Physics – Uspekhi **46** (3) 315 – 324 (2003)

CONFERENCES AND SYMPOSIA PACS number: 01.10.Fv

Joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences and the Joint Physical Society of the Russian Federation (27 November 2002)

A joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) and the Joint Physical Society of the Russian Federation was held on November 27, 2002 in the Conference Hall of the P N Lebedev Physics Institute, RAS.

The following reports were presented at the session.

(1) **E V Tkalya** (D V Skobel'tsyn Research Institute of Nuclear Physics, M V Lomonosov Moscow State University, Moscow) "Properties of the optical transition in the ^{229}Th nucleus";

(2) **A N Sissakian** (Joint Institute for Nuclear Research, Dubna, Moscow Region) "Thermalization phenomenon in hadron physics".

An abridged version of the reports is given below.

PACS numbers: 23.20.Lv, 23.60.+e, 27.90+b, 32.30.Jc
DOI: 10.1070/PU2003v046n03ABEH001379

Properties of the optical transition in the ^{229}Th nucleus

E V Tkalya

1. Introduction

'Nuclear light', or the gamma radiation emitted by an atomic nucleus in the optical range, will probably be discovered experimentally in one or two years. Observing this phenomenon requires not only the object proper, i.e., the atomic nucleus making a transition with optical energy in the excitation spectrum. One also needs certain 'external' conditions to be met, conditions in which the gamma emission in question will be the dominating decay channel. These two necessary factors are highly nontrivial and differ dramatically from the situation that one usually has to deal with in nuclear spectroscopy.

2. The nucleus

In excitation spectra of atomic nuclei, closely spaced energy levels (within several dozen or hundred electron-volts) are not that rare. However, it is practically impossible to observe the radiative transitions between such states because of the very small partial widths of such processes. The only way to observe nuclear light is to find a nucleus with a low-lying (with an energy of several electron-volts) isomeric state. A nucleus of this kind is well-known — it is that of the isotope ^{229}Th.

Uspekhi Fizicheskikh Nauk **173** (3) 323 – 332 (2003)
Translated by E Yankovsky; edited by A Radzig

First indications of the existence of a low-lying (with an energy lower than 100 eV) nuclear state in ^{229}Th were obtained by Kroger and Reich [1] in the mid-1970s. In the fifteen years that followed, the upper bound on the energy of the first excited level was gradually reduced, until at the beginning of the 1990s it became clear that we are dealing with a state with a record-low energy $E_{is} = 3.5 \pm 1.0$ eV [2, 3], whose value corresponds to the ground-state transition in the optical (!) range.

It must be immediately noted that there can be no doubt as to the existence of the given level. It forms the base of the rotational band with the asymptotic quantum numbers $K^{\pi}[Nn_z\Lambda] = 3/2^+[631]$ in the Nilsson model. The other levels relevant to the band are known, the only exception being the first level, with spin $3/2^+$. An independent corroboration of the existence of a low-lying state has been achieved experimentally in the reaction ^{230}Th(d, t)^{229}Th [4], with the upper bound on the level energy being 7 keV.

All possibilities of nuclear spectroscopy methods as applied to the given problem have been exhausted. New ideas of how to search for such an exotic state must be based on a correct understanding of the level's decay channels.

3. Decay channels for the $3/2^+(3.5 \pm 1.0$ eV) level in an atom

The ionization potential of an 'isolated' thorium atom is 6.08 eV. Hence, the excited state $3/2^+(3.5 \pm 1.0$ eV) cannot decay in the atom as a result of gamma-ray internal electron conversion (the second-order process in the electromagnetic coupling constant e in Fig. 1).

What remains is either emission of a real photon by the nucleus (the first-order diagram in Fig. 1) or decay through the atomic shell in third-order perturbation theory (see Fig. 1) [5]. The shell in this case acts as an electron bridge between the nucleus and the photon. Hence the name of the process (the electron bridge).

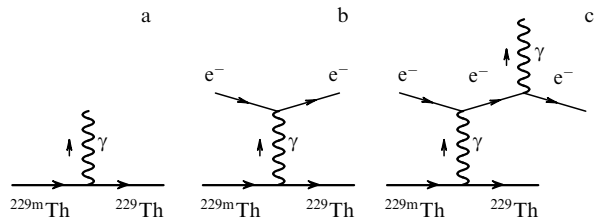

Figure 1. Decay processes of the low-lying state in Th-229: (a) direct nuclear emission; (b) internal electron conversion and conduction electron conversion in the metal, and (c) direct diagram of the decay process in the electron-bridge channel.

