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An Assessment of Nuclear Isomers as an Energy Storage Medium

E. P. Hartouni

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Edward P. Hartouni

Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA, 94550
925-422-3801; hartouni1@llnl.gov

Abstract. Nuclear Isomers have been suggested as a potential high energy density medium that might be used to store energy. This talk assesses the state of the science supporting key elements of using nuclear isomers in energy storage applications. The focus is on the nuclear isomer ^{178m2}Hf which has been most widely suggested for energy storage applications. However, the science issues apply to all nuclear isomer. The assessment addresses the production of the nuclear isomer, and inducing the release of the isomer. Also discussed are novel speculations on photon and/or neutron chain reactions, both as a "pure" material as well as mixed with other materials.

Keywords: Nuclear Isomers, Photonuclear, Super-Elastic Scattering

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INTRODUCTION

Two attributes of nuclear isomers: their relatively long lifetimes and the relatively large energy difference between the isomer and the nuclei's ground state, superficially suggest that they might provide the basis for a high energy density medium with applications to energy storage technologies. Important to the realization of this suggestion are two "micro-physics" requirements that set limits on the efficiency of the storage process: 1) the ability to produce the nuclear isomer and 2) the ability to extract the energy from the nuclear isomer. We have recently concluded a theoretical assessment of the nuclear physics relevant to the application of nuclear isomers (Hartouni, *et al.,* 2008). The smallness of the relevant reaction cross sections to the total cross sections for a variety of nuclear reactions confirm the extremely small yields of production for nuclear isomers, and are consistent with experimental observations.

The possibility that atomic nuclei existed with the same atomic number and atomic charge, but with distinct radioactive decay properties was speculated by Frederick Soddy in a discourse delivered in 1917 (Soddy, 1917). These elements have since become known as nuclear isomers and the nature of their difference from the nuclei that share their atomic number and mass is attributed to the meta-stability of the nuclear states that exist for those nuclei, a consequence of the complex structure of the nuclei. While the complete identification of nuclear isomers is not likely to ever be achieved, an extensive body of experimental and theoretical work exists describing the physical properties of nuclear isomers. The most recent comprehensive review of nuclear isomers, however, is over 50 years old (Goldhaber and Hill, 1952). There exists a modern discussion of the physics of nuclear isomers addressing possible energy storage applications (Walker and Dracoulis 1999).

The fact that nuclear isomer states were meta-stable suggests the possibility that their decays might be induced in some nuclear reaction. If nuclear isomers with life times of order of years and low energy de-excitation exist, the nuclear isomer might present the possibility of "storing" energy, available to be released as needed at some later time. Typical nuclear levels are of order 1 to 10 MeV above the nuclear ground state. The lack of a mechanism to induce the nuclear isomer decay has been an inhibition to the development of energy storage concepts. Aside from

some Russian research, a 1992 report (Poppe, Weiss and Anderson, 1992) reopened the discussions when advances in theoretical nuclear physics allowed better calculations of nuclear isomer transitions. The possibility of using nuclear isomers for γ-ray lasers was also discussed in the early 1960s in the western literature (Vali and Vali, 1963).

In 1968 the discovery of the ^{178m2}Hf nuclear isomer was reported by an irradiation of HfO_2 in a high flux reactor neutron source (Helmer and Reich, 1968) with a half-life of 31 years. The nuclear isomer state properties were measured, the energy above ground state is roughly 2.5 MeV. The Hf nucleus structure was explored through spectroscopy and the type of isomer was identified, it is a so called *K*-isomer.

The reported observation of an extremely high rate of (γ,γ') reactions with incident X-rays (Collins *et al*, 1999) on ^{178m2}Hf suggested the possibility that some anomalous physical mechanism might provide a low energy "trigger" to induce the high energy decay, opening the door to possible energy storage and recovery. Subsequent experiments failed to verify this result (see; Ahmad *et al*., 2001). In the intervening time both the theoretical and experimental understanding of nuclear isomers, and ^{178m2}Hf in particular, has been enlarged. This improved understanding makes it less likely that nuclear isomers including ^{178m2}Hf could be utilized for energy storage in a practical manner.

