X RAY AND GAMMA RAY LASERS

M. Ragheb
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INTRODUCTION

The incentive for generating x ray and gamma ray lasers can be inferred from the equation for the energy carried by a photon of electromagnetic radiation.

$$E_\gamma = h\nu = \frac{c}{\lambda} \tag{1}$$

where: h is Planck's constant = 6.626×10^{-34} [Joules.sec] = 4.135×10^{-21} [MeV.sec],

c is the speed of light = 2.997×10^{10} [cm/sec],

ν is the frequency, [Hertz], [sec^{-1}], λ is the wave length [cm].

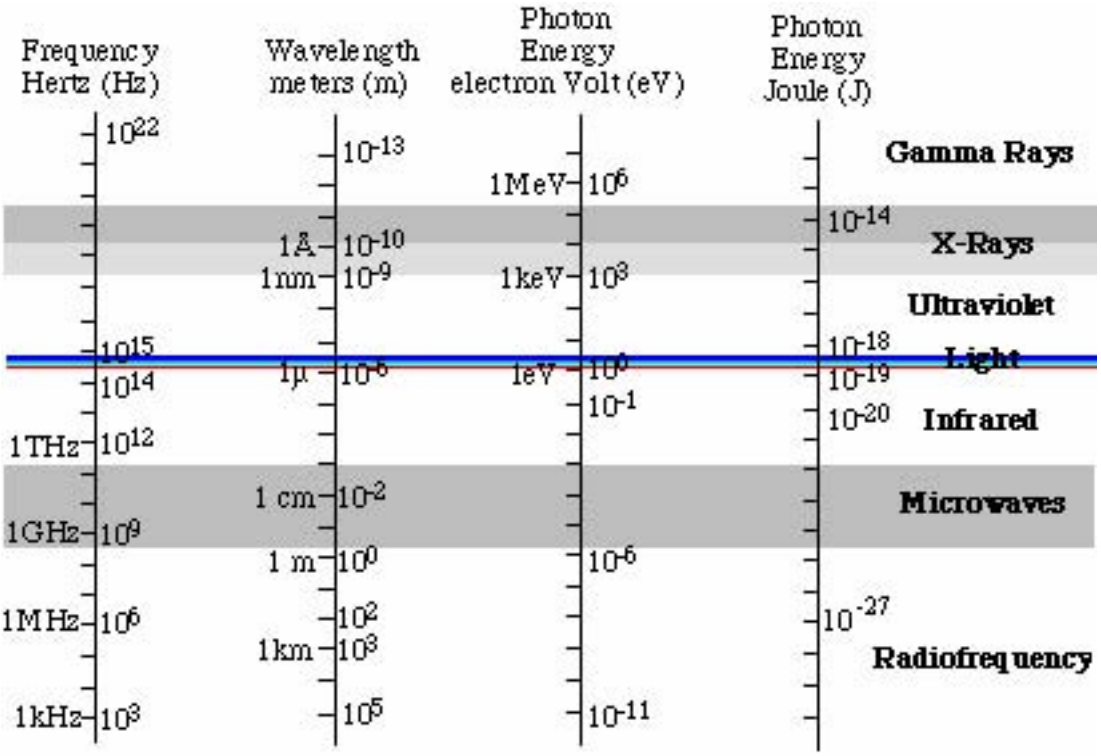

Fig. 1: The electromagnetic spectrum.

Short wave length radiation as x rays or gamma rays implies a high energy being carried by the photon since the wave length appears as a small number in the denominator of Eqn. 1. From Fig. 1, x ray photons would carry energy in the keV region, and gamma rays carry energy in the MeV region, as compared to light in the eV region.

The idea of generating x ray lasers dates back to the 1970s, when scientists realized that laser beams amplified with ions would have much higher energies than beams amplified using gases.

Nuclear explosions were considered as a power supply for these high-energy lasers. This became a reality at the time of the Strategic Defense Initiative (SDI) of the 1980s, when x ray laser beams initiated by nuclear explosives possibly surrounded by rods of titanium, palladium or tantalum were generated underground at the Nevada Test Site. At the Lawrence Livermore National Laboratory (LLNL) the Novette laser, precursor of the Nova laser, was used for the first laboratory demonstration of an x ray laser in 1984.