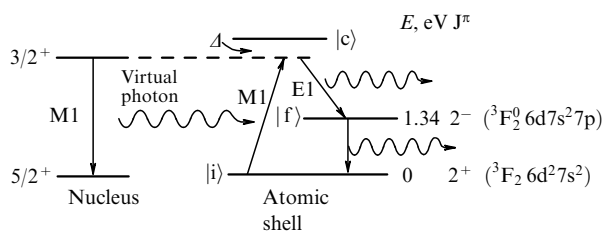

Figure 2. Decay of the low-lying isomeric state of Th-229 via the electron-bridge process.

The density of the excited states of the thorium atom in the 2.5 – 4.5-eV range amounts to 10^2 eV^{-1}. The spins of a larger number of states are known, but the electronic configurations and terms are unknown [6]. There is no way in which we can predict how close in energy the isomeric nuclear state is to one of the excited states and to what state precisely. Hence, all estimates by the decay probability involving the electronic shell in the thorium atom are sure to be order-of-magnitude estimates.

The probability of occurrence of the inelastic electron bridge in Fig. 2 can be written in the single-level approximation as follows

$$W_{\mathrm{EB}} \sim P_{\mathrm{INEET}} \Gamma_{\mathrm{A}}^{\mathrm{rad}}\,, \tag{1}$$

where P_{INEET} is the relative excitation probability of an intermediate atomic level at a nuclear transition (what is known as the inverse NEET process, where NEET stands for nuclear excitation by electronic transition [7, 8]), and $\Gamma_{\mathrm{A}}^{\mathrm{rad}}$ is the radiation width of an atomic transition from the intermediate state to the final state (we use the relativistic system of units in which $\hbar = c = 1$). The relative excitation probability in the nuclear transition can be estimated by the formula

$$P_{\mathrm{INEET}} \sim \frac{E_{\mathrm{int}}^2}{\Delta^2}\,, \tag{2}$$

where Δ is the difference in the transition energies (see Fig. 2), and the interaction energy of the nuclear, $J_{\mathrm{N}}^{\nu}(\mathbf{r}_{\mathrm{N}})$, and electron, $j_{\mathrm{e}}^{\mu}(\mathbf{r}_{\mathrm{e}})$, currents in the second-order QED perturbation theory is given by

$$E_{\mathrm{int}} \sim \int \mathrm{d}^3 r_{\mathrm{e}}\, \mathrm{d}^3 r_{\mathrm{N}}\, j_{\mathrm{e}}^{\mu}(\mathbf{r}_{\mathrm{e}})\, D_{\mu\nu}(\mathbf{r}_{\mathrm{e}} - \mathbf{r}_{\mathrm{N}})\, J_{\mathrm{N}}^{\nu}(\mathbf{r}_{\mathrm{N}})\,, \tag{3}$$

with $D_{\mu\nu}(\mathbf{r}_{\mathrm{e}} - \mathbf{r}_{\mathrm{N}})$ being the photon propagator.

We take the value of the nuclear reduced transition probability, which will be needed for numerical calculations, from paper [9], where it was found that with allowance made for Coriolis mixing of the rotational bands $B_{\mathrm{W.u.}}(\mathrm{M1}; 3/2^+ \to 5/2^+) = 4.8 \times 10^{-2}$, with W.u. denoting the Weisskopf units. In this case, the characteristic interaction energy E_{int} amounts to roughly $10^{-5} - 10^{-6}$ eV. A typical width of the atomic radiative transition is $\Gamma_{\Delta}^{\mathrm{rad}} \sim 10^{-8}$ eV. Hence, if for Δ we take a value equal to the reciprocal average density of atomic levels, viz. 10^{-2} eV, then for the decay probability of the low-lying isomeric state of thorium via the electron-bridge channel, we have $W_{\mathrm{EB}} \sim 10^{-1} - 10\ \mathrm{s}^{-1}$. At the same time, the probability of direct nuclear emission, calculated by the ordinary formula

$$\Gamma_{\mathrm{N}}^{\mathrm{rad}}(L;\omega) = \frac{8\pi}{\left[(2L+1)!!\right]^2}\,\frac{L+1}{L}\,\omega^{2L+1} B(L), \tag{4}$$

does not exceed $2 \times 10^{-4}\ \mathrm{s}^{-1}$ for gamma radiation in a vacuum [10]. Thus, there is indeed a finite probability of observing the decay of the isomeric nuclear state $3/2^+(3.5 \pm 1.0$ eV) through the extremely exotic electron-bridge channel. In the experiment we will have two photons: the first is emitted directly via the inelastic electron bridge, and the successive one in the relaxation of the atomic shell. The electronic states depicted in Fig. 2 are candidates for participation in the process described.