ENERGY STORAGE PHYSICS

The many general aspects of energy storage and recovery are depicted in Figure 1. The two axis of the diagram illustrate both the process of creating the storage medium, and the process for extracting the energy stored in the medium. Along the "energy flow" axis, the most important initial consideration is the requirement of gain

$$G = \frac{E_{out}}{E_{in}} \tag{1}$$

for the particular energy system, where G is the gain of the system, the ratio of the total energy put into the system, E_{in} to the energy available from the system E_{out}. A complete analysis of a technical energy system would include all of the efficiencies involved converting the input electrical energy (see Figure 1) to the output electrical energy. For this analysis the primary will be calculating the effective gain of the (γ,γ') reaction.

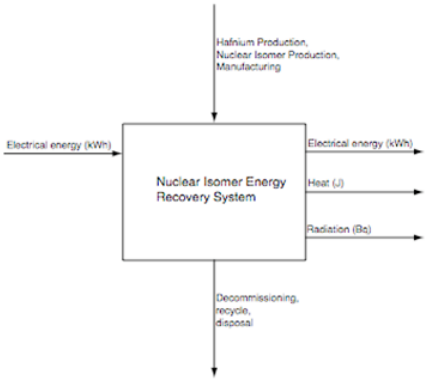

FIGURE 1. Technical energy system flow chart for a "Nuclear Isomer Energy Recovery System." Energy flow goes from left to right, non-energy "wares" flow from top to bottom.

The production and disposition of a technical energy system have a set of costs and considerations independent of the energy flow for the system. In this particular assessment the aspects of producing the nuclear isomer was considered, as it is the most "expensive" step in the process.

Energy Density of Medium

The maximum energy density of a nuclear isomer energetic medium can be estimated by taking the nuclear isomer excitation energy and multiplying it by the total number of atoms in a kilogram of the material. The excitation energy of ^{178m2}Hf is roughly 2.5 MeV and the energy density of the medium is then 3×10^6 kJ/kg. Compare this to the

similar calculation for ^{238}Pu, a radioisotope commonly used for a thermal source in space craft power systems. The decay proceeds *via* α-decay with an average energy of 5.6 MeV leading to an energy density of ~2×10^6 kJ/kg, comparable to the nuclear isomer ^{178m2}Hf.

Presuming that ^{178m2}Hf decays *via* γ-rays, an absorber may have to be provided; if the amount of ^{178m2}Hf is insufficient to absorb the γ-rays efficiently. The absorption length is energy dependent and ranges from 30 g/cm^2 at 2.5 MeV to roughly 1 g/ cm^2 at 300 keV to as small as 0.2 g/ cm^2 at 100 keV (these are typical for Pb absorbers). Depending on the geometric configuration of the power source design, it may be necessary to provide additional mass surrounding the fuel to efficiently convert the high energy γ-rays (> 300 keV) produced in the decay process. The break point is roughly 1kg of material in a single mass. The addition of this mass will reduce the effective energy density of the nuclear isomer. Note that the extremely short range of α particles precludes the need for additional absorbers in the case of ^{238}Pu.

Micro-physics Relevant to Energy Release

We consider two basic cases of energy release relevant to this discussion of energy release. The first case is that of spontaneous emission. Such systems release energy independent of presence of the radiation produced in the release process. The second case is particle-induced energy release. "Trigger" particles are used to induce the energy release. The resulting reaction "daughters" will play a role in energy release if the conditions are met for multiplying the trigger particles.

In current uses of radioisotopes like ^{238}Pu, spontaneous emission plays the role of energy release. The 87.7 year half-life of ^{238}Pu equals a decay rate of 5.2×10^{-10}/s. For a kilogram of material, this 1.3×10^{15} decays/s (35 kCi). With a 5.5 MeV per decay energy release, the power generated is 1.2 kW (initial value). ^{178m2}Hf has a spontaneous decay with a half-life of 31 years, which would release 2 kW of power for 1 kg of material (initial value). The time dependence of the power output follows the exponential decay depending on the life-time of the radioisotope, ^{178m2}Hf will generate 1 kW after 31 years, ^{238}Pu 0.6 kW after 87.7 years.

