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Economics of Isomeric Energy

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Abstract—A high energy density source based on nuclear isomers may be conceptually attractive, but it is unrealistic if the energy's price is too excessive. This paper estimates the price of isomeric energy, and shows that isomers can become practical only for low-energy applications.

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INTRODUCTION

A chemical source such as gasoline or a battery contains on the order of a million times less energy than what some nuclei can contain in the same mass. But, making the energy useful encounters many obstacles. Some of these are intrinsic to physics. For example, a nucleus releases almost all its energy in a single or, at most, a few photons at the same time, while the intended application often needs the energy subdivided in some other form that is more compatible with chemical energy. Others are pedestrian, but no less important. The primary one is how do you make enough of the necessary material for practical use, and what is its price?

The physics problems must be addressed by additional research and development in nuclear physics and nuclear engineering, but the cost issue can already be delimited with a minimum of technical information. This paper estimates a lower limit to the price of energy stored in nuclear isomers from data for isomer production available in the literature. The intent is to get a modestly quantitative feel for what isomers can or cannot be expected to do if the physics behaves as desired. Whether it does is another, and to us more interesting, problem that we hope to make progress in over the next year.

The process can also work in reverse. Given an order of magnitude indication for the allowable cost of a particular application, it should be possible to derive an estimate for the acceptable values of the corresponding physical quantity. It is, then, easy to see whether the available data support the application. Or, when these data do not exist and we are working toward measuring them, knowledge of the order of magnitude will guide the selection of the diagnostics.

As always, the acceptable value will change with the application. It will become clear later that isomeric energy may well cost too much when large amounts of energy are involved, and also that isomeric energy is not too expensive for certain specialty applications. Performing simple assessments along these lines will make research on nuclear isomers more effective.

Last year, we presented a somewhat similar approach for a more physics-related issue. In some concepts, the isomeric nuclei give up their energy on irradiation by *x* rays, i.e., by triggering. When the circumstances are right, the triggering *x* rays could perhaps come from the decays themselves, and, in this case, the nuclear energy might come out explosively in a short burst through a photonic chain reaction similar to the neutronic chain reaction that occurs in nuclear explosives. In other concepts, the triggering *x* rays come from an external source. Rough order of magnitude estimates are sometimes sufficient to state under which circumstances one or neither of these approaches are feasible. Can the radiation affect the isomeric nucleus' radioactive decay easily enough (i.e., is the triggering cross section large enough)? When the minimum cross section needed for the process is many orders of magnitude higher than experiments suggest or than theory indicates [1], the chances for these approaches becoming practical and/or useful are infinitesimally small.

In the presentation, we took the opportunity to mention that intense pulses of *x* rays are available from plasma radiation source (PRS), a radiation source that has not yet been considered for experiments with isomers. The PRS produces a large pulse of softer *x* rays, around a few kiloelectronvolts, that may match the energy band of interest in an isomer such as ^{242m}Am. Its nucleus has an energy level at about 4.3 keV, roughly the same energy as that from one of the electron shells. An accidental resonance between these levels could possibly enhance the nuclear excitation cross section by orders of magnitude. These facts suggest that Am is an interesting target material to confirm isomeric transition.

SOME REMARKS ON ISOMER ENERGETICS

Fission of a single nucleus gives hundreds of megaelectronvolts per nucleus, while the energy from the nucleus' radioactive decay is almost two orders of magnitude lower (for α emission, typically around 5 MeV per nucleus). Six orders of magnitude lower is the

energy per atom in conventional batteries and conventional explosives, a few electronvolts per atom. Nuclear energy is, therefore, very attractive for batteries and explosives, applications that benefit from a high energy per mass. Nuclear energy is spectacularly successful when the energy can be liberated from the nucleus in a convenient way, actively by neutrons or passively by spontaneous decay.

Also important is energy conversion, that is, how to transfer the nuclear energy into a useful form with a reasonable efficiency η. In nuclear reactors, the energetic fission products distribute their directed energy amongst the atoms in the material to become heat. The heat drives conventional electrical generators with a reasonably high efficiency of $\eta \sim 0.3$ and higher. In almost all types of nuclear batteries, the spontaneous radioactive decay also gives heat, but the conversion is thermoelectric with $\eta \sim 0.1$ or, perhaps, a little higher.