We are coming to the end of our description of the decay of an isomeric state in an isolated atom. The last question is: Why may higher-order processes in e dominate over the first-order process or direct nuclear emission? Note that this situation is standard for nuclear spectroscopy in the low-energy range (up to 10 keV). Even in electric dipole nuclear transitions, the internal electron conversion is the dominating decay channel for nuclear levels with energies of several kiloelectron-volts and lower. The reason is simple. The multipole expansion of the photon propagator

$$D_{\mu\nu}(\mathbf{r}_{\mathrm{e}} - \mathbf{r}_{\mathrm{N}}) = g_{\mu\nu} \exp \frac{\left(\mathrm{i}\omega|\mathbf{r}_{\mathrm{e}} - \mathbf{r}_{\mathrm{N}}|\right)}{|\mathbf{r}_{\mathrm{e}} - \mathbf{r}_{\mathrm{N}}|} \sim \omega \sum_{LM} \ldots h_L^{(1)}(r_{\mathrm{e}}\omega) \ldots j_L(r_{\mathrm{N}}\omega)$$

contains Hankel functions $h_L^{(1)}(r_{\mathrm{e}}\omega)$ of the first kind of the electron variable. During the processes of the interaction between the nucleus and the atomic shell, at least one of the electronic states is a bound state localized at distances smaller than the Bohr radius. This is the scale over which effective integration in the process amplitude is performed. Notice that the transition energy is also low. As a result, the argument of a Hankel function always meets the condition $r_{\mathrm{e}}\omega \ll 1$, and the function itself becomes very large, since near zero it has the form

$$h_L^{(1)}(r_{\mathrm{e}}\omega) \sim \frac{-\mathrm{i}(2L-1)!!}{(r_{\mathrm{e}}\omega)^{L+1}} \gg 1\,.$$

This balances the smallness introduced by the extraneous electron – photon vertex into the amplitude and, hence, the probability or cross section of the process.

In concluding this section we note that thorium is a chemically active element and easily oxidizes. Special measures are needed to save its valence shells from chemical bonds. A well-known and highly developed way to do this is to freeze in thorium atoms to an inert-gas matrix that is transparent in the optical range. There are also other ways. And for this reason the process we have just described can be implemented experimentally.

4. Decay channels for the $3/2^+(3.5 \pm 1.0$ eV) level in a condensed medium

The stage of optical measurements from 1997 to 1999 [12 – 16] showed how complicated it is to observe an isomeric transition. The experiments conducted by Irwin and Kim [12], Richardson et al. [13], Utter et al. [14], and Shaw et al. [15] were relatively similar. In the alpha decay of the ^{233}U nucleus, the low-lying level $3/2^+(3.5 \pm 1.0$ eV) in ^{229}Th becomes populated with a probability of about 2%. With a sample containing 100 mg of ^{233}U, we can expect about 7×10^5 isomeric decays of the $3/2^+(3.5 \pm 1.0$ eV) state of ^{229}Th to occur every second. Such an activity is sufficient for optical measurements to produce results.

In all the experimental work that we have just mentioned, the researchers dealt not with atomic thorium but with one of

its chemical compounds. In due course it became clear that all, or almost all, of the detected optical radiation could be attributed with a high degree of probability to the luminescence of various chemical compounds, initiated by the bombardment of alpha particles [14–16, 11]. Therefore, it is advisable to examine the decay of the low-lying isomeric state in matter more thoroughly.

Decay in metal. Let us examine an experiment in which a thin layer of an active substance containing one of the chemical compounds with ^{233}U is deposited on a substrate. Upon alpha decay of ^{233}U, the daughter ^{229}Th nuclei, among which, the reader will recall, 2% are in the isomeric state $3/2^+(3.5 \pm 1.0$ eV), may be ejected into the vacuum and decay on the walls of the chamber (usually outside the field of vision of the optical system); they could also slow down and decay in the substrate or in the material of the target proper. The last two cases are the most interesting ones.

If the target layer is thin enough, for instance, it comes out to 30–40 Å, as was probably the case in the experiment of Utter et al. [14], most of the thorium atoms are slowed down in the substrate material, for which noble metals such as gold and platinum are usually used. Upon alpha decay of ^{233}U, the recoil nucleus ^{299}Th acquires an energy of about 100 keV. According to Ref. [17], the range of such nuclei in metals amounts to several dozen atomic layers (about 200 Å). A metal of such a thickness is practically transparent to visible light and is not an obstacle for detecting the photons generated in the decay of the low-lying isomer ^{229m}Th. At the same time, there is another possible decay channel in a metal, a channel corresponding to the second-order diagram in Fig. 1 — deexcitation of the isomer via conduction electrons. This process is similar to inelastic electron scattering by nuclei. The process has no energy threshold in the metal, since the nucleus gives off energy in this case. (Isomer decay in the metal can also be interpreted as conduction electron conversion. But in contrast to conventional internal inversion, here the initial state of the electron is not a bound atomic state.)