Particle-Induced Energy Release

Assuming that the "trigger" particle interacting with the nuclear isomer is lost, the mean energy released per interaction is

$$\langle e_{out} \rangle = \sum \left\langle \varepsilon_{\text{interact}} e_i \times \frac{\sigma_i}{\sigma_{\text{tot}}} \right\rangle, \tag{2}$$

where the ratio of cross sections $\sigma_i/\sigma_{\text{tot}}$ is the probability for reaction i which release energy e_i. The brackets indicate averaging over the distribution of the incident trigger particles. The probability of the trigger particle interacting with the nuclear isomer is

$$\varepsilon_{\text{interact}} = 3\times10^3 \left(\frac{\rho L}{1 g/cm^3} \right) \left(\frac{\sigma_{\text{tot}}}{1 \text{ barn}} \right) \left(\frac{200}{A} \right), \tag{3}$$

where ρ is the density of the energetic medium, L its thickness, A the atomic mass and σ_{tot} the total cross section. The "microscopic" gain of this system will be the ratio of the average output energy, equation (2), to the energy required to produce a single trigger particle (not the same as the energy of the trigger particle). Maximizing the gain requires that $\varepsilon_{\text{interact}}$ be close to unity, which in turn puts geometric constraints on the system since ρ, A and σ_{tot} are physical constants of the particular nuclear isomer.

In order to determine the microscopic gain of the energy release, it is necessary to determine the relevant reactions, their cross sections and the energy released. This determination will depend on the type of "trigger" particle and its energy.

Triggering by Photons

The two reactions of importance to energy release by "trigger" photons are: atomic scattering and nuclear photo-absorption. Atomic scattering does not lead to energy release of the nuclear isomer state (though it is responsible for the conversion of γ-ray energy to heat), it does, however, eliminate photons from the trigger particle distribution. The nuclear photo-absorption results in exciting the nuclear isomer to some higher energy state, which then either decays back down to the nuclear isomer state (no net energy release) or decays to the ground state (with net energy release). The energy out for the de-excitation is $e_{out} = e_{res} + E_{exc} \approx E_{exc}$. E_{exc} is the nuclear isomer excitation energy. The cross section for nuclear photon-absorption is σ_γ, and the fraction of this cross section which results in de-excitation to the ground state is f, leads to the de-excitation cross section $f\sigma_\gamma$. The average energy release is given by

$$\left\langle e_{out} \right\rangle \approx E_{exc} \left\langle \frac{\sigma_\gamma}{\sigma_{tot}} \right\rangle . \tag{4}$$

In the case that the de-excitation is due to direct photon absorption the cross section σ_γ for a nucleus in state i to excite to state j is estimated by

$$\sigma_\gamma \left(E = E_{res} \right) = 2.5 \times 10^3 b \left(\frac{1\ MeV}{E_{res}} \right)^2 \left(\frac{2J_j + 1}{2J_i + 1} \right). \tag{5}$$

Here E_{res} is the energy difference between states i and j, which have angular momentum J_i and J_j, respectively.

The nuclear photo-absorption can occur only if the triggering photon has an energy within the resonant width of the states i and j, which we take to be Γ_0. The nuclei are not at zero temperature, however, and this increases the width of the state. Assuming that the behavior of the nuclei in the solid with respect to absorbing MeV photons is close to atoms in a gas of the same temperature, the thermal broadening of the resonance width is approximated by

$$\Gamma_{thermal} \approx \Gamma_0 + 1\ eV \left(\frac{E_{res}}{1\ MeV} \right) \tag{6}$$

The thermal average of the photo-absorption cross section, the nuclear resonance fluorescence (NRF) cross section is then

$$\sigma_{NRF} = \sigma_\gamma \left(\frac{\Gamma_0}{\Gamma_{thermal}} \right). \tag{7}$$

This leads the calculation of energy release for this process being

$$\left\langle e_{out} \right\rangle = E_{exc} \left(\frac{f\sigma_\gamma \left(\Gamma_0 / \Gamma_{thermal} \right)}{\sigma_{tot}} \right) \left(\frac{\Gamma_{thermal}}{\Gamma_{beam}} \right). \tag{8}$$

Here the width of the trigger photon source appears as Γ_{beam}.

