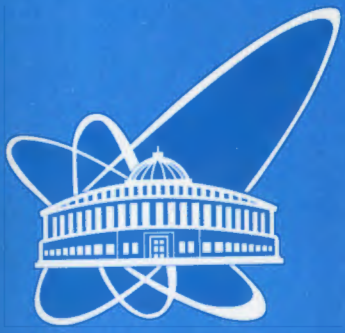

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POSSIBLE WAYS FOR TRIGGERING THE ^{179m2}Hf ISOMER

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1. Introduction

The idea to observe the induced decay of a nuclear level has been known in the literature for more than 50 years, and the application of such a process to the creation of the gamma-ray laser has also been proposed. In photon-induced nuclear reactions using bremsstrahlung sources, the population and induced de-population of nuclear isomeric states were conclusively observed. Astrophysical science employed this knowledge for the evaluation of the production and burn-up of some special nuclear states in stellar conditions. This effect strongly influences the cycles of isotope production in stars and, finally, their observed abundances. Refs. [1-3] provide a good orientation to this topic.

Another branch of applications relies on the creation of pulsed γ-ray sources and, in the extreme, of a γ-ray laser. Most experiments along this line have been performed on the long-lived ^{180m}Ta and ^{178m2}Hf isomers and these remain of considerable importance. The bremsstrahlung from medical units, and recently synchrotron radiation, have been used for these experiments. The general problem of x-ray driven gamma emission is reviewed in Ref. [4].

The probability of induced de-population of an isomeric level strongly depends on the intrinsic microscopic structure of the participating nuclear states. In deformed nuclei are found the well-known K isomers that are formed due to the partial conservation of the K quantum number. The importance of K conservation and the possibilities for K-mixing were discussed, for instance, in Refs. [5,6]. The ^{178m2}Hf isomer is considered to be the mostly promising K-isomer because of its high excitation energy, about 2.45 MeV. The specific energy stored in the form of nuclear excitation is highest for ^{178m2}Hf in comparison with other isomers. In addition, one may expect the presence of some level with K-mixed wavefunction not far above the isomeric state because the K-mixing amplitude generally grows strongly with the excitation energy [7,8]. Based on this expectation, experiments on triggering of ^{178m2}Hf have been developed extensively during the last few years. In principle, however, it was clear even earlier that other isomers can also be attractive for a triggered release of "clean" nuclear energy. Previously, we and other authors have listed long-lived isomers that may be potentially useful for investigation, but detailed analysis only began in 2000.

In Ref. [9], the properties of ^{177m}Lu and ^{242m}Am isomers were discussed based on nuclear spectroscopic and nuclear reaction data. Their advantages for triggering experiments were concluded because of the favorable position of a triggering level, appropriate decay properties and effective production possibilities. Recently, the description a technical project for the creation of ^{177m}Lu isomeric targets has been appeared in the literature [10], meaning that some steps for isomer applications are in progress.

An additional proposal on a way to use individual excited sates of definite nuclides for pumping or triggering was presented in Refs. [11-13] and concrete properties of some states were analyzed. New ideas of the hybridization of the atomic-nuclear excitation, of possible suppression of the Auger conversion in highly ionized plasma and of possible nuclear fluorescence past restoration of a solid lattice were also given in Refs. [11-13]. Another group of nuclear states was described in Ref. [14], in which numerical estimations of triggering cross-sections via photon absorption, NEET and Coulomb excitation mechanisms were obtained in a classical manner. Unfortunately, the resulting values were extremely low, eliminating optimistic expectations for real experiments. The Coulomb excitation approach to pumping was introduced in Ref. [15], and at that time it was already clear that a reasonably high rate of nuclear level pumping can be achieved only for the electromagnetic transitions of collective nature when the reduced probability is enhanced by a factor of 100 above the standard Weisskopf strength. Therefore, it was not unexpected that the calculations of Ref. [14] predicted very low probabilities for strongly hindered transitions. New mechanisms should be sought to enhance the possibilities of triggering.

In the present article, we will stress the properties of the ^{179m2}Hf isomer as a candidate for triggering experiments. This high-spin ($25/2^-$) K isomer has a reasonably long half-life ($T_{1/2}$ = 25.1 d) and a rather high excitation energy of 1,106 keV, corresponding to the accumulation of about 0.5 MJ/mg specific energy. Being triggered, this nuclide would emit a series of photons in the ultrashort wave band of γ rays of 200 to 300 keV. New possibilities for triggering experiments will be described. In particular, triggering may be strongly realized in plasma surroundings within an electron cyclotron resonance ion trap.