A nuclear isomer is a long lived excited state of the nucleus. Its decay to the nuclear ground state is inhibited. An isomer thus can store a large amount of energy. Nuclear isomers with a long half life and a high energy release such as $_{72}Hf^{178m}$ offer the possibility to be standalone energy sources. If that energy can be controllably released rather than gradually over time, a nuclear battery can be built. If it is instantaneously released, it could be used as a rocket propellant or an explosive. The idea of generating gamma ray lasers dates back to the late 1990s.

Gamma rays amplification by the stimulated emission of radiation from nuclear isomers may become a reality as "gasers." Lasers is an acronym standing for: light amplification by the stimulated emission of radiation. Whereas light as electromagnetic radiation normally involves photons with energies in the electron volts (eV) energy range, gamma rays with a higher frequency and a shorter wave length would carry energies in the Million electron volts (MeV) range.

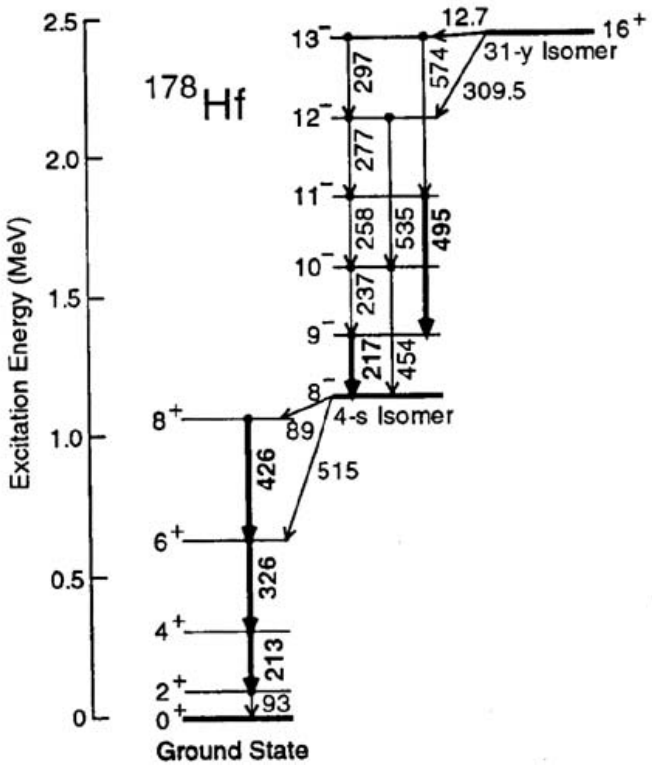

Fig. 2: Decay Diagram of the 31 years half life $_{72}Hf^{178m}$ isomer.

If realized, this promises to provide surgeons with penetrating radiation as scalpels to treat deep and small sized tumors in the human body. On the other hand, there has been speculation that the USA Department of Defense was considering the development of a weapon that would release high-energy gamma rays from isomeric nuclei. If a device that exploits this energy source could be devised, it would have an energy release approaching that of a nuclear device.

Gamma rays are quanta of electromagnetic radiation of very short wavelength and very high energy, on the order of a million times more energetic than visible light photons, and at least 10 times more energetic than x-ray photons. When a nucleus undergoes a spontaneous transition from an excited state to a lower-energy state, it emits one or more gamma rays, just as an excited atom emits visible photons upon de-excitation.

There are some nuclear species that have very long-lived excited states, called isomers. When a nucleus is in such a state, it stores this excitation energy, which is subsequently released spontaneously in the form of gamma rays.

An example is an isomer of the nucleus hafnium: $_{72}Hf^{178m}$, shown in Fig. 2. Hafnium is a heavy metal with the atomic number 72. This isomer has a half-life of 31 years, and excitation energy of 2.5 million electron volts (MeV). The energy stored in an ounce of pure $_{72}Hf^{178m}$ could heat 120 tons of water at room temperature to the boiling point. The energy content of $_{72}Hf^{178m}$ is large compared with chemical explosives, and about 100 times smaller than that of the fissile materials in nuclear weapons.

To put this energy into use as a gamma ray laser or gaser, a mechanism is required to release the energy quickly, on demand, and in a controllable manner, not at the useless pace of several decades through normal radioactive decay.