Triggering by Neutrons

Neutrons have been proposed as a trigger particle for nuclear isomer energy release. The pertinent energy release reaction is (n,n'), where the fraction of nuclear isomer de-excitations are described as for photons by f_n, to give the partial cross section: $f_n\sigma_{nn'}$. The average energy release is describes as in equation (4):

$$\left\langle e_{out} \right\rangle = E_{exc} \left(\frac{f_n \sigma_{nn'}}{\sigma_{tot}} \right). \tag{9}$$

the main competition to this cross section being the (n,γ) reaction, which eliminates neutrons from the system.

Micro-Physics Requirements on Nuclear Isomers

The micro-physics of the system gain can put constraints on the nuclear isomer characteristics that aid in assessing the application of nuclear isomers for energy systems. The maximum gain achievable in these systems is just the ratio of the excitation energy to the resonance energy $G^{max} = E_{exc}/E_{res}$. For ^{178m2}Hf assuming a resonance γ transition

at 10 keV this would be $G^{max} = 2.5\ MeV/\ 10\ keV = 250$. Condition 1) is that the nuclear isomer has a de-excitation transition that is within 10 keV of the isomer state.

To achieve as large a gain as possible, the terms in equation (8) multiplying E_{exc} must be close to unity. Using equation (5) and assuming the angular momentum ratio is 1, then $\sigma_\gamma = 2.5\times10^7\ b$. The total cross section is approximated by $\sigma_{tot} \approx \sigma_{atomic} + \sigma_\gamma\ \Gamma_0/\Gamma_{thermal}$ for a 10 keV photon, $\sigma_{atomic} = 6.7\times10^4\ b$. Using equation (13) we estimate $\Gamma_{thermal} \approx \Gamma_0 + 10\ meV$. There are two conditions from equation (8): 2) the natural width of the resonance $\Gamma_0 > 0.3\ meV$ and 3) that the fraction of nuclear photo-absorption reactions resulting in de-excitation $f \approx 1$.

For de-excitation by (n,n') equation (9) requires that 1) the fraction of (n,n') that result in de-excitation $f_n \approx 1$. Condition 2) is that the (n,n') reaction is a substantial fraction of the total cross section, $\sigma_{nn'} \approx \sigma_{tot}$.

Triggering Nuclear Isomers

The basic idea of nuclear isomer triggering is shown in Figure 2. A *K*-isomer exists because of the conservation of the *K*-quantum number, the projection of the angular momentum of the quasi-particle states onto the axes of symmetry of a prolately deformed nucleus. The transition to other nuclear states is "hindered" not forbidden, because the *K*-quantum number is not strictly conserved.

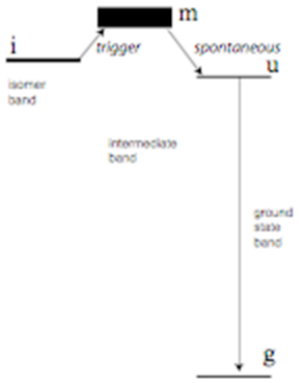

FIGURE 2. A schematic energy level diagram showing nuclear isomer de-excitation. The nucleus sits at the isomer band head state "i." A trigger reaction takes the nucleus to a *K*-mixing band, "m" in some intermediate band that then spontaneously decays to the ground state band upper level "u" and eventually to the ground state "g."