2. Production of ^{179m2}Hf

The high-spin and high-K isomer in ^{179}Hf was discovered 30 years ago [16], using the producing reaction of ^{176}Yb(^{4}He, n)^{179m2}Hf. The quantity of isomer produced was sufficient for its identification, spectroscopic studies and decay scheme construction. But the absolute yield of isomeric nuclei was not reported. Later, within a program of irradiations for accumulation of ^{178m2}Hf in a similar reaction, ^{176}Yb(^{4}He, 2n), the ^{179m2}Hf isomer was also detected and its absolute yield and excitation function were measured [17]. It was clear that ^{179m2}Hf was produced with a cross-section that was much lower (by a factor of about 20) compared to ^{178m2}Hf. This means a possible accumulation of only about 10^{13} atoms of ^{179m2}Hf after a one-month irradiation with a high-current cyclotron using a 30-MeV ^{4}He-ion beam. Such a quantity restricts the possibilities for practical applications, as well as the majority of experiments using ^{179m2}Hf as a target.

Recently, production of the ^{179m2}Hf isomer has been successfully observed [18] in the spallation of Ta to Re targets with intermediate energy protons in the range of 200 - 660 MeV. Its yield is even a little higher than the yield of ^{178m2}Hf. As is known, many current trigger experiments with ^{178m2}Hf targets use material produced in the spallation reaction at the Los Alamos 800-MeV high-current proton-beam facility. But this production method can not be used for ^{179m2}Hf because of its 25.1-d half-life. The massive irradiated targets at Los Alamos were kept for cooling during (10 – 20) years before processing because of their extremely high activities. The ^{179m2}Hf nuclide would be decayed completely after such long cooling, while such a period makes little impact on the quantity of ^{178m2}Hf ($T_{1/2}$ = 31 years). Thus, until 2003 an effective method for ^{179m2}Hf target preparation was unknown.

An irradiation of a hafnium metal target of natural isotopic composition was arranged [19] in the Dubna IBR-2 reactor. The yield of ^{179m2}Hf was reliably detected by γ-spectrum

measurements after activation of the target. It was shown that ^{179m2}Hf can be stored in an amount above 10^{16} atoms after irradiation in standard reactors as the result of the ^{179}Hf(n, n'γ)^{179m2}Hf reaction with fast neutrons of the fission spectrum. If a purified highly-enriched ^{179}Hf target is used in reactor irradiations, one may expect the production of a rather clean activity of ^{179m2}Hf. The number of atoms produced should be enough for many experiments with this isomeric material, but for some types of studies the presence of stable ^{179g}Hf nuclei in much larger amounts may create a significant background. Prior to such experiments, methods for separation of isomeric and ground states of the same nuclide would be needed. Technical possibilities for this separation exist today [20], being in preparation specially for hafnium.

The potential for production of significant amounts of ^{179m2}Hf opens some new options for trigger experiments and requires a careful analysis of possible triggering experiments with this special isomer.

3. Possible schemes for triggering of ^{179m2}Hf

The partial level scheme of ^{179}Hf is shown in Fig.1, in accordance with Refs. [21, 22]. Three bands are shown there in addition to the m2 isomeric state and were selected according to some advantageous properties that make these bands interesting for triggering. Three different ways for triggering can be considered, one for each of the shown bands. The different properties of each band, when used to provide an intermediate state for triggering, lead to a great variation among the technical methods likely to be most effective for the observation of triggering.