X RAY LASERS

INTRODUCTION

Nova, Livermore's largest laser, has set the standard for x-ray laser research and has been the benchmark against which x ray laser research has been measured. Nova used a very high-energy pulse of light about a nanosecond, 10^{-9} second, or a billionth of a second long to cause lasing at x ray frequencies. Because these high energy pulses heat the system's glass amplifiers, laser sources must be allowed to cool between shots. Laser sources can thus be fired only about six times a day.

LASER CHIRPED PULSE AMPLIFICATION

Scientists had theorized for years that an x ray laser beam could be created using an extremely short, picosecond pulse, which would require less energy. But very short pulses overheated the glass amplifiers, destroying them. Laser chirped pulse amplification, developed in the late 1980s, gets around that problem by expanding a very

short pulse before it travels through the amplifiers and then compressing it to its original duration before the laser beam is focused on a target. If chirped-pulse amplification is combined with lower energies, the pulses do not overheat the glass amplifiers, so the system can be fired several times a day.

A small tabletop x-ray laser that can be fired every three or four minutes was developed at the Lawrence Livermore National Laboratory (LLNL). By using two pulses, one of about a nanosecond and another in the trillionth of a second, 10^{-12} second or a picosecond, range, their laser uses far less energy and does not require the cooling off period (Fig. 4).

USE OF SOFT X RAY LASERS

X ray lasers produce soft x rays, which is to say their wavelengths are a bit longer than those used in medical x rays. Soft x rays cannot penetrate a piece of paper, but they are ideal for probing and imaging high energy density ionized gases or plasmas. X ray lasers are an invaluable tool for studying the expansion of high density plasmas, particularly laser-produced plasmas, making them useful for the fusion program.

Basic research using x ray lasers as a diagnostic tool can fine tune the equations of state of a variety of materials, including those used in nuclear weapons and under investigation by the Stockpile Stewardship Program.

These lasers also have applications for the materials science field, by supplying detailed information about the atomic structure of new and existing materials.

Plasmas do not behave as theoreticians expect them or wish them to do. To verify the plasma modeling codes and provide them with calibration or fudging factors, experiments are needed. With an experiment every three or four minutes on the tabletop x-ray laser, large quantities of data can be produced quickly.

GENERATION OF STABLE X RAY LASING PLASMA

In x ray lasers, a pulse of light strikes a target, stripping its atoms of electrons to form ions and pumping energy into the ions, exciting or amplifying them. As each excited ion decays from the higher energy state, it emits a photon. Many millions of these photons at the same wavelength, amplified in step, create the x ray laser beam. The highly ionized material in which excitation occurs is a plasma by itself, which should not be confused with the plasma that the x ray laser beam is later used to probe.

X ray lasers are specifically designed to produce a lasing plasma with as high a fraction of usable ions as possible to maximize the stability and hence the output energy of the laser. If the target is made of titanium, which has 22 electrons, the ionization process strips off 12 electrons, leaving 10, which makes the ions like a neon atom in electron configuration. Neonlike ions in a plasma are very stable, closed shell ions. They maintain their stability even when faced with temporal, spatial, and other changes. Also, when palladium atoms are stripped of 18 electrons, their ions become like a nickel atom, which is also closed-shell and stable.

COMPACT MULTIPULSE TERAWATT (COMET) LASER DRIVER

In the Nova laser at LLNL, a high-energy, kilojoule pulse lasting a nanosecond or slightly less must accomplish three functions: produce an initial line-focus plasma, ionize it, and excite the ions. Because the excitation, or heating, is happening relatively slowly compared to other plasma behavior, this process is called quasi-steady-state excitation.

The tabletop x-ray laser is configured differently from Nova (Fig. 3). It uses the Compact Multipulse Terawatt (COMET) laser driver to produce two pulses. First, a low-energy, nanosecond pulse of only 5 joules strikes a polished palladium or titanium target to produce the plasma and ionize it. The pulse must accomplish less than the Nova pulse, so less energy is needed.