To make a qualitative estimate of the decay probability of ^{229m}Th$(3/2^+, 3.5 \pm 1.0$ eV) in what is known as a standard metal [18], we use the simplest free-electron approximation [19] (in this model, the conduction electrons are interpreted as a gas of free particles). The decay probability is calculated by the formula

$$W \sim n_e \, v_e \, \sigma_{e,e'} ,$$

where n_e is the conduction electron number density, v_e is the electron velocity, and $\sigma_{e,e'}$ is the cross section of the process.

Suppose that the energy of the initial electron state is $E_i \approx \mathcal{E}_F$, where $\mathcal{E}_F$ is the Fermi energy. Accordingly, the electron velocity is equal to the Fermi velocity: $v_e \sim v_F = \sqrt{2\mathcal{E}_F/m}$. As a result of inelastic scattering by the isomeric nuclei ^{229m}Th, the conduction electrons acquire additional energy $\omega_N = 3.5 \pm 1.0$ eV. If the work function of the electrons in the metal is smaller than ω_N, they remain in the metal after scattering from the nuclei.

An estimate of the inelastic scattering cross section was made in Ref. [20], and it was found that $\sigma_{e,e'} \sim 10^{-27}$ cm^2. Then using the values of $n_e \approx 6 \times 10^{22}$ cm^{-3} and $\mathcal{E}_F \approx 5.5$ eV from Ref. [18], we arrive at the probability $W \sim 10^4$ s^{-1}, i.e., the lifetime of the thorium isomer in the metal is roughly 10^{-4} s.

This probability is much higher than the estimate of 10^{-1}–10 s^{-1} for the decay probability of the low-lying level of the ^{229}Th nucleus through the electron-bridge channel. Hence, the conversion involving conduction electrons may indeed be the dominating decay channel of the $3/2^+(3.5 \pm 1.0$ eV) state in the metal.

It is interesting to note that if for the substrate we use a felicitously selected semimetal in which the conduction electron number density is lower by two to three orders of magnitude than that in platinum, the probability of emission of optical photons becomes appreciable.

Decay of recoil nuclei in the semiconductor $^{233}UO_2$. Especially interesting is the problem of decaying the low-lying isomer ^{229m}Th that forms as a result of alpha decay of ^{233}U in the material of the target proper, i.e., in the semiconductor $^{233}UO_2$. Such a situation emerges for a large number of recoil ^{229}Th nuclei if the target thickness exceeds the free path of the recoil nuclei. The semiconductor $^{233}UO_2$ has an energy gap width of 2.8 eV [21]. As a result of alpha decay of ^{233}U, an excited ^{229}Th nucleus may at the end of its range occupy an interstitial position in the lattice or take the place of one of the uranium atoms, knocking it out of its position in the crystal. In the latter case, the uranium atom finds itself in an interstitial position.

In all these variants, the initial band structure of the semiconductor $^{233}UO_2$ undergoes a perturbation. As a result, additional levels appear in the forbidden band, and these levels may play an important role in the decay of the thorium isomer. The nuclear transition energy is sufficiently high for an electron to be moved from the valence band to the conduction band. Next, the new levels participate either in radiationless relaxation of energy (into phonons) or in emission of radiation in the IR range. It is quite possible that there is no emission of radiation in the visible range, accompanying the decay of the thorium isomer in the semiconducting crystal $^{233}UO_2$.

Decay in the insulator $^{229}ThO_2$. Thorium dioxide is a common, well-studied chemical compound. It is an insulator with an energy gap width of 6 eV and a refractive index $n \simeq 2$ for 3.1-eV photons [22]. Conversion of the nuclear transition that would involve electrons from the valence band is impossible: there is simply not enough energy to move an electron to the conduction band.

In principle, an electron-bridge process is possible here. However, the forbidden band of an ideal insulator (such an insulator is considered here) contains no electronic states. Hence, in the decay of the low-lying nuclear isomeric state through the electron-bridge channel in $^{229}ThO_2$, states of the continuous spectrum from the conduction band act as intermediate states. The mismatch between the energies of the nuclear and electronic transitions in this case exceeds 1 eV. Moreover, there can be only an elastic electron bridge, i.e., magnetic dipole (M1) radiation in the 'second' electronic transition from the intermediate state to the final state in Fig. 2. The probability of occurrence of such an electron bridge is negligible [5].

As a result, the main decay channel for the low-lying level $3/2^+(3.5 \pm 1.0$ eV) in $^{229}ThO_2$ may be the direct nuclear emission in the optical range, i.e., 'nuclear light'. The decay probability of an isolated nucleus in a vacuum can be calculated by formula (4). Without allowance for the effect of the medium, one finds $T_{1/2} = \ln 2/W_\gamma \simeq 80$ min–8 h in the energy range $\omega = 4.5$–2.5 eV.