I. One possible means of triggering may exploit an assumed K-mixed component of the wavefunction for states in the ground-state band (g.s.b.), in particular for the $21/2^+$ and $23/2^+$ levels. The up-conversion scheme of triggering was discussed earlier for ^{178m2}Hf and ^{177m}Lu isomers. A favorable, low-multipolarity E1 transition is possible for triggering by resonance absorption of photons in the excitation of the $23/2^+$ g.s.b. level in ^{179}Hf from the $25/2^-$ m2 state. Unfortunately, the energy of this transition is rather high, being 246 keV, meaning that for the release of γ radiation by triggering of the isomer, one has to use incident radiation of comparable wavelength. This is not economic from the perspective of quantum efficiency. The transition to the lower-lying member of the g.s.b. having $21/2^+$ is accompanied by the release of 21 keV in each event. The transition has a multipolarity of M2 and occurs in the spontaneous decay of the ^{179m2}Hf isomer. A triggered transition to the lower-lying level should also be possible, similar to the excitation of the higher level. The mechanism is quite different, however, being not resonance photon absorption but stimulated resonance emission. The rate of isomer decay can be increased due to such stimulated emission and also as a result of stimulated electron conversion under photon irradiation. Quantitative estimations of the possible decay acceleration are difficult because of several unknown probabilities of the processes. Experiments on resonance stimulation of ^{179m2}Hf isomer decay under 21-keV photon irradiation look promising and can be realized with bright synchrotron (wiggler) radiation sources.

II. This approach may be discussed because a $7/2^+$ level is known in ^{179}Hf and is located very close above the m2 isomer. One can see in Fig.1 that the transition energy corresponds to the far UV band being 70 eV, however, a large spin difference makes this transition seemingly impossible. Still, in a very dense radiation bath like that produced by a high-intensity free electron laser or high-power optical laser beam, the

transition may have a detectable probability via multiphoton absorption or other mechanisms that include the coupling of nuclear and atomic excitations. The latter topics are discussed below after a description of the technical possibilities to operate with highly-ionized atomic states in the plasma created by modern ion sources or by the interaction of short, powerful laser bursts with a solid.

III. Another triggering way via the band built on the 19-s lived ^{179m1}Hf isomer looks attractive. The m1 state is not populated in the m2 spontaneous decay, and if m1 appears following irradiation of an m2 sample, then triggering will be strongly confirmed. High experimental sensitivity is the advantage of this method of observation. However, a problem arises due to the large difference of spin and K quantum numbers between the initial and final levels in triggering. Accordingly to Ref. [23], there exists the possibility to ameliorate this restriction using capture of an additional photon.

A sample should be exposed simultaneously to gamma photons for the resonance nuclear transition and to a high-density optical laser beam. The transition to the 15/2$^-$ state of this band requires a resonance photon energy near 90 keV (see Fig.1), i.e. within the frequency band covered by the bremsstrahlung and synchrotron radiation sources. The multipolarity is L = 5, instead of L = 9 in case II. And even additional photon capture in the scheme of Ref. [23] might be not enough for the successful reduction of the hindrance factors. The same is definitely true as well for II and really new mechanisms should be proposed to realize these high-multipolarity electromagnetic transitions. As mentioned above, the Coulomb excitation reaction does not improve the situation decisively, but some processes included the hyperfine interaction of nucleus and atomic shells can be valuable.

4. Technical schemes of triggering

Historically, the triggering of isomers was suggested to a photon-induced processes, either through self-triggering in stimulated emission, or through the up-conversion scheme via photon absorption from an isomer to a short-lived level. The experiments with ^{180m}Ta and ^{178m2}Hf isomers follow the up-conversion scheme and use incident bremsstrahlung or synchrotron radiation as the triggering agent. The highest sensitivity could be reached with the beams from undulators or wigglers installed in electron synchrotrons. Experiments are in progress [25-27] using the brightest synchrotron light sources at SPring-8 and Argonne and Brookhaven National Laboratories. The experimental details are described in the cited references. The photon absorption scheme remains attractive for triggering of isomers and for the ^{179m2}Hf isomer in particular. The first and third approaches described above for ^{179m2}Hf can be experimentally tested using intense x-ray sources.

Another technical possibility arises when one uses the radiation environment in the dense plasma created by a short pulse of laser light interacting with a solid. The excitation of the isomeric state in ^{181}Ta has been reported [28] and explained as a photon absorption process from the continuous spectrum of plasma radiation which is quite intense near the energy needed for the isomeric state excitation, i.e. near 6.24 keV.

In our works [11,12] the idea to use atomic-nuclear resonance in a highly-ionized plasma, in addition to photon absorption, was stressed. It was realized that a large-amplitude resonance between nuclear and atomic transitions requires matching not only the frequencies (transition energies) but also the widths of the resonances. The atomic transition is normally

shorter-lived than the nuclear one, and the width of the latter is much smaller. The narrow nuclear transition should be coupled with the wider atomic one and the overall resonance amplitude is reduced. In this way, a low probability near 10^{-7} for nuclear excitation by electron transition (NEET) can be understood in agreement with the measurements [29] for ^{197}Au nuclei.