Nuclear isomers can store almost as much energy per nucleus as isotopes. But, isomers have a unique feature: the stored energy can be accessed without neutrons with electromagnetic radiation. The absence of neutrons suggested to some that isomerically stored energy could open up many new applications of nuclear energy, from humble microbatteries that can be turned on by an *x*-ray pulse to nuclear explosives supported by a photonic chain reaction.

In our presentation at the 2005 AFOSR Isomer Workshop in Dubna, we reanalyzed the possibility of a photonic chain reaction based on isomers. Our conclusions agree with those of others: a photonic chain reaction fueled by the energy stored in isomers cannot occur in a realistic material. The reason is simple: electrons absorb radiation much more easily than nuclei. Figure 1 illustrated the argument for hafnium. In the present presentation, this same figure serves as the background, reminding us that a conventional and, therefore, uninteresting, physical phenomenon such as photoelectric absorption continues to exist, even though our attention focuses on the new and interesting physics of isomers. While the uninteresting phenomena can be temporarily ignored on paper, nature does not let them be ignored in reality.

In Fig. 1, the photoelectric cross section of hafnium, $\sigma_p(h\nu)$ is the line with the *x*-ray absorption edges, one close to 50 keV and a few between 8 and 10 keV. The top line is the maximum cross section for dipole excitation of the nucleus by photons marked by RNS (resonant-nuclear scattering), while the bottom dashed line is the Compton cross section for a free electron. The red line in the figure at 10 keV is the largest nuclear excitation cross section σ_{max} for the ^{178m2}Hf isomer claimed in the literature [2]. More reliable and precise measurements [3] give a limit that is more than 5 orders of magnitude lower. This would be off the scale in the figure. Comprehensive experimental [4] and theoretical [1] reviews confirm the null results. But, even a discrepancy of 5 orders of magnitude in this particular cross

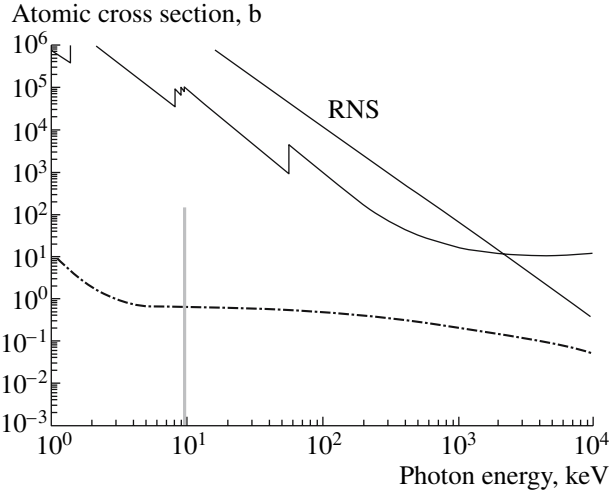

Fig. 1. Cross sections for Hf.

section makes little difference for the limited purpose of estimating the feasibility of a chain reaction in a material that consists entirely of atoms with their nuclei in the excited isomeric state. Whether such a material can be produced, and at what price, was not part of last year's cross-section comparison; it is what we consider here.

The width $\Delta_n(h\nu)$ of a nuclear resonance $\sigma_n(h\nu)$ is not and, in fact, cannot be shown in Fig. 1. On the correct scale, the actual width is so much narrower than the line that it would be invisible. As an example, the resonance width for one well-known nucleus, ^{57}Fe, is only about 5 neV, and even if that were to be 1 eV for Hf, the integrated cross section would not be larger than 0.1 b keV, otherwise down to perhaps 10^{-9} b keV.

The integrated cross section $\int d(h\nu)\sigma_n(h\nu) \sim \Delta_n(h\nu)\sigma_{max}$ for the interaction of photons with nuclei is clearly many orders of magnitude smaller than its electronic analogue $\int d(h\nu)\sigma_p(h\nu)$. In this cross section, even the photoelectric part $\int d(h\nu)\sigma_0(h\nu/h\nu_0)^{-3} \sim \sigma_0 h\nu_0/2 \sim 5 \times 10^5$ barns keV is much larger than any integrated cross section for the Hf nucleus. Another nonnegligible component is the Compton cross section for Hf's 72 electrons, $8Z\pi r_e^2/3 \sim 50$ barns, integrated over an ~megaelectronvolts range. This gives an order of magnitude smaller number, $\sim 5 \times 10^4$ b keV.