This hindrance factor is empirically determined to be

$$f_\nu \equiv \left(\frac{T^\gamma_{1/2}}{T^W_{1/2}} \right)^{1/\nu} \tag{10}$$

where $\nu \equiv |\Delta K| - \lambda$, the difference of the absolute value of the change of *K* between the states and the multipolarity λ of the transition (λ=1 for E1 transition, *etc.*). $f_\nu \approx 100$ empirically, T^γ is the lifetime of the transition, T^W is the Wiesskopf single particle estimate, equation (5). For an E1 transition to between the ^{178m2}Hf isomer band and the ^{178}Hf ground state, $\nu = 16 - 1 = 15$, and the state lifetime extended from equation (5) by 10^{16}. It is possible that a transition takes place to some intermediate band in the ^{178}Hf nucleus, say the *K*=8 band, which would reduce the hindrance factor to 10^8. States in this band may mix *K* and allow a pathway for transitions to the ground state band as shown in Figure 2. This hindrance factor should reduce the $\sigma_\gamma\Gamma_0$ product in equation (8). There are two sets of reported experimental results, a reported observation that set this cross section to 10^{-21} cm^2 keV (Collins, 1999) and a null experiment which put a limit no higher than 10^{-27} cm^2 keV (Ahmad, 2001). Using these values in equation (8) puts limits on the intrinsic width of the state Γ_0. Using 10^{-21} cm^2 keV and making the $\sigma_\gamma\Gamma_0/\Gamma_{thermal}/\sigma_{tot} = 0.9$ would require $\Gamma_0 < 0.01\ keV$. This requirement is easily met for nuclei, though it limits the second ratio in equation (8) to a value $\Gamma_{thermal}/\Gamma_{beam} < 0.0004$. The average energy out per trigger particle is no more than roughly 1 keV.

Using the value 10^{-27} cm^2 keV, Γ_0 is irrelevant in setting the ratio as the thermal motion dominates the width, and $\sigma_\gamma\Gamma_0/\Gamma_{thermal}/\sigma_{tot} \approx 0.001$. This is multiplied by $\Gamma_{thermal}/\Gamma_{beam} \approx 4\times10^{-6}$ giving an overall factor of 4×10^{-9} multiplying the excitation energy. In this case the average energy out is no more than 10 meV. The value of the fraction of these interactions that eventually populate the ground state band *f* is yet to be determined. Coulomb excitation experiments, which populate the isomer state from the ground state, find the fraction of reactions that do this is less than 1% (Hayes *et al*., 2007). This can be used as an estimate for *f*, further reducing the average energy out.

The energy output for neutron processes can be calculated using equation (9). The cross sections for ^{178}Hf are not measured. However, there are calculations which are validated with some ^{178}Hf data, as well as identical calculations for other nuclear isomers that agree with observations (Hartouni, 2008). The relevant cross sections are shown in Figure 3. For neutrons with energy < 10 keV, the ration of $\sigma_{nn'}/\sigma_{tot}$ is roughly 10^{-3}, the average energy output per trigger particle, equation (9), can be no greater than 2.5 keV. This ratio has a maximum at a neutron energy of roughly 8 MeV, where $\sigma_{nn'}/\sigma_{tot} \approx 1/3$ implying the average energy out is roughly 80 keV.

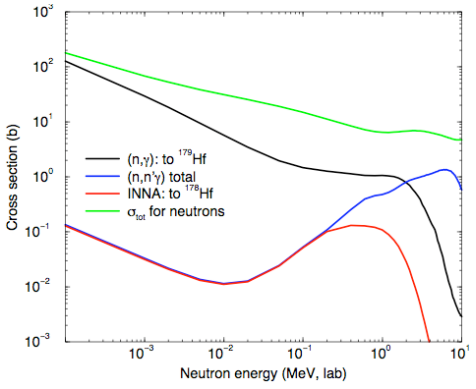

FIGURE 3. Neutron cross sections for ^{178}Hf calculated using TALYS.