The situation for triggering of the ^{242m}Am isomer was analyzed in Refs. [12,13]. It was clarified that the conversion of the ionization energy within atomic shells via Auger and Coster-Kronig non-radiative processes could be another important factor, reducing the NEET probability. Fortunately, in hot plasma surroundings auto-ionization processes are suppressed because of the high charge state of ions and the removal of a majority of the outer electrons. This serves as a feedback mechanism for the enhancement of radiative and NEET processes. The presence of many charge states is also valuable for exact matching of the nuclear and atomic energies, because the atomic transition energy depends on the charge state. An atomic-nuclear width mismatch exists in the case of triggering for the ^{242m}Am isomer. Indeed, the radiative lifetime of a vacancy in the M shell of the americium atom is estimated [30] to be about 10 fs, while the triggering level located by 4.2 keV above the isomeric state in the ^{242}Am nucleus has the lifetime of about 100 ps. These different width values lead to a decrease of NEET probability. However, the relatively long time of nuclear fluorescence can be very important in another advantageous aspect.

In Ref. [12] it was proposed that nuclear level pumping in a hot dense plasma can be combined with lasing in a solid. The time scale of the processes following the pulsed release of energy in solid was considered, and it was concluded, based on known experiments, that the solid matter could be recovered and re-crystallized within a time scale of about 100 ps. The nuclear fluorescence characteristic time can be such order of magnitude or longer, i.e. the radiance happens in almost cold crystalline matter. This is favorable for the increase of a probability of the collective radiance within the Mössbauer scheme of the γ-ray laser. In literature, dominates the understanding that a hot pumping contradicts the using of Mössbauer resonance processes. Now we suppose [12] that this may be not absolutely true in all cases.

In ref. [13], the possible hybridization of the atomic and nuclear excitation is stressed and there is proposed that the plasma surrounding in modern ion-sources or ion traps (the same as in laser plasma) can also be productive for the nuclear level pumping via atomic-nuclear resonance. The role of hybridization for ^{179m2}Hf triggering is discussed in the next section within the scheme of a nucleus-atomic compound system. Here more details on the ion source are given.

Electron cyclotron resonance ion sources (ECRIS) and ion traps (ECRIT) have found wide application in accelerator techniques and in physical studies during the past 15 years. The typical layout of ECRIT elements is shown in Fig.2. Ions are confined in the cylindrically symmetric cavity by a magnetic field in the axial direction created by two solenoids and in radial direction by the hexapole magnet. The ionization of the residual atoms in the vacuum is produced by electrons accelerated in the microwave electromagnetic field. The electrons circle around magnetic field lines under the condition of cyclotron resonance and the high density of electrons creates a plasma in the central volume of the cavity. The microwaves and working gas are supplied from the right side along the axis and the left side can be used for the extraction of ions in the ECRIS version of the array or for diagnostics by the X-ray radiation emitted from the plasma.

It is well-known that the plasma density in an ECR array increases with the frequency applied and with the magnetic field strength. At the more or less standard frequency of about 15 GHz, a plasma density above 10^{12} ions/cm^3 can be achieved. The typical time of confinement is about 1 ms before ions (atoms) are absorbed by the wall. However, if hot walls are used one can expect multiple cycle of usage for each individual atom. The spectrum of ion charge-states extracted from ECRIS is rather wide and a high grade of ionization can be reached. The 20^+ and 30^+ ions of heavy element atoms are typically produced in ECRIS.

In singly-ionized atoms of a heavy element, the lifetime of vacancy for inner shells like L and M should be about 0.1 - 1.0 fs accordingly to Ref. [30]. This is due to both Auger auto-ionization and radiative transitions of free or outer electrons to fill the vacancy. In ECR surroundings, when an ion is stripped to a high charge-state, these processes are significantly retarded. Indeed, free electrons are accelerated to the keV energy range and the probability of recombination is greatly reduced. When the outer shell electrons are removed, Auger conversion is stopped.

In a more quantitative approach, an ion can capture an electron, but it becomes stripped again. The yield of a specific charge-state is defined by the cross-section ratio for the electron capture and loss. This means that the ion remains in its most likely charge state almost 50% of the time because of the balance between capture and loss processes.