The discrepancy between the integrated cross sections for electronic and nuclear effects is so large that even the 250-fold more energetic photon emitted by the ^{178m2}Hf nucleus, 2.5 MeV given off by the nucleus versus the 10 keV that might be needed for triggering, cannot make up the difference. It is clear that a chain reaction is patently impossible, even with the unrealistically large photonuclear cross section as shown in the figure

Table 1. Nominal prices for energy in different applications

Source	Energy density (kJ/kg)	Power density (kW/kg)	Price ($/kJ)	Remarks
Prime power	NA	NA	2×10^{-5}	@ 0.06 $/kW
Car battery	200	1	2×10^{-2}	12 V, 100 Ah, 4.3 MJ
NiMH AA	500	1	0.2	1.5 V, 2.5 Ah, 13.5 kJ
^{238}Pu	4×10^{8}	0.15	4000	@ 100.000 $/g (ROM estimate)
Space power	4×10^{5}	1.5×10^{-4}	4×10^{6}	Mass of accessories 1000 times fuel

and an unrealistically large resonance width. Photoelectric absorption dominates so completely that almost all photons disappear before they interact with a nucleus, and even photons whose energies might be resonant with nuclear levels are taken off-resonant by frequent Compton collisions.

This conclusion is in complete accord with experience—that is, it is very difficult to find a clear unambiguous signature of a photonuclear process in the midst of the many competing photoelectron processes. The difficulties associated with measuring small cross sections, such as those for photoexcitation of isomers, come up again in a paper by our group [5] in these proceedings. With our equipment, we could not find photoexcited nuclei.

As is well known, a neutronic chain reaction has similar problems with contamination by neutron absorbers. A chain reaction cannot occur when these absorb too many neutrons or when the neutrons diffuse too early to the outside. Almost all devices that depend on a neutronic chain reaction for their operation have neutron reflectors, and they are built with very pure materials. Furthermore, the chain reaction is easily controlled by the deliberate insertion of neutron-absorbing rods.

In what follows, we want to discuss a complementary cross section that is just as important for any practical application of isomeric energy storage vis-*a*-vis the production cross section for the energetic isomer. At the time of the conference, we had only done the simplest of analyses, and this paper contains only a small addition to what was presented.

ISOMER PRODUCTION

Nuclear energy from isomers differs in one important respect from the more familiar nuclear energy from fission: fissionable nuclei are found in nature. Fissionable nuclei contain energy that is somehow left over from cosmic processes such as supernova explosions. Likewise, the radioactive decay energy that drives standard ^{238}Pu nuclear batteries is cosmic energy that, in the end, comes from natural fissionable nuclei, albeit after various transformations in nuclear reactors. In contrast, all of the isomers contemplated for practical applications to date do not contain energy naturally; they only store energy brought in from the outside. (Most isomers are not naturally abundant.) In this respect, the isomer is an energy storage medium, just as are coal or oil. These store solar energy from millions of years of sunlight. The only isomer that does contain cosmic energy (from the Big Bang) is ^{180m}Ta, and this isomer is extremely rare and its energy content is too low for applications. In most cases considered for energy applications, the excited isomeric states that store energy must be generated by external particle bombardment, i.e., accelerators or reactors.

Storing energy in isomeric nuclei is a perfect nuclear analog to chemical energy storage, from explosives through lithium or zinc in batteries to the hydrogen that may, at some point, power our cars. Unlike conventional nuclear energy that comes with uranium, the energy that must be put into the isomer costs money.

How much it costs to store the energy in some carrier is not the only criterion for a particular application, or even the most important one. In fact, energy costs are usually irrelevant for specialty applications that need only a little energy. As an example, it seems perfectly acceptable to pay $1 per Joule for a $1000 microbattery that contains 1 kJ, and delivers it at a constant level of 1 μW over 30 years. But, whenever an application demands a lot of energy, the cost of the energy can be crucial. It is inconceivable that an Army battalion can afford to buy 1000 hand grenades when the ~10 MJ energy stored in each grenade's explosive costs $10000000 in energy alone. At the moment, the costs of production, acquisition, and logistics dominate for such items, not the cost of the primary energy.

The minimum cost of isomeric energy is, therefore, an important factor for future applications, and it can already be estimated, within rough limits, with a minimum of physics information. In fact, how much it costs to store energy in isomers is directly given by some of the cross sections that physicists like to calculate and measure. In the presentation, we inferred a lower limit for the price of isomeric energy stored in ^{178m2}Hf. Later, we may carry out similar estimates for other isomers of interest and consider other production processes that may be more energetically favorable.

