the electromagnetic field is small. We shall calculate P_2 assuming, to be specific, that $J_2 = 0$. In fact, the calculation reduces to the evaluation of the probability of autoionization decay of the state of the two-particle system

$$P_2=2E^{\mathrm{Im}}/\hbar, \tag{2}$$

where E^{Im} is the imaginary part of the energy of the autoionization state, which can be estimated from the formula

$$E^{\mathrm{Im}}=\frac{\pi e^2}{k(2l+1)^2}\left[\int d\mathbf{r}\psi_{kl}(\mathbf{r})f(\mathbf{r})\psi_{1s}(\mathbf{r})\right]^2, \tag{3}$$

$$f(\mathbf{r})=\int d\mathbf{r}'\,\varphi_{N_2J_2}(\mathbf{r}')\frac{1}{|\mathbf{r}-\mathbf{r}'|}\varphi_{N_1J_1}(\mathbf{r}'), \tag{4}$$

where $k=[2(\Delta E^p - E^i_\mu)/m_\mu]^{1/2}$ and m_μ is the mass of the meson. The function $f(r)$ has the following asymptotic behavior:

$$f(r)\sim r^l\langle J_2|r^{-(l+1)}|J_1\rangle\approx r^l/r_n^{l+1},\quad r\to0,$$
$$f(r)\sim r^{-(l+1)}\langle J_2|r^l|J_1\rangle\approx r_n^l/r^{l+1},\quad r\to\infty, \tag{5}$$

where

$$r_n\approx1.5\cdot10^{-13}(2Z)^{1/3}\ \mathrm{cm}, \tag{5'}$$

which we have approximated by the function

$$r_n^l(1-e^{-r/r_n})^{2l+1}/r^{l+1}, \tag{6}$$

which satisfies the asymptotic equations given by (5). The integral with respect to the meson coordinate can then be evaluated analytically. The electron conversion probability can be evaluated in a similar way. The table lists the numerical results for the meson conversion probability P^μ_2 and the electron conversion probability P^e_2 in the case where $\Delta E^p \approx E^i_\mu \gg E^i_e$.

It is clear from the table that, in all cases, $P^\mu_2 \gg P_1 \gg P^e_2$ and the ratios P^μ_2/P_1, P^μ_2/P^e_2 increase rapidly with the transition multipole order. It follows that when $\Delta E^p > E^i_\mu$ the preferred reaction in the specimen exposed to the mesons is periodic meson capture by metastable nuclei, followed by meson conversion. The nuclear excitation energy is then completely carried away by the meson and is subsequently partially released during the slowing down of the meson in the specimen. The remainder of this energy is radiated in the form of γ rays during the capture of the slowed-down meson. A meson captured by an unexcited nucleus is retained by it and is removed from the reaction process.

4. CASE WHERE $\Delta E^p_{N_1J_1} < E^i_\mu$. RESONANCE EFFECT

Let us now suppose that the ionization energy of the mesic atom is greater than the nuclear excitation energy. In this case, the most probable situation is the capture of the meson to the lowest 1s state, so that there is no change in the state of the nucleus. A nucleus of this kind, like the unexcited nucleus, is a trap for the meson. However, when $\Delta E^p_{N_1J_1}$ exceeds the energy of excitation of the meson at least to the j, $j-1$ or $j+1$, j state, a third decay channel is opened and corresponds to diagram C_1 or C_2. The contributions of these diagrams to the transition amplitude are proportional to the following sums over the virtual states of the meson nj and proton NJ_2+1:

$$S(C_1)=\sum_n\langle n_2j-1|\mathbf{r}|nj\rangle\left\langle N_2J_2,nj\left|\frac{1}{|\mathbf{r}-\mathbf{r}'|}\right|1s,N_1J_1\right\rangle(\Delta E^\mu_{nj}+\Delta E^p_{N_2J_2})^{-1}, \tag{7}$$

$$S(C_2)=\sum_N\langle N_2J_2|\mathbf{r}|NJ_2+1\rangle\left\langle NJ_2+1,n_2j\left|\frac{1}{|\mathbf{r}-\mathbf{r}'|}\right|1s,N_1J_1\right\rangle\cdot(\Delta E^\mu_{NJ_2+1}+\Delta E^\mu_{n_2j})^{-1}. \tag{8}$$