This does not imply that all electrons are frozen into the inner orbitals of the ion. In reality, the cross-section for bound electron excitation can be higher than the electron capture cross-section, and the electron shells of the ion are systematically perturbed with the excitation of electrons to higher shells. In a capture event, high angular momenta atomic levels are also populated. One can resume that in highly charged ions the outer electrons are removed, but vacant levels are systematically fed by the excitation of inner-shell electrons. This provides the unique possibility of confining strongly-ionized atomic species for a long time and of observing their excitation and fluorescence.

In particular, the described processes may be very useful for the nuclear conversion of the atomic ionization energy. When Auger conversion is stopped, the electron excitation can decay only with the fluorescence-photon emission or with the transfer of energy to the matching nuclear transition. To consider this case, let us discuss some numerical estimates for ^{242}Am. The hypothetical nuclear triggering level at 52.8 keV has a half-life of about 10^{-10} s accordingly to standard nuclear spectroscopic calculations and taking into account the experimental conversion coefficient. The width of this state is 10^{-4} of the M-vacancy radiative width and the nuclear/atomic width ratio seems relatively moderate. The NEET probability, however, is defined by the partial width of the triggering transition, not by the full width of the triggering level. The low-energy (4.2 keV) E2 radiative transition to the nuclear trigger level is characterized by a width as low as 10^{-8} of the upper-level's total width. As a result, the probability of NEET is estimated to be $\sim 10^{-12}$. Such an estimation contains the Weisskopf strength of a single-particle nuclear transition but considers there to be no hindrance by the K-quantum number. Taking into account the likely K hindrance, even lower values are expected although this effect may not be large because NEET includes an electron transition. It is well-known that hindrance factors for electron conversion are reduced in comparison with those for the photon emission process. In any event, 10^{-12} can be taken for orientation as a more or less optimistic estimation of the NEET probability in ^{242}Am.

The absolute calculation of the triggering yield in ECRIT conditions is quite difficult because some parameters are still unknown. The estimated values are given in Table 1. As was discussed, an individual atom can be kept in the ECR volume as long as 0.1 - 1.0 s if it is multiply desorbed from the hot walls. During 1 s, the atom remains mostly in a high-charge state and its inner shells are multiply excited to unoccupied levels. Each time there is some probability for nuclear excitation that should be multiplied by the number of attempts and the number of atoms.

Table 1. Isomeric atom in ECRIT; estimated parameter values.

Parameter	Value	Remark
Number of isomeric atoms in plasma	10^{13}	10% concentration
Time of confinement	$(10^{-3}$-$10^{0})$s	Dependent on the array design
Electron excitation rate	~10^{5}/ion·s	Deduced from the measured current of ions
Detectable rate of triggering	≥10^{4}/s	For 10^{13} nuclei of ^{242m}Am
Detectable NEET probability, P_{NEET}	≥10^{-14}	Lower limit
Triggering rate with $P_{NEET}=10^{-10}$	~10^{8}/s	High productivity

The whole volume of the active ECR zone may contain 10^{13} isomeric atoms. Based on the total beam current extracted from an ECRIS, one may assume that the electron excitation rate for ions is as high as 10^5/s. Combining these numbers with the NEET probability (10^{-12}) one deduces the triggering event rate to be 10^6/s. This is definitely enough for the detection of triggering and even a rate lower by 2 orders-of-magnitude can be successfully detected for the case of ^{242m}Am accordingly to [9]. It should be noted, however, that such a rate of triggering, being a lower limit, corresponds to an extremely low NEET probability of about 10^{-14}. Thus, one concludes that ECRIT can be very productive for nuclear excitation and triggering. With higher physical probability, the yield of radiation can achieve a level interesting for applications, not only for the measurements of significant parameters. In the following section, we discuss transitions between atomic-nuclear hybrid states. Hopefully, the hindrance factors can be reduced and the probability of nuclear excitation thereby enhanced.

5. Role of atomic-nuclear compound states

If one uses scheme II for ^{179m2}Hf triggering (see Fig.1) the transition will have a rather low energy, only about 70 eV. A similar energy nuclear transition in ^{235}U can be excited in hot plasma conditions accordingly to [31]. In the case of ^{179}Hf, a high multipolarity, L = 9, almost cancels the transition strength. But such restrictions would be significantly moderated in a model that considers the electromagnetic transition in the compound system that includes both nuclear and atomic subsystems. An approach to the compound states has been discussed in Refs. [32, 33].