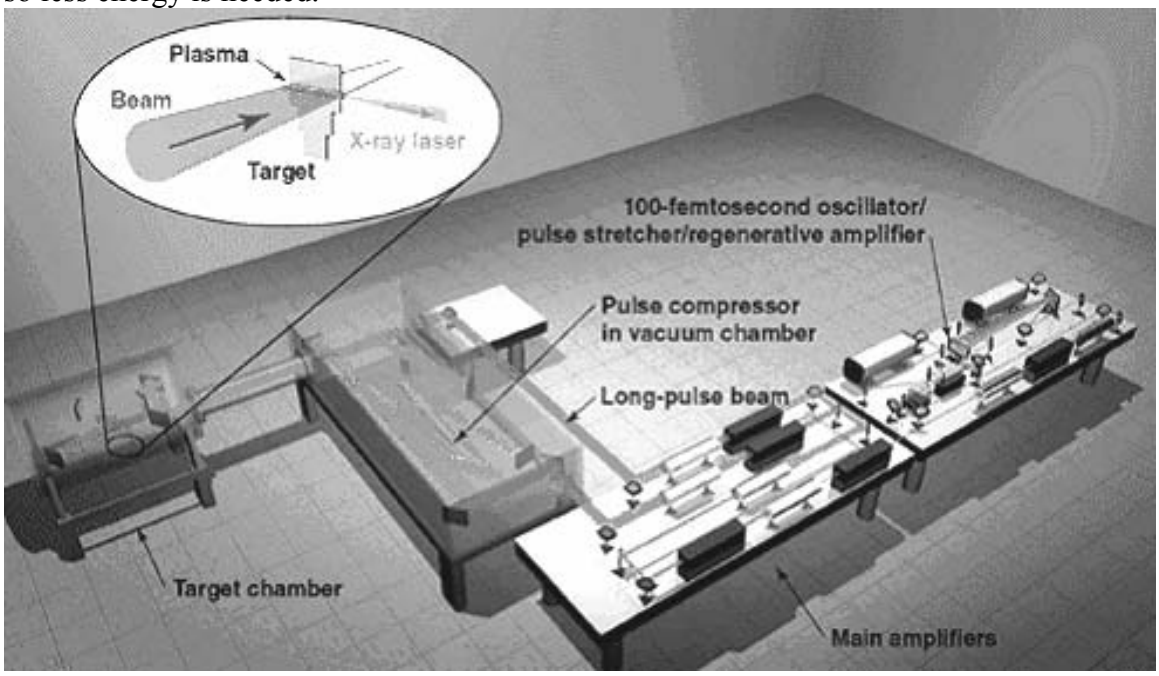

Fig. 3: The Compact Multipurpose Terawatt (COMET) table top x ray laser.

A laser beam irradiates a stepped target producing a plasma which generates an x ray laser beam.

Then a 5-joule, picosecond pulse, created by chirped-pulse amplification, arrives at the target a split second later to excite the ions. Although the picosecond pulse uses 100 times less energy than a Nova pulse, its power is ten times higher because the pulse is one thousand times shorter. And its power density, which adds the length of the target to the power equation, is also very high.

Picosecond transient plasma excitation plays a major role in the laser's effectiveness. During the ionization process, the plasma expands rapidly. In the quasi-steady-state approach used with Nova, excitation occurs while the plasma is continuing to expand and be heated so that much of the deposited energy is lost from the lasing process. With the transient scheme, excitation happens so fast that more ions in the plasma can contribute to the lasing.

For plasma research purposes, the tabletop x ray laser almost has it all: low energy requirements, high power, a repetition rate of a shot every four minutes, and a

short wavelength. The shorter the wavelength of the laser, the more effective it becomes at penetrating high-density plasmas.

NEON LIKE AND NICKEL LIKE X RAY LASERS

Neon-like titanium and nickel-like palladium transient schemes have been studied. The first transient-gain was produced in a nickel-like, x ray lasing at 14.7 nanometers with a laser pump of less than 10 joules (Fig. 4). Various ways to maximize the laser's output, including using different target designs and delaying the arrival of the picosecond pulse to match the propagation of the x-ray laser in the gain region, were considered.