The sums S_n and S_N in (7) and (8) represent summation over the discrete spectrum plus integration over the continuous spectrum. It is clear that the probability of decay along this third channel should be sensitive to the resonance situation, i.e., the process should be sharply accelerated when the total energy of a certain discrete virtual state of the two-particle system approaches the energy of the state $\varphi_{N_1J_1}\psi_{1s}$. This possibility is realized, for example, when the nuclear excitation energy $\Delta E^p_{N_1J_1}$ approaches the excitation energy of a particular mesonic level nj. Under these conditions, the contribution of diagram C_1 is found to increase. Figure 2b shows the proton and meson level scheme for this case. The resonance leads to a strong mixing of the states $\varphi_{N_1J_1}\psi_{1s}$ and $\varphi_{N_2J_2}\psi_{nj}$. The two mixed states are connected by a dipole mesonic transition to the state $\varphi_{N_2J_2}\psi_{n'j+1}$, which leads to their de-excitation at a rate characteristic for dipole meson transitions. The

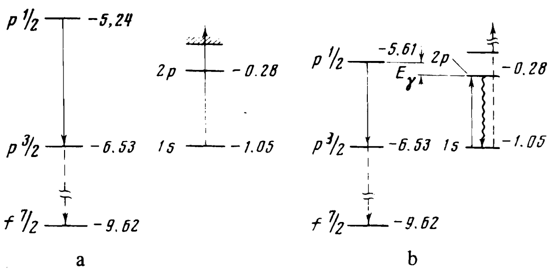

FIG. 3. Energy level scheme for the proton (left) and meson (right) in $^{49}_{21}\mathrm{Sc}_{28}$: (a) actual position of the $p^1/_2$ level, (b) $\Delta E^p(p^1/_2-p^3/_2) = 0.92$. The transition of the proton and meson during the first and second stages is shown by the solid and broken lines, respectively.

result of this de-excitation is that both the proton and the meson are in the ground state.

Let us now estimate the width of the interval of proton and meson energy difference for which the resonance will occur:

$$\Delta E \approx \iint d\mathbf{r}\, d\mathbf{r}' \varphi_{N20}(\mathbf{r}) \psi_{nJ_1}(\mathbf{r}') \frac{e^2}{|\mathbf{r}-\mathbf{r}'|} \psi_{1s}(\mathbf{r}') \varphi_{N_1J_1}(\mathbf{r}). \tag{9}$$

Proceeding as in the calculation of P_2, we obtain the following expression for $n = J_1 + 1$:

$$\Delta E \approx \left(\frac{J_1+1}{J_1+2}\right)^2 \frac{5(10^{13} r_n[\mathrm{cm}])^{J_1}(0{,}01Z)^{J_1+1}}{(2J_1+1)[(2J_1+2)!(2J_1+1)^{2J_1+3}]^{1/2}}. \tag{10}$$

This quantity increases very rapidly with increasing J_1. When $J_1 = 1$, the levels coincide to within a few keV and, when $J = 3$ is reached, they coincide to within a few eV. Thus, resonance phenomena should not play an appreciable role for highly forbidden transitions of high multipole order. The fact that the matrix element (10) is small does not mean, nevertheless, that the first-order correction in the meson-proton interaction will decrease equally rapidly with increasing J. This is valid only for the discrete part of the sum over the virtual states in (7), whereas the contribution of the matrix elements for the transition to the continuum falls much more slowly, as was demonstrated in the calculation of P_2^μ.

It is pointed out in[14–16] that, when the meson is captured by a heavy nucleus, the latter may undergo radiationless excitation to a level from which a nuclear reaction is possible. The processes discussed in[14–16] correspond to diagram C_2 with $j = 1$ (only the dipole-dipole interaction between the meson and the proton was taken into account), where the wavy line now represents the nuclear transition operator. The maximum probability of the nuclear reaction is expected in the case of resonance between the mesonic and nuclear levels. As already noted, the main channel under these conditions is radiative decay, which occurs at the high rate characteristic for dipole mesonic transitions. As a result, the probability of the nuclear reaction should be negligible. We note in this connection that a further reaction channel resembling autoionization decay, and involving the ejection of nucleons, opens when the meson energy is sufficient for the removal of a nucleon or a group of nucleons. For example, in the single-particle model, the probability of ejection of a proton can be estimated from the same formula that was used to calculate the meson ejection probability P_2^μ because the parameters of the proton and meson states are present in this expression in a symmetric fashion. It is clear that the probability is relatively high and that, when $\Delta J = 0$, it is of the same order as the probability of radiative decay.