The total angular momentum of the compound system*) J_c is formed as a vector sum of nuclear and atomic spins. This is illustrated in Fig.3 for the specific case of ^{179m2}Hf triggering via method II. The initial compound state contains the isomeric nucleus with I_n = 25/2 and a valence electron in the O V shell with j_a = 5/2. The final state corresponds to the nucleus in the triggering level with I_n = 7/2 and the electron at N VII orbit with j_a = 7/2. The transition between initial and final states combines the nuclear triggering transitions plus O V→ N VII

*) $J_c \equiv F$, where the symbol F is used in some publications

electron transition. In total, the compound system changes angular momentum by a value of $\Delta J_c = 3$, compared with $\Delta I_n = 9$.

The transition rate should be increased by many orders-of-magnitude, like 10^{15} - 10^{20}, when the multipolarity is changed from L = 9 to L = 3. So that a reasonable probability of triggering can be expected within the compound mechanism - octupole transitions are among the most typical for the nuclear case. But two additional problems should be discussed.

First, what happens to the K-hindrance factor within such a scheme? In Fig.3, one can see that all vectors I_n, j_a and J_c are aligned along the symmetry axis of the nucleus shown in a form of an ellipsoid. The quadrupole deformation is really a property of the ^{179}Hf nucleus, and the K-quantum number is defined as the projection of angular momentum onto the symmetry axis. When alignment takes place as in Fig.3, the compound state formally should have $K_c = J_c$. The additional hindrance by K does not exist because $\Delta K_c = \Delta J_c = L = 3$. The established rule defines the degree of K hindrance to be (ΔK - L) and there is no hindrance if (ΔK - L) = 0. Thus, the scheme shown in Fig.3 provides a rather low multipolarity of the electromagnetic transition and excludes the effect of K hindrance even when the pure nuclear transition is strongly forbidden by ΔI and ΔK.

A second question arises: What is the amplitude of the hybridization of atomic and nuclear states? They may be completely decoupled and still compound states may arise, in principle, but with very low contribution to the wavefunction. Even if only a little admixture is present in the wavefunction of the system, this can be important at the case of strongly forbidden transitions. When the transition is almost stopped due to high ΔI and ΔK values, the admixture of compound states may allow a small but reasonable probability. It would not be easy to calculate the amplitude of hybridization quantitatively, although some physical arguments can be proposed.

A 70 eV virtual photon responsible for the triggering of the ^{179m2}Hf isomer has a wavelength of λ=2.8 × 10^{-7} cm, i.e. larger than the radius of the vacant N VII orbital. This is also true for other cases, when deeper-orbit vacancies are used for NEET. One can think that the electromagnetic wave covers both a nucleus and the electron orbit within one wavelength and this provides a feedback for the nuclear-atomic states coupling.

Let us characterize in more detail the ^{179m2}Hf triggering via way II using the compound states shown in Fig.3. In the singly-ionized atom the atomic transition O V → N VII has an energy of about 10 eV which is not enough for nuclear excitation of the $7/2^+$ level located 70 eV above the $25/2^-$ isomer. But when more electrons are removed, the energy of electron transition grows significantly and matching with the nuclear transition energy can be reached. Also, the Auger conversion is excluded when weakly bound electrons are stripped. Due to that, the N VII vacancy can decay only via radiative process or nuclear conversion, when a valence electron appears in the O V orbital. The lifetime of the vacancy is increased to be longer than 1 ps [30] while the nuclear lifetime of the $7/2^+$ triggering level at 1,105.91 keV should be about 0.01 ps accordingly to standard nuclear estimations. In this case, the nuclear to atomic widths ratio is reversed, $\Gamma_n >> \Gamma_a$, unlike the more typical situation when $\Gamma_n << \Gamma_a$. Consequently, in the conditions of atomic-nuclear resonance the nuclear conversion should dominate beyond the radiative decay of the N VII vacancy.

Finally, energy matching in this scheme can be reached and the widths mismatch works in favor of nuclear conversion of the atomic transition. Thus, the probability of ^{179m2}Hf triggering is restricted only because the nuclear transition is deeply suppressed by high ΔI and ΔK values. But, as we discussed above, in the scheme of compound atomic-nuclear states, the ΔI and ΔK restrictions are moderated or even nearly cancelled. The probability of the process is defined by the amplitude of the atomic-nuclear hybridization with formation of the compound states. The latter amplitude is not yet reliably calculated, but might not be too small to have a positive effect.