Source Efficiency Considerations for Triggering Particles

The energy required to produce the trigger particle is an important aspect of the maximum possible gain. Producing X-rays using a bremsstrahlung source with an end-point energy of 50 keV, and taking a nominal tube input power of 500W the X-ray yield results in roughly 50 MeV per x-ray. For this particular source, the K_α peak is at 10 keV with a F.W.H.M. of roughly 0.5 keV, containing roughly 5% of the total X-ray flux. The average X-ray energy is 25.5 keV with a F.W.H.M. of roughly 23 keV.

For neutrons the most efficient source is via spallation reactions with high energy protons. A 1 GeV proton produces between 20 and 30 spallation neutrons, roughly 50 MeV per neutron produced.

Gain for Trigger Particle Processes

Apply equation (1), using the trigger particle input energy as the denominator, the photon triggered energy release yields gains of between 0.1 and 10^{-6} depending on the photo-absorption cross section that is applied. However, if the actual energy of making the trigger photon is used, these gains fall to the range between 10^{-5} to 10^{-10}.

Neutron processes fare no better. The range of gains depends on the neutron energy. At high energy, the gain peaks at 8 MeV, where using the trigger particle energy $G = 0.01$, if the cost for making the neutron is included, $G \approx 2\times10^{-3}$. The gain value rises to 0.25 at a neutron energy of 10 keV and continues to rise with decreasing neutron energy, to 250 at 100 eV neutron energy. The spallation source cost of neutron production averages over all neutrons, and is constant with trigger neutron energy. The gain using the source cost for the neutrons ranges from 0.02 at 8 MeV to 5×10^{-5} below 10 keV.

Particle Multiplication

In the case where the trigger particles are multiplied by the reaction, the total energy release is increased by the sum of the creation of additional trigger particles as a result of the interactions. The energy is then $E_{out} = M \langle e_{out} \rangle$, where M is the multiplication. The average energy out of any of the reactions $\langle e_{out} \rangle$ is given by

$$\langle e_{out} \rangle = \sum e_i \left\langle \frac{\sigma_i}{\sigma_{tot}} \right\rangle, \tag{11}$$

where the reaction probability σ_i/σ_{tot} is averaged over the trigger particle distributions. In general, this distribution would require a detailed transport calculation in order to obtain an accurate solution of E_{out}.

Considering the infinite medium case (where no trigger particle escapes the medium), the multiplying reaction is characteristic of a time (or length) scale set by the typical interaction time. The concept of 'generation' applies to the number of particles in one characteristic time which begets the next generation of particles. The ratio of the number of particles a generation to the previous generation is written as

$$k = \sum \nu_i \left(\frac{\sigma_i}{\sigma_{tot}} \right), \tag{12}$$

where ν_i is the number of particles produced in the reaction i, this is equal to zero in the case of absorption, 2 for (n,2n), etc. The total number of particles produced for a single incident particle is then the sum of these

$$M = \sum k^n = \frac{1}{1-k'} \tag{13}$$

for $k < 1$, for $k > 1$ M is unbounded.

In the case of multiplying photons, sum over the cascade of de-excited photons $j = 1, \nu$, calculating the probability of each of them producing ν_j photons

$$k = \frac{1}{\nu} \sum_{j=1}^{\nu} \left(\frac{\sigma_{j,\gamma} f_j}{\sigma_{j,tot}} \right) \nu_j \tag{14}$$

and where the contribution of elastic and inelastic scattering is neglected. Typically $\nu_j \approx \nu$, and restricting the sum over photons which induce de-excitation (with output energy e_i) provides the criticality estimate

$$k \approx \sum_{j=1}^{\nu} \left(\frac{\sigma_j}{\sigma_{j,tot}} \right). \tag{15}$$