5. NUMERICAL EXAMPLE

As an example, consider the nucleus $^{49}_{21}\mathrm{Sc}_{28}$. It contains one proton above the doubly magic core $^{48}_{20}\mathrm{Ca}_{28}$. Figure 3a shows the energy level scheme for this nucleus. The $p^1/_2$ level is connected by an $E4$ transition to the ground state $f^7/_2$, and by an $E2$ transition to the lower-lying $p^3/_2$ level. The $p^3/_2$ and $f^7/_2$ levels are connected by an $E2$ transition. Magnetic transitions between these levels are also possible, but they do not affect the qualitative character of the situation. The lifetime of an isolated nucleus in an excited state is of the order of 10^{-11} sec. Since a cascade quadrupole transition $p^1/_2-p^3/_2-f^7/_2$ is possible, the $p^1/_2$ level is not stable. Nevertheless, these states are convenient for the purposes of illustration because, on the one hand, all the above processes are possible in this case and, on the other hand, the single-particle model is applicable.

Following[17,18], we assume that the proton moves in the effective field of the core

$$V - 25 f(l, j) V'/r. \tag{11}$$

For the purely nuclear part of the interaction V we assume the form illustrated in Fig. 4, i.e.,

$$\begin{aligned} &V_0 - a[r^4/4 - r^3(R_1+R_2)/3 + r^2 R_1 R_2/2], \quad r<R_2, \\ &0, \quad r>R_2. \end{aligned} \tag{12}$$

This potential is convenient for numerical calculations because, in contrast to the Woods–Saxon potential used in[17,18], it does not lead to a divergence in the spin-orbit interaction $-25f(l,j)V'/r$ as $r \to 0$. The electrical potential of the core is assumed to be that due to a uniformly charged sphere

$$U(r) = \pm Ze^2 \begin{cases} 3/2R - r^2/2R^3, & r<R \\ 1/r, & r>R \end{cases}. \tag{13}$$

The positive sign in this expression corresponds to the proton and the negative sign to the meson. A standard procedure involving the variation of the parameters V_0, R_1, R_2, R was used to obtain a fit between the calculated

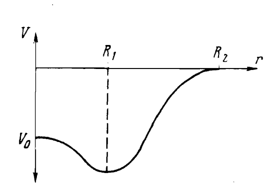

FIG. 4. The nuclear potential $V(r)$.

and experimental energies of the ground and first excited states of the proton. With $V_0 = -47.6$, $R_1 = 2$, $R_2 = 7.65$, $R = 4.75$, we obtained the following proton states: $E(f^7/_2) = -9.62$, $E(p^3/_2) = -6.53$, $e(p^1/_2) = -5.24$. The meson states were: $E(1s) = 1.05$, $E(2s) = -0.272$, $E(2p) = -0.281$ (all the energies are in MeV and all the lengths are expressed in units of 10^{-13} cm).

The techniques used to evaluate integrals such as (3) and infinite sums of radial integrals (7) and (8) were developed in detail in[19,20] in the case of atoms and molecules. It is shown there that the entire calculation of the contribution of diagrams of the first two orders for the matrix elements with arbitrary single-particle and two-particle potentials reduces to the solution of a set of ordinary differential equations with finite boundary conditions for $r = 0$. This system includes equations for the initial and final state functions for the meson and proton ψ_{nl} and φ_{NJ}, the equation for the first-order correction to the state function for the two-particle system (meson and proton), and the equations for the potentials and the required integrals. The equations were solved numerically on a computer.