To account for the effect of the dielectric medium, we write down the formula for the probability of emission of

magnetic dipole radiation as follows

$$W_{\mathrm{m}}^{\mathrm{M1}} = 2\pi \left| \langle | \hat{\boldsymbol{\mu}} \cdot \hat{\mathbf{H}}_{\mathrm{m}}^{+} | \rangle \right|^2 \rho_{\mathrm{m}}(\omega). \tag{5}$$

Here, $\hat{\boldsymbol{\mu}}$ is the operator of the magnetic dipole moment of the radiating system, and $\hat{\mathbf{H}}_{\mathrm{m}}^{+}$ is the operator of the magnetic field in the medium. Usually, the interaction Hamiltonian is written in terms of the local-field operator. In our case of a nonmagnetic insulator, the local and mean magnetic fields coincide. Moreover, the dielectric medium does not renormalize the magnetic component of the field with respect to the magnetic field in a vacuum. Hence, the entire difference between the probabilities of magnetic dipole transitions in the medium and in the vacuum is determined by the renormalization of the phase volume. In the medium one has $\mathbf{k}^2 = \epsilon\omega^2$, where ϵ is the dielectric constant. Therefore, the value of $k^2\,\mathrm{d}k/\mathrm{d}\omega$ increases in the medium by a factor of $\epsilon^{3/2}$, i.e., n^3 times [10]. Thus, in the medium the probability of an M1 radiative transition increases n^3-fold. Accordingly, the most probable lifetime of the $3/2^+(3.5 \pm 1.0$ eV) state in $^{229}ThO_2$ is within the 10-min – 1-h range [10]. (We must make a reservation here that this estimate has been given on the assumption that $n \simeq 2$ not only at $\omega = 3.1$ eV, as in Ref. [22], but also in the entire energy range from 2.5 to 4.5 eV. The numerical result can be corrected somewhat depending on the real value of n.)

It is extremely complicated to verify the effect of an infinite dielectric medium on the radiative process in the atom. In this sense, the example of the decay of the $3/2^+(3.5 \pm 1.0$ eV) level in $^{229}ThO_2$ may be useful for experimental studies.

Alpha decay of the $3/2^+(3.5 \pm 1.0$ eV) level

The general regularities of another possible decay channel for the first excited level of Th-229, namely the alpha decay, have been studied in Ref. [23].

The ground state of the ^{229}Th nucleus forms the base of the rotational band $5/2^+[633]$ and decays with a period $T_{1/2}^{\mathrm{gr}}(\alpha) = 7880$ a preferably to levels of a similar band in the daughter nucleus ^{225}Ra. An analysis of the spectrum of the excited states of the ^{225}Ra nucleus suggests that the low-lying isomeric level of Th-229 has a much shorter lifetime $T_{1/2}^{\mathrm{is}}(\alpha)$ with respect to α-decay than that of the ground state. Indeed, in the daughter nucleus ^{225}Ra, the level $3/2^+3/2[631]$ (149.96 keV), which has the same quantum numbers as the isomeric ($|\,\mathrm{is}\rangle$) state $^{229\mathrm{m}}\mathrm{Th}(3/2^+, 3.5$ eV), resides 86.3 keV below the level $5/2^+5/2[633]$(236.25 keV), at which the transitions preferably end up in the decay of the ground state of ^{229}Th. High-energy alpha particles pass more easily through the Coulomb barrier of the nucleus. The transition $|\,\mathrm{is}\rangle \to 3/2^+3/2[631]$(149.96 keV) is a favored transition, as is the transition $|\mathrm{gr}\rangle \to 5/2^+5/2[633]$(236.25 keV). The hindrance factors (HF) for favored alpha transitions usually range from 1 to 4. Systematization of the data on reduced alpha-decay widths of odd isotopes of Rn, Ra, Th, Pu, U, and Cm has shown that, for transitions to states with the same quantum numbers as those of the ground states of the decaying nuclei, the reduced α-widths are practically identical with those for the U and Cm isotopes where no changes in nuclear deformation occur, as well as for the isotopes of Th and Ra, where the deformation parameter decreases somewhat in the course of α-decay. Among the nuclei with $A \geqslant 221$, in which the ground state possesses the quantum numbers $3/2^+3/2[631]$, there are four that undergo alpha decay: ^{225}Th, ^{229}U, ^{223}Ra, and ^{227}U. The hindrance factors for favored α-transitions are known for the first two nuclei: HF = 2.2 for ^{225}Th, and HF = 1.7 for ^{229}U. Bearing all this in mind, we can take HF ≈ 2 as the most probable value of the hindrance factor for the alpha transition $|\,\mathrm{is}\rangle \to 3/2^+3/2[631]$ (149.96 keV).