For neutrons, assuming that every (n,n') reaction results in a de-excitation, and that the (n,γ) reaction is responsible for all the neutron absorption, we can write the approximate criticality as

$$k \approx 1 - \frac{\sigma_{n\gamma}}{\sigma_{tot}}. \tag{16}$$

Particle Multiplication Applied to Single Trigger Particle Gains

The single trigger gains can be increased in a multiplying assembly if the various cross sections for the controlling processes exist. In the case of photon triggers, the multiplication M required to provide a gain $G = 1$ fall in the range of 10^5 to 10^{10}. Criticallity, equation (15), would then sum to $1 - 10^{-5}$ to $1\text{-}10^{-10}$. The γ cascade multiplicities that equation (15) is summed over are of order 10. On average, the cross section ratios $\sigma_j/\sigma_{j,tot} \approx 0.1$ to induce the transition. This is highly unlikely, however, given the resonance nature of the transition, for which $\sigma_j/\sigma_{j,tot} \approx 0$. The multiplication could take place if at least one of the cascade γ's matched the resonant energy. This puts an additional constraint on the nuclear isomer. In particular, if an intrinsic γ transition exists, which de-excites the nuclear isomer; it would reduce the effective lifetime of the isomer.

In the neutron case, to obtain a gain $G = 1$, M=20 for 8 MeV neutrons, and $M=2\times10^4$ below 10 keV. This would imply that $\sigma_{n\gamma}/\sigma_{tot} \approx .05$ at 8 MeV (it is roughly 10^{-3}) and $\sigma_{n\gamma}/\sigma_{tot} \approx 5\times10^{-5}$ below 10 keV (where it is no smaller than 0.1).

This opens the door to high energy neutron multiplication for energy production but requires multi-neutron reactions (which do not occur).

Proposals to use "superelastic" (n,n') reactions together with a neutron generating reaction, *e.g.* ^{9}Be(n,2n) (Muradian, 2004) have been studied. The ^{9}Be(n,2n) has the lowest neutron energy thresholds of all (n,2n) reactions, the proposed scheme uses the n' from the ^{178m2}Hf (n,n') where it has increased in energy (INNA is INelastic Neutron Acceleration). This neutron then interacts with the ^{9}Be resulting in 2 neutrons. Detailed transport calculations have shows no multiplication, but rather the net effect of adding ^{9}Be to the ^{178m2}Hf decreases the available neutrons, it is a "poison" for multiplication.

Nuclear Isomer Production

^{178m2}Hf is produced in reactors by (n,γ) reactions on ^{177}Hf with a cross section of 2.6×10^{-6} b. The burn-up reaction cross section is roughly 100 times the production cross section. The thermal neutron capture cross section of ^{177}Hf is 373 b. The yield of the nuclear isomer can be calculated

$$N_{178m2} = N_{177}\left(\frac{\sigma_{\text{production}}}{\sigma_{\text{total}} - \sigma_{\text{burnup}}}\right)\left(e^{-\sigma_{\text{burnup}}\Phi} - e^{-\sigma_{\text{total}}\Phi}\right), \quad (17)$$

where N_{178m2} and N_{177} are the number of ^{178m2}Hf and ^{177}Hf nuclei, respectively, and Φ is the neutron flux. For neutron fluence of order 10^{15}/cm^2/s, 1kg of HfO_2 (assume natural abundance) will yield roughly 1 ng of ^{178m2}Hf. This process converts 10^{-12} of the ^{177}Hf to ^{178m2}Hf. Compare this to ^{238}Pu production from more than 0.1 times the initial ^{237}Np in reactor irradiation.

CONCLUSION

The application of nuclear isomers to power systems, specifically ^{178m2}Hf, has been studied from the standpoint of the required gain at the "micro-physics" level. We find that the minimal requirements that the gain at the lowest level of the energy generation should be large (at least ≈ 1) are not met for this physical system. This limitation is due to the physical characteristics of the nuclear isomer state, and not due to engineering limitations. Further, the physical limitations are not peculiar to a specific nuclear isomer, but are due to a class of physical attributes shared by all nuclear isomers.

Further, these same physical attributes limit the production rate of nuclear isomers. Producing large quantities of nuclear isomers is not likely to be practical for applications requiring more than trace quantities.

These considerations make the practical application of nuclear isomers for power systems highly improbable.

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