A similar scheme may also be useful for the third way of ^{179m2}Hf triggering, but with some modification. In this way, the excitation of a hypothetical triggering level requires 90 keV photon absorption so bremsstrahlung or synchrotron radiation photons should be used. The multipolarity of the nuclear transition is high, being $L = 5$, and nuclear excitation is normally stopped due to that. If the isomeric atom is ionized and excited, some atomic transition may accompany the 90 keV photon absorption. The spin deficit can be supplied by the simultaneous atomic transitions and then the nuclear-excitation gateway becomes open. Appropriate conditions can be created by exposing the isomeric sample simultaneously to hard x-ray radiation and to powerful pulses of optical laser photons. This would be the nuclear excitation assisted by electron transitions.

The triggering of ^{242m}Am by the electron transition to M or L vacancy [12] in the americium atom uses, in principle, a scheme similar to the discussed above in method II for ^{179m2}Hf triggering. Only the energy of transition is 60 times higher. But again the combination of nuclear and atomic spins might be helpful to exclude the retardation of the transition due to the ΔI and ΔK differences. So that, the NEET probability of 10^{-12} for ^{242m}Am triggering estimated in the previous section should be increased rather than decreased. If in reality it is on the order of 10^{-10}, the triggering rate reaches 10^8/s, i.e. 200 times higher than the spontaneous decay rate. Thus, in ECRIT conditions, the rate of decay can be strongly accelerated, and this is important for applications.

6. Summary

Within a mechanism of atomic-nuclear resonance, or NEET, the isomer triggering yield is restricted mostly by 3 different reasons:

1. A frequency de-tuning between nuclear and atomic transitions;
2. The mismatch of widths of nuclear and atomic states; and
3. A strong retardation of nuclear transitions because of high multipolarity and K-hindrance.

In an atom that is deeply ionized to high-charge states, the appropriate transitions can be found for NEET in some nuclei, and the de-tuning problem is solved because of the charge-dependent position of the atomic levels. The probability of nuclear conversion of the atomic transition is normally reduced by a few orders-of-magnitude due to the widths mismatch. But at some cases, for instance in ^{179m2}Hf triggering, the nuclear conversion is not suppressed, but dominates because of the reversed width ratio. The third reason is most fundamental, and there is a possibility to decrease the retardation factors or even cancel them in a model of the atomic-nuclear compound states. The strength of manifestation of such states depends on the amplitude of the atomic-nuclear coupling that results from the hybridization of the wavefunctions.