The calculations done in Ref. [23] show that the partial penetration probability of the potential barrier for an alpha particle with an energy $E_\alpha = 4930$ keV and an angular momentum $L = 0$ in the $|\,\mathrm{is}\rangle \to 3/2^+3/2[631]$(149.96 keV) transition is higher by a factor of 3.7 than that in the $|\mathrm{gr}\rangle \to 5/2^+5/2[633]$(236.25 keV) transition.

For other transitions from the isomeric state to the $3/2^+[631]$ band, the approximate values of the hindrance factors can also be extracted from the data on alpha decays of ^{225}Th and ^{229}U. Here, the error in calculating $T_{1/2}^{\mathrm{is}}(\alpha)$ will be relatively moderate, since all the levels of the band in question in the ^{225}Ra nucleus are located above the base level and are populated with a lower probability due to the larger height of the potential barrier. Similar estimates have been made for the states of other rotational bands.

A numerical calculation of the alpha decay constant $\lambda_{\mathrm{is}}^{\alpha}$ for the isomer $^{229\mathrm{m}}\mathrm{Th}(3/2^+, 3.5$ eV) with hindrance factors varying within the established limits has yielded the following range of values: $2 \leqslant \lambda_{\mathrm{is}}^{\alpha}/\lambda_{\mathrm{gr}}^{\alpha} \leqslant 4$, where $\lambda_{\mathrm{gr}}^{\alpha}$ is the alpha decay constant for the ground state of Th-229 [23]. The spectrum of the alpha radiation emitted upon transition from the isomeric state is more hard than the decay spectrum for the ground state [23]. We also note the presence of a small, at a level of about 1 – 2%, admixture of isomeric $^{229\mathrm{m}}\mathrm{Th}(3/2^+, 3.5$ eV) nuclei, which can be determined by measuring the 4930-keV line in the alpha spectrum.

Note one more result that is important for the problem under discussion. There are indications [24] that the 101.7-keV energy level possesses the quantum numbers $3/2^+3/2[631]$ (rather than the 149.96-keV level, as is assumed today) in the spectrum of ^{225}Ra. If this is the case, the alpha decay constant of the $3/2^+(3.5 \pm 1.0$ eV) state increases severalfold and becomes larger than the alpha decay constant for the ground level of Th-229 by a factor of 8 to 10.

6. Excitation of the $3/2^+(3.5 \pm 1.0$ eV) level

Experiment with synchrotron radiation. The most consistent way of determining the energy of the low-lying isomeric state in Th-229 is represented as follows. The target made of the insulator $^{229}ThO_2$ is irradiated with a beam of synchrotron radiation consisting of 29.19-keV photons. The ^{229}Th nucleus has a level $5/2^+(29.19$ keV) belonging to the same rotational band as the low-lying state $3/2^+(3.5 \pm 1.0$ eV). The width of the radiative transition from the ground state to the $5/2^+(29.19$ keV) state is well known ($\simeq 5.6 \times 10^{-9}$ eV) [11], which makes it possible to calculate the excitation cross section. What is also known is the branching factor ($\simeq 0.8$) for the transition from the $5/2^+(29.19$ keV) level to the sought-for low-lying state $3/2^+(3.5 \pm 1.0$ eV). Calculations show that with a beam of synchrotron radiation from the Argonne National Laboratory (Argonne, IL), in a target containing 10 mg of ^{229}Th, approximately 10^7 isomeric nuclei $^{229\mathrm{m}}\mathrm{Th}(3/2^+, 3.5 \pm 1.0$ eV) will form every second within the standard geometry of the experiment. This is a sufficiently large quantity to be able to measure the energy of the optical photons produced in the decay of the isomer in the dielectric medium.

Excitation by laser light. After the wavelength of the nuclear transition is measured by the method we have just described, we can excite a large number of ^{229}Th nuclei to the isomeric state by applying laser radiation tuned to the respective wavelength. The cross section of this process can be estimated easily from the formula

$$\sigma_{\gamma}^{(1)} = \frac{\lambda_{\mathrm{N}}^2}{2\pi} \frac{\Gamma_{\mathrm{N}}^{\mathrm{rad}}(\omega_{\mathrm{N}}; \mathrm{gr} \to \mathrm{is})}{\Delta\omega_{\mathrm{L}}}, \tag{6}$$

where the width of the radiative transition from the ground state to the low-lying state is $\Gamma_{\mathrm{N}}^{\mathrm{rad}}(\omega_{\mathrm{N}}; \mathrm{gr} \to \mathrm{is}) \simeq 10^{-20}$ eV [11], and $\Delta\omega_{\mathrm{L}}$ is the width of the laser line. For a laser with a characteristic line width $\Delta\omega_{\mathrm{L}}/\omega_{\mathrm{L}} \sim 10^{-6}$, the excitation cross section amounts to 10^{-25} cm^2 [11].