Table 1 gives the typical energy costs for some standard energy sources. At the moment, household energy in the US is very cheap at about $0.06 for the common

energy unit (1 kW h = 3.6 MJ). Energy available from batteries is much more expensive unless they can be recharged. Thus, the table provides data for rechargable batteries as if they could be charged only once. Exceedingly expensive are energy and power for special applications, e.g., those in space. The table suggests a few numbers for the radioactive isotope ^{238}Pu by itself, and for the electrical energy from a complete radioactive battery that uses ^{238}Pu as the energy source. In this, the auxiliary elements, such as radiation shielding, the thermoelectric conversion unit, the support structure, etc., are taken to be 1000 times heavier than the radioactive fuel itself, and to cost 100 times more. These numbers are rough order of magnitude estimates that come from casual conversations with Department of Energy scientists who would build such units (none have been built recently, however). The price for radioactive materials such as ^{238}Pu is admittedly arbitrary. There is no open market in Pu, and the isotope itself is free. It is waste in a purification process that is carried out for other reasons. The derating factors are included, because an isomer battery might also have to be derated.

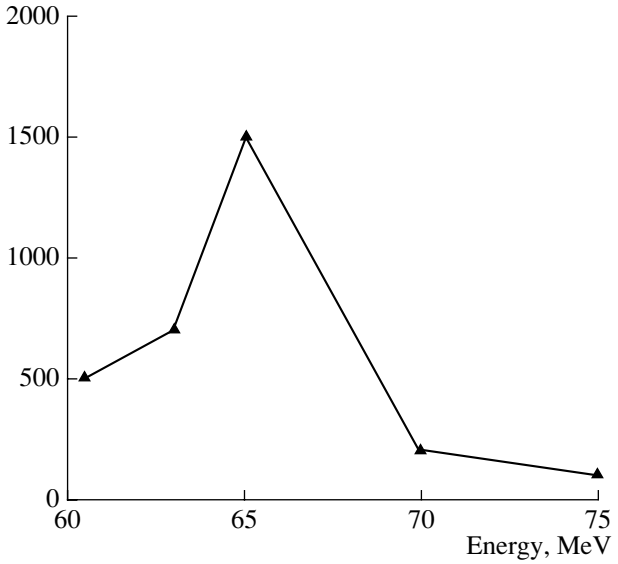

Fig. 2. Cross section for the production of ^{178m2}Hf with energetic ^{9}Be.

The Army would prefer other radioactive nuclei than the α emitters that are the most common sources of energy in nuclear batteries, in large part because α emitters are radiologically problematic on Earth. Table 1 does not include them, because their cost is not qualitatively different than the standard sources at maybe an order of magnitude higher because of the additional shielding that may be needed.

Isomers contemplated for batteries would emit fast β or energetic γ, whose energy can conceivably be converted directly into electrical energy. Direct conversion is sometimes deemed to be favorable because, according to the simplest analyses, it promises a very high conversion efficiency (which often decreases when the analysis becomes more realistic and may disappear in practice).

At the meeting, we only presented the cost of energy stored in ^{178m2}Hf derived for one particular process—the production of ^{178m2}Hf with energetic ^{9}Be nuclei. Reasonable data have been gathered for this process by one of us and his colleagues [6]. During the discussion, Dr. Karamian kindly pointed out his papers [7–9] that contain additional data on the production of ^{178m2}Hf with other light projectiles, in which he highlights additional fundamental and practical issues. The present paper goes slightly beyond the presentation by adding some estimates for the price of storing energy in isomers using the cross sections measured by Karamian [7, 8].

Figure 2 shows the production cross section [6] for the reaction ^{9}Be(α, 3n)^{176}Yb $\longrightarrow$ ^{178m2}Hf. The few experimental points in this graph suggest a maximum cross section σ_m below about 5 mb (5×10^{-27} cm^2), centered at an energy of 65 or 7 MeV per nucleon. In this experiment, the energetic Be nuclei collide with cold stationary Yb. A standard handbook [10] calculates how far Be ions at 65 MeV penetrate into various cold materials (in Table 42.8). Interpolation gives a penetration depth equivalent to 100 mg/cm^2 mass per unit area of Yb, corresponding to a stopping cross section $\sigma_{stopping} \sim 3 \times 10^{-21}$ cm^2, or 3000 b. The ratio of cross sections $\sigma_m/\sigma_{stopping} \sim 10^{-6}$ implies that only one in a million ^{9}Be projectiles converts a Yb nucleus into an energetic ^{178m2}Hf nucleus.