The probability of autoionization decay of the mesic atom for different nuclear transitions turned out to be as follows: $P_2(p^1/_2 - p^3/_2) = 3.30 \times 10^{15}$, $P_2(p^1/_2 - f^7/_2) = 2.62 \times 10^{12}$, $P_2(p^3/_2 - f^7/_2) = 7.45 \times 10^{14}$. Because of the angular-momentum and parity selection rules, the nucleus participating in these transitions should transfer an angular momentum ΔJ not less than 2, 4, and 2, respectively. The results listed in the table differ from these figures mainly because the proton matrix elements $\langle J_2 | r^l | J_1 \rangle$ and $\langle J_2 | r^{-(l+1)} | J_1 \rangle$ were overestimated. The point is that (5′) does not take into account the rapid reduction of these matrix elements with increasing ΔJ due to the fact that the radial parts of the orbitals $\varphi_{N_1 J_1}$ and $\varphi_{N_2 J_2}$ shift into different regions during this process, and their product increases the number of oscillations. This is not valid for multiparticle transitions where high values of ΔJ can be achieved as a result of the rotation of the nucleus as a whole whilst the radial functions for both states can be very similar. Thus, for multiparticle transitions, the estimates given in the table may turn out to be more realistic.

If the mesic atom is initially in the $p^1/_2\,1s$ state, then, as already noted, we have the cascade de-excitation with the ejection of the meson during the first stage and the emission of the γ ray during the second. In the present case, the presence of the meson does not affect the rate of deexcitation of the nucleus because this rate is determined by the rate of the radiative $p^3/_2 - f^7/_2$ transition, the multipole order of which is equal to two, as in the case of the first transition.

If we are to use this model to describe the case where the second channel is closed and the third is open, let us make the arbitrary assumption that $\Delta E^p(p^1/_2 - p^3/_2) = 0.92$ MeV (Fig. 3b). The energy of the nuclear $p^1/_2 - p^3/_2$ transition is then insufficient for the transition of the meson to a state in the continuum, but is sufficient for its excitation to the $2p$ state. Moreover, this energy does not fall into the resonance region. Diagram C_1 then describes the $p^1/_2 - p^3/_2$ proton transition which is accompanied by the virtual excitation of the meson to states in the nd series, the emission of a γ ray with energy $\hbar\omega = E^p(p^1/_2) + E^\mu(1s) - E^p(p^3/_2) - E^\mu(2p)$. This is followed by the dipole $2p-1s$ meson transition. The probability of this process was found to be $P_3 = 1.5 \times 10^{13}$ sec^{-1}. It is clear that this value is greater than the probability of the radiative $p^1/_2 - p^3/_2$ transition and the probability of the radiationless $p^1/_2 - f^7/_2$ transition which is small because of the high value of ΔJ. The subsequent $p^3/_2 - f^7/_2$ transition occurs in a radiationless fashion in a time of 10^{-15} sec, and involves the ejection of the meson.

6. EXPERIMENTAL POSSIBILITIES

The necessary condition in an experimental search for the de-excitation of metastable nuclei during muon capture is that the muon-capture probability of the specially chosen excited nucleus is comparable with or greater than the capture probability for the other (unexcited and impurity) nuclei in the target exposed to the mesons. This clearly shows that the target must contain an enhanced number of excited nuclei. The minimum size of the target must be of the order of or greater than the meson mean free path Λ for nuclear capture (target area $\sim \Lambda^2$, target thickness $\sim \Lambda$). Hence, it follows that the condition for the minimum number of excited nuclei in the target is

$$N_{\min} \geqslant \Lambda^3 n_0, \qquad (14)$$

where n_0 is the density of atoms in the target. If we use preliminary slowing down of the mesons to energies of 0.1–0.3 MeV, their mean free path in the target will be only $\Lambda = 0.1$ cm, so that the necessary number of metastable nuclei for $n_0 = 2 \times 10^{22}$ cm^{-3} turns out to be $N_{\min} \gtrsim 2 \times 10^{19}$. The radioactivity of this speck of excited nuclei (1 mm^3) is $R = N_{\min}/T$, where T is the half-life, so that, when $T = 100$ days, we have $R = 1000$ Ci.

A target containing $N = 10^{19}$ excited nuclei can be produced in a time much less than $T = 100$ days by the methods available in nuclear chemistry,[1,2] but the laser separation of nuclei is particularly convenient.[3] The highly efficient method of selective ionization of atoms in laser and electric fields,[21,22] using a relatively simple laboratory system, makes it possible to achieve complete separation of isomeric nuclei in beams of intensity equal to 10^{18}–10^{19} atom/sec. When the relative concentration of excited nuclei is $f = 10^{-5}$, it is possible to accumulate metastable nuclei at a rate of 10^{13}–10^{14} sec^{-1}. This ensures that the necessary number of excited nuclei can be accumulated in a time of the order of 2–20 days, which is much less than their half-life T.