In a target containing 10 mg of ^{229}Th, a 1-W laser with a relative line width $\Delta\omega_L/\omega_L \sim 10^{-6}$ will excite every second over an area of 0.1 cm by 0.1 cm from 10^{13} to 10^{14} ^{229}Th nuclei to the low-lying state $3/2^+(3.5 \pm 1.0$ eV).

This method of excitation is not the optimal one. The inverse electron bridge [25, 8, 26] depicted in Fig. 3 has in the single-level approximation the cross section

$$\sigma_{\mathrm{IEB}}^{(3)} \sim \frac{\lambda_{\mathrm{L}}^2}{2\pi} \frac{\Gamma_{\mathrm{A}}^{\mathrm{rad}}(\omega_{\mathrm{L}}; \mathrm{i} \to \mathrm{c})}{\Delta\omega_{\mathrm{L}}} P_{\mathrm{NEET}}, \tag{7}$$

where $P_{\mathrm{NEET}} \simeq E_{\mathrm{int}}^2/\Delta^2$ is the relative excitation probability of the nucleus in the atomic transition, and $\Gamma_{\mathrm{A}}^{\mathrm{rad}}(\omega_{\mathrm{L}}; \mathrm{i} \to \mathrm{c})$ is the width of the atomic radiative transition from the ground state to the intermediate state at the lasing frequency. With the same values of the parameters as in the estimation of the nuclear decay probability through the electron-bridge channel, we get for the cross section $\sigma_{\mathrm{IEB}}^{(3)} \sim 10^{-19} - 10^{-21}$ cm^2. Accordingly, the excitation rate is such here that the population inversion is possible in the target, and it is also possible to observe the accelerated alpha decay of Th-229 nuclei and other interesting phenomena.

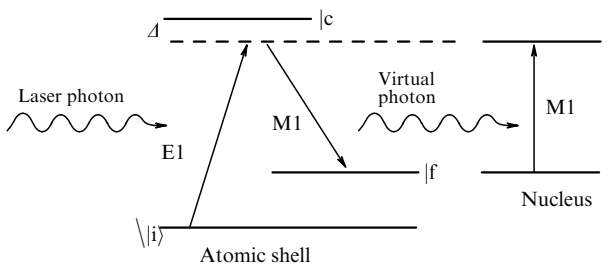

Figure 3. Layout of the excitation of the low-lying isomeric state in Th-229 by photons in the inverse electron-bridge process.

The reasons for such large cross sections compared to those of direct photoexcitation are obvious: (a) multipole exchange which allows excitation of the atom in an E1 transition and of the nucleus in the NEET process already in an M1 transition, and (b) the earlier discussed properties of the photon propagator at small energies and in the presence of bound electronic states. One must bear in mind that the scheme works only if certain conditions are met, namely, the energy of the nuclear isomeric level is close to the energy of a relatively strong atomic M1 transition, and the intermediate and ground atomic states are linked by a strong E1 transition. Favorable conditions of this type may not occur, however.

7. Conclusions

Th-229 found in a state with an energy of 3.5 ± 1.0 eV, which is quite unusual for nuclei, could become the object of exciting investigations at the junction of far-apart areas of physics. Some of the possibilities are listed below.

(1) A probe for studying the chemical environment and the properties of condensed media and surfaces. Such a research is being conducted with $^{235\mathrm{m}}\mathrm{U}(1/2^+, 76.8$ eV) nuclei. Compared to the uranium nucleus, thorium has a number of advantages. The main advantages are (i) that the decay involves valence electrons which are most sensitive to the chemical environment, and (ii) that there is the opportunity of multiple excitation of the implanted nucleus and repeated measurements.

(2) Creation of population inversion in a system of nuclei via highly effective laser excitation. The acceleration of alpha decay of Th-229 through the excitation of the state $3/2^+(3.5 \pm 1.0$ eV) by applying low-intensity laser radiation.

(3) Excitation of the nuclear isomer by surface plasmons [27]. By 'concentrating' surface electromagnetic waves within a thin layer it is possible to increase the energy flux density by several orders of magnitude. The small track length of plasmons with energies in the 2.5–4.5-eV range is a negative factor, however. As a result, the given method of excitation may increase the gain by a factor of 10 to 100 in comparison to laser excitation.

(4) 'Nuclear light' is produced by the direct nuclear emission of radiation in the optical range in the insulator $^{229}\mathrm{ThO}_2$. A test of the chance of increasing the probability of nuclear decay in a dielectric medium by a factor of n^3 in comparison to the probabilities of decay in vacuum. The possibility of studying the properties of a cavity. A highly stable nuclear source of light for metrology.