Each ^{178m2}Hf nucleus stores about 2.5 MeV, or 1/30 of the Be nucleus' energy. The energy transfer efficiency η is, then, on the order $\eta \sim 0.03 \times 10^{-6}$. The energy stored in ^{178m2}Hf is at least 1/η more expensive

Table 2. Some data for ^{178m2}Hf production with different projectiles

Projectile	Energy (MeV)	σ_m (mb = 10^{-27} cm^2)	Energy cost ($/J)	^{178m2}Hf/projectile	Reference
Proton (^{1}H)	650	0.3	0.2	35×10^{-6}	Karamian [7]
Helium (α, ^{4}He)	36	1		2.5×10^{-6}	Oganessian [11]
Beryllium (^{9}Be)	65	5	1	0.03×10^{-6}	Farrell [6]

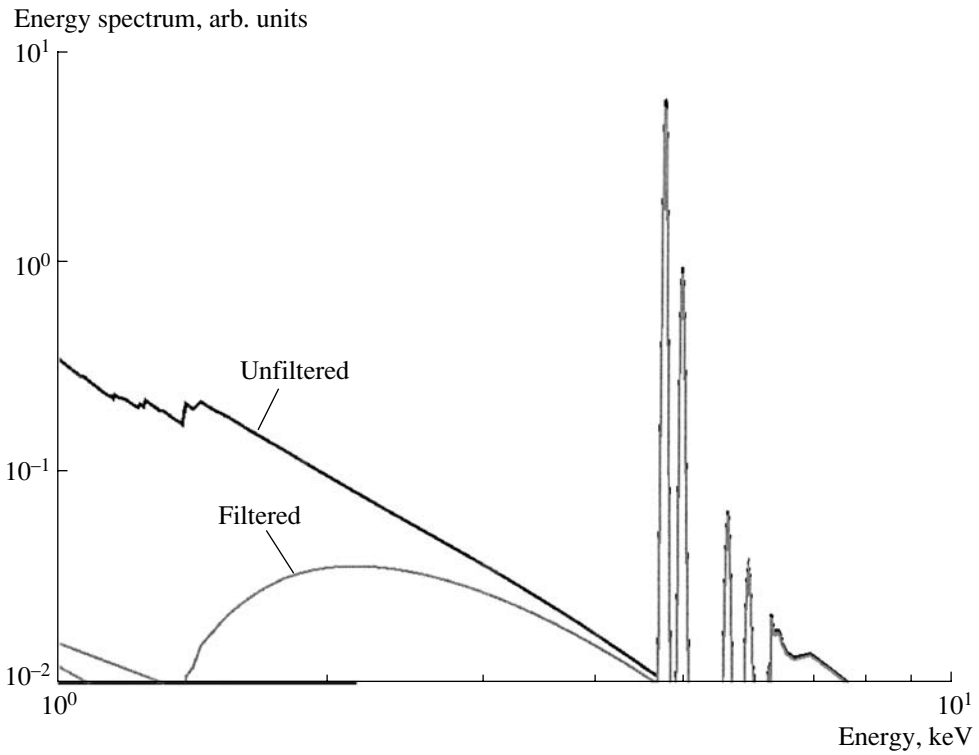

Fig. 3. X-ray spectrum of a Ti z-pinch on the Z machine at Sandia National Laboratories. The raw PRS spectrum (black line) is compared to the 0.5 mm Li-metal shielded measurement (grey line).

than the prime energy cost P. From Table 1, $P \sim 2 \times 10^{-5}$ \$/kJ, so that $P/\eta \sim$ \$660/kJ or just about \$1/J.

The price point just estimated is, of course, the lower bound. In fact, the price for a ^{178m2}Hf sample with 1 J stored in 2.5×10^{12}\$ nuclei costs at least 1000 times more. At the moment, by far the largest cost is in the processing, which would be substantially higher, again, if pure material were desired. Note that no process has yet been demonstrated that separates the energy-containing isomers from the same atom's inert ground state. Even though the energy cost of the isomer is a wild underestimate, it is clearly a definite lower bound that can give a definite minimum price for a system that uses the isomer.