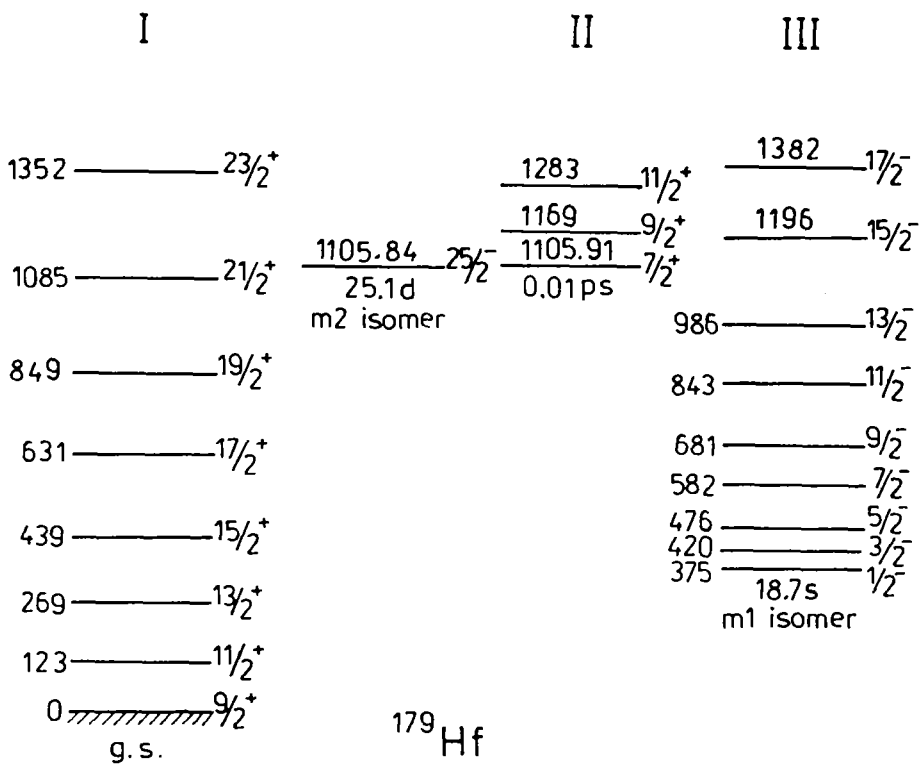


Fig.1. Level bands in ^{179}Hf – candidates for three ways of ^{179m2}Hf isomer triggering.

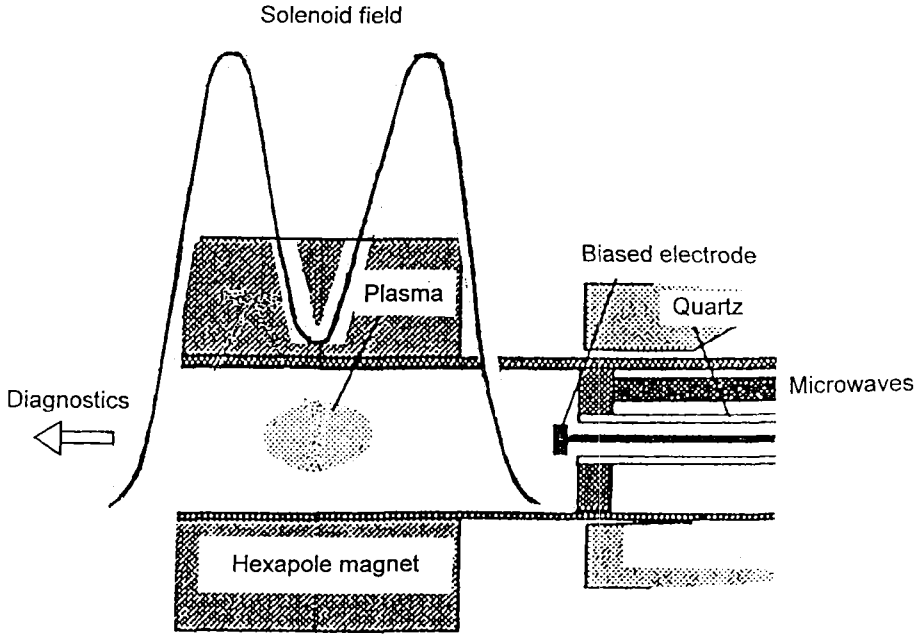
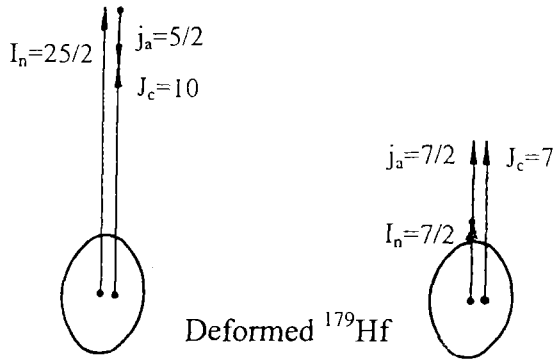


Fig.2. Schematic layout of a typical ECR array.

$25/2^- \rightarrow 7/2^+$ nuclear transition plus

0 V→N VII atomic transition



Initial state	Final state
I_n=25/2	I_n=7/2
j_a=5/2	j_a=7/2
J_c=10	J_c=7

$\Delta J_c = \Delta K_c = 3$

Fig.3. Atomic-nuclear compound states that can be formed before and after ^{179m2}Hf triggering.

New experiments on isomer triggering in plasma surroundings using modern electron cyclotron resonance ion trap, ECRIT, are proposed. They can be productive not only as a test of technical parameters of the ECRIT array, but also for the estimation of some fundamental physical values, like the amplitude of atomic-nuclear hybridization.

The approaches to real triggering of the ^{179m2}Hf isomer are newly developed. The behavior of the ^{179m2}Hf and ^{242m}Am atomic-nuclear systems in ECRIT is treated in some quantitative details.

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