The detection of a meson ejected during nuclear de-excitation, and the subsequent participation of this meson in the de-excitation of other nuclei, requires the slowing down of the emitted meson to an energy of about 2 keV at which it can be captured by a nucleus. The initial energy of the emitted meson is $E_\mu^0 = \Delta E^p_{N_1 J_1}$. If the initial energy of the meson is a fraction of a MeV, it can be slowed down in a distance of the order of 0.1

cm. In the opposite case, when E_μ^0 is of the order of a few MeV, the size of the target must be much greater.

The maximum number of nuclear deexcitations by a single muon is determined by the ratio of the muon lifetime in the material (in fact, this time is determined by the muon lifetime in the K orbit of the atom) to the time taken to slow it down from the initial energy E_μ^0 to something of the order of 2 keV:

$$P=\tau_{0K}/\tau_{\mathrm{sl}} . \tag{15}$$

For light atoms $\tau_{0K}=2\times10^{-6}$ sec and for heavy atoms $\tau_{0K}=8\times10^{-8}$ sec.[23] The time taken by the meson to descend down the level scheme until it reaches the K state is only 10^{-13} sec[23] and can be neglected. The slowing down time for 0.1–0.2 MeV mesons is $\tau_{\mathrm{sl}}=3\times10^{-12}$ sec, so that, in this case, the number of de-excitations is $P=10^5-10^6$. For mesons with energies of a few MeV, the slowing down time increases to 10^{-10} sec and $P=10^3-10^4$. Thus, the most convenient case is that involving the ionization of the mesic atom with the ejection of a low-energy meson, which will, at least in principle, ensure 10^6 de-excitations per meson from the accelerator.

The rate of de-excitation of nuclei in the target is determined by the meson flux I at the target (in meson/sec) and the multiple de-excitation factor P. When

$$PI>N_{\min}/T \tag{16}$$

the rate of de-excitation of nuclei by the mesons exceeds the rate of natural decay. When $P=10^6$, $T=10^7$, and $N_{\min}=2\times10^{19}$, the necessary muon intensity at the target is $I=2\times10^6$ meson/sec. This is comparable with the intensity that can be produced by the Los Alamos meson factory (8×10^8 mesons per second over a cross section of 200 cm^2).[24]

The requirement of high stability of states ($T^p\approx10^7$ sec) and the simultaneous requirement of high transition energy ($\Delta E^p\gtrsim E_\mu^i\approx Z^2\,2.8$ keV) restrict the region of nuclei for which the above effect is in principle possible. Thus, the approximate formula for the probabilities of electric multipole transitions shows that $P_l<10^{-7}$ for $\Delta E^p\gtrsim E_\mu^i$ in the case of $E4$ transition only for nuclei with $Z\leqslant10$, whereas, for $E5$ and $E6$ transitions, this condition becomes $Z\leqslant20$ and $Z\leqslant30$, respectively. For these nuclei, currently known transitions with the required multipole order have $\Delta E^p<E_\mu^i$ and $\Delta E^p>E_\mu^i$. An example is the 2^5-pole transition in ^{30}Al ($\Delta E=3.2$ MeV $\approx5E_\mu^i$, $T=72$ sec). The relatively high rate of decay is explained in this case by the relatively high transition energy ($P_1\approx\Delta E^{11}$). However, in most cases, the metastable states with high ΔJ decay in cascade, in which the first slow transition has an energy that is insufficient for meson conversion. For example, consider the decay $N_1J_1\to N_2J_2\to N_3J_3$, where $J_1=6$, $J_2=2$, $J_3=0$, $\Delta E(J_1\to J_2)=0.1$ MeV, $\Delta E(J_1\to J_3)=1.5$ MeV. In the absence of the meson, the first transition occurs through electron conversion in a time $T\approx10^7$ sec, and the second is a radiative transition, taking $T\approx10^{-10}$ sec. In the presence of the meson, the main channel is the direct decay $N_1J_1\to N_3J_3$ with meson conversion in a time $T\approx10^{-12}$ sec. Therefore, a target exposed to the mesons may exhibit new low-energy transitions accompanied by meson conversion, and practically any long-lived isomer in which high-energy transitions are in principle possible is suitable for the observation of the effect.

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