(5) A verification of the exponential nature of the law of decay of an isolated metastable state in large time intervals. So far only five such experiments have been carried out, including the first measurements done by E Rutherford in 1911, when the exponential behavior of the law was followed up to $27T_{1/2}$. Today, the law has been verified up to $45T_{1/2}$. The combination of highly effective laser excitation of the low-lying isomeric state in Th-229 with an optimal collection of optical photons will make it possible to relatively easily pass the barrier of $50T_{1/2}$ [28]. It must be noted, however, that such experiments are extremely complicated and require the utilization of the most advanced technologies on hand. In this sense they reflect the general level of scientific and technical progress.

(6) The moderation of gamma decay of the low-lying nuclear level in the dielectric matrix $^{229}\mathrm{ThO}_2$ placed inside a spherical cavity with reflecting walls, between mirrors, etc. For the first time, the possibility has emerged of carrying out well-known experiments in atomic physics using a nuclear transition.

(7) Laser cooling of the crystal $^{229}\mathrm{ThO}_2$. Impurity introduction can separate the excitation and decay channels for a nuclear level. Also, a highly intensive narrow laser line can be used to directly excite the nucleus within the transparency window of the crystal and at the same time to ensure a rapid decay of the nuclear level through impurity states in a process similar to the electron bridge.

I am very grateful to A M Dykhne, S M Nikitin, V D Ozrin, and M V Subbotin for their useful remarks and the interest shown in discussions of many problems mentioned in this report. Partial support of the present work was provided by

the Russian Foundation for Basic Research (grant No. 01-02-16199).

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PACS numbers: **12.38.–t**, 12.40.Ee, 13.85.Hd

DOI: 10.1070/PU2003v046n03ABEH001380

Thermalization phenomenon in hadron physics

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1. Introduction

This report describes nonequilibrium processes using the example of multiple hadron production in which the attainment of the thermodynamic equilibrium is brought about by dissipation of the kinetic energy of the colliding particles into the hadron masses. The dynamic peculiarities of these processes are limited by the need to take into account the constraints responsible for the 'nonescape' of color charge, so that, generally speaking, the formation of a thermalized state is a fairly rare event. The necessary and sufficient condition for a meaningful description of such processes has been found. By its very meaning this condition is similar to the 'correlations depression' condition which, according to N Bogolyubov, comes into play as an equilibrium state is approached by the system. Physically, such a situation occurs in highly multiple production processes. The first experimental indications of the possibility of observing thermalization phenomena are given.

A thermodynamic description is appealing chiefly because it admits a complete description of a complex system with the use of a limited number of parameters. These are usually temperature, pressure, specific volume, and chemical potential. Otherwise, when a thermodynamic description is impossible (say, when the system is highly nonequilibrium), one must know $3n-4$ independent parameters in order to completely specify an n-particle distribution function.

Strictly speaking, the concept of temperature, namely the main thermodynamic parameter, is admissible only for systems (possibly, subsystems) that are in thermodynamic equilibrium, for which a homogeneous energy distribution over all the degrees of freedom is a characteristic feature. Here, the homogeneity of the energy distribution must be maintained with exponential accuracy, while the fluctuations in the neighborhood of the respective average energy (temperature) must be Gaussian. In other words, for example, the energy spectra of the particles must correspond to a Boltzmann – Gibbs distribution, while temperature fluctuations must correspond to a Gaussian distribution. Then the temperature may be considered as a 'good' parameter.

It can be stated that if a system has such a good parameter, it is in energy equilibrium in the sense that there are no macroscopic energy fluxes in it. Such a system is said to be thermalized. A detailed discussion of this problem can be found in Ref. [1].

Thus, if one uses the concept of temperature, the system is in thermal equilibrium, with the result that it is enough to know the average energy of the particles to describe it. One must bear in mind, however, that in general the system may be out of equilibrium with respect to other parameters.

Conditions of complete thermalization are not often encountered in nature. For instance, the thermodynamic description cannot generally be applied to describing biological systems, although it is known that the temperature of a biological system may be a good parameter. Thermodynamic description has limited application also in subatomic physics, while on the molecular level examples of such descriptions abound.

What then obstructs thermalization of a multiparticle system? This question may be examined fairly rigidly within the proposed S-matrix interpretation of thermodynamics (see the literature cited in Ref. [1]). For instance, in addition to ordinary kinetics, internal constraints, as a result of which not all degrees of freedom have equal status, may obstruct thermalization. In some cases, the nature of these constraints may lie hidden in the symmetry of the action or Hamiltonian. It is this situation that is realized in hadronic physics.

Distribution functions. N N Bogolyubov was the first to pose the question of how many measurable, or what is called 'partial', distribution functions are really needed to describe multiparticle systems (see the monograph [2]). Precisely, he noticed that to examine all the quantities that