Table 2 compares how well different projectiles do energy-wise in making ^{178m2}Hf. For protons, Karamian [8] gives the cross sections. However, for the energy estimate, it is easier to use the number of ^{178m2}Hf nuclei produced by a single projectile given in the original paper [7]. A 650-MeV proton (on Ta) leaves about 90 eV in the 2.5 MeV excitation energy of the 3×10^{-5} ^{178m2}Hf nuclei it produces, for an energy efficiency of around 10^{-7}. For 36 MeV α particles, the energy efficiency is similar, and so it should be for energetic Li ions. We do not have data on making ^{178m2}Hf with lithium, but it seems likely that the process should exist as well.

Storing energy in isomers is expensive for all of the methods mentioned here (and no better for other [9] approaches). As already mentioned, 10 MJ energy in a notional isomeric hand grenade costs from \$1 M to \$10 M in energy alone, and the actual price would be substantially higher. Therefore, an Hf-based hand grenade is clearly impractical. However, the present rough order of magnitude estimates do not exclude isomeric energy in all kinds of low energy applications, in particular nuclear microbatteries that may need only 1 kJ. While the nuclear batteries of interest [5] do not use ^{178m2}Hf, we expect that the cost estimates for the appropriate materials will give similar results.

PRS RADIATION FOR ISOMER EXPERIMENTS?

Most attempts to measure how well external radiation liberates the energy stored in an isomer are performed with x rays from traditional bremsstrahlung machines, supplemented by only a few measurements with synchrotron radiation. In the past, pulsed sources have been used on occasion [12], and we should expect new results from related measurements planned for the near future [13]. These high-energy bremsstrahlung machines are appropriate for exploratory research on isomers, because the harder radiation might access so-called gateway states. These are energetic metastable nuclear levels that would morph into an energetic isomer.

One interesting, but low-energy, case may be ^{242m}Am. It has a nuclear level at 4.3 keV whose triggering cross section could conceivably be enhanced by an accidental resonance with an atomic shell, also around 4.3 keV. At these energies the plasma radiation source [14] (PRS) can provide an extremely high flux of *x* rays, so that the PRS might offer a unique way to excite ^{242m}Am.

Figure 3 shows the *x*-ray spectrum for a plasma radiation source in titanium [15] calculated for a typical 20-MA peak current pulse on Sandia's Z machine by a first principles radiation-hydrodynamics model. In less than 10 ns, the titanium PRS radiates about 100 kJ. About half of this energy is in the K lines that are so prominent in Fig. 3. The fluence expected over a 1 cm^2 sample at 10 cm or so distant from the PRS is, then, around 100 J. The spectrum emitted by the PRS itself is the top line, while the bottom (red) line is a spectrum behind a 0.5-mm-thick filter made from lithium metal. This lithium filter halves the fluence at 2 keV, but barely affects the spectrum above 4 keV. A 4-mm-thick Li filter would halve the fluence at 4 keV, so that it should be possible to protect the Am from the worst effects of the PRS *x* rays and still excite Am electronic shells.

Contemplating such an experiment is interesting only when the irradiation excites a nuclear decay with a short half-life from ms to 100 s. Otherwise, the Ti PRS produces the same fluence in 10 ns as a continuous source in 100 s (at 1 W/cm^2 in monochromatized and focused synchrotron radiation). When short half-lives must be measured, pulsed irradiations become very useful.

The principal difficulty in performing such a triggering experiment on Sandia's Z machine may well be the sample's radioactivity. For radiological reasons, the sample must be enclosed before, during, and after the pulse. The pulse is so powerful that it destroys most of the hardware within a 10-cm radius. Putting the sample behind a strengthened lithium *x*-ray window is one of a variety of techniques needed for such an experiment.

CONCLUDING REMARKS AND ACKNOWLEDGMENTS

This paper gives a rough order of magnitude estimate for one of the non-physics, but still essential, requirements for energy storage in isomers to become practical—the price of storing the energy itself. At the present stage of research, the knowledge about isomers is not yet good enough for engineering estimates, where a two-factor discrepancy can make or break an application. Instead, the estimates are more like astrophysics, where a difference of an order of magnitude does not normally affect the conclusion. In the coming year, we intend to do similar estimates for other isomers.

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