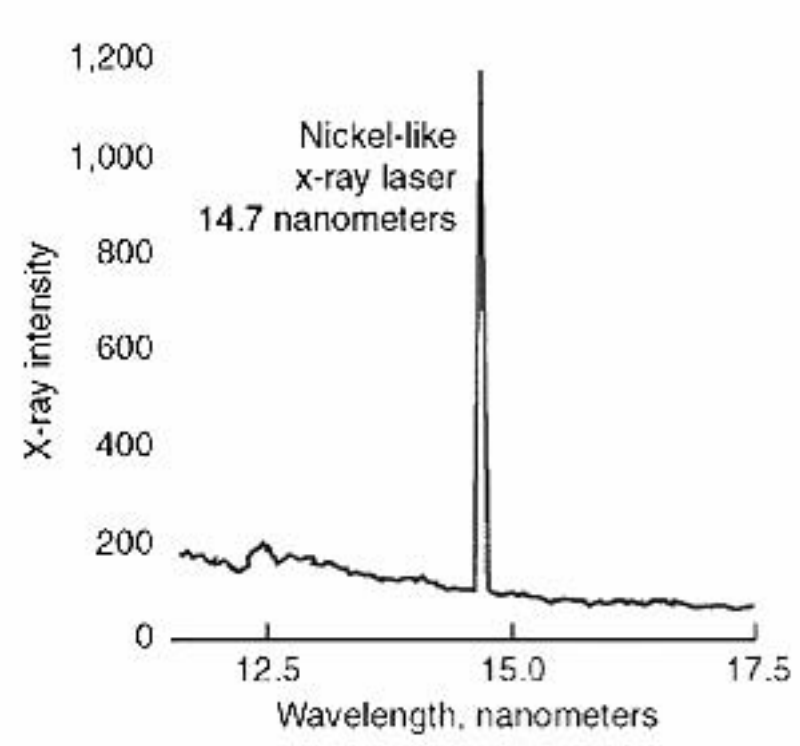

Fig. 4: Nickel like x ray laser lasing at 14.7 nanometer with a line brighter than the other emission lines.

GAMMA RAY LASERS

INTRODUCTION

A nuclear isomer has a nucleus with a higher energy state than its ground state. This excited state is very long lived compared with the usual lifetimes of excited nuclear states. This longer lifetime results because the transition to the nuclear ground state requires a large change in the spatial structure of the nucleus, for a shape isomer, or in the angular momentum or spin of the nucleus between the isomer and the nuclear ground

state, for a spin isomer. Both these types of isomers release energy as electromagnetic radiation in the form of gamma rays to reach the ground state.

Nuclear isomers possess a wide range of lifetimes from the picosecond to the year range. An example is ${}_{83}Ta^{180m}$ whose half life is 10^{15} years with an excitation energy of 75 keV. Its decay is inhibited because the angular momentum of the isomer's nucleus is quite different from the nucleus of the ground state. In its ground state ${}_{83}Ta^{180}$ it is quite unstable and it decays within just 8 hours. Interestingly the isomeric state can be found in naturally occurring samples, but not the ground state.

Another isomer is ${}_{72}Hf^{178m}$ with a half life of 31 years, and a large excitation energy of 2.4 MeV. One kilogram of pure ${}_{72}Hf^{178m}$ embodies an energy content of one terajoule or 10^{12} joules. If accelerated decay can be achieved, just one gram of 100 percent isomeric ${}_{72}Hf^{178m}$ could release one gigajoule or 10^{9} joules of energy, more than the energy release from about 200 kgs of Trinitrotoluene (TNT), high explosive.

PRODUCTION OF ISOMERIC HAFNIUM

A proton linear accelerator generated 800 MeV protons at the Los Alamos Neutron Science Center and bombarded a target of tantalum causing spallation. Spallation is a nuclear reaction occurring in a heavy nucleus, which upon significant excitation can expel up to 20-30 neutrons. An (n,p) reaction occurs in tantalum, leading to the production of isomeric hafnium:

$$ {}_{0}n^{1} + {}_{73}Ta^{178} \rightarrow {}_{72}Hf^{178m} + {}_{1}H^{1} \qquad (2) $$

The irradiated tantalum contains about 4 nuclei of ${}_{72}Hf^{178m}$ per 10,000 nuclei of ${}_{72}Hf^{178}$, which can be chemically separated from the tantalum.

TRIGGERING THE ENERGY RELEASE

The sequence for triggering the release of the energy stored in an isomeric state is theoretically described by an integrated cross section for the pumping of that level with a continuum of x rays. The population is transferred through a gateway state where the selection rules that would otherwise limit the process do not apply. The normal decay from the gateway is accompanied by the emission of immediate fluorescence that leads to the principal state from which the sustained output of power will be emitted. Such processes fall into the general category of shown schematically in Fig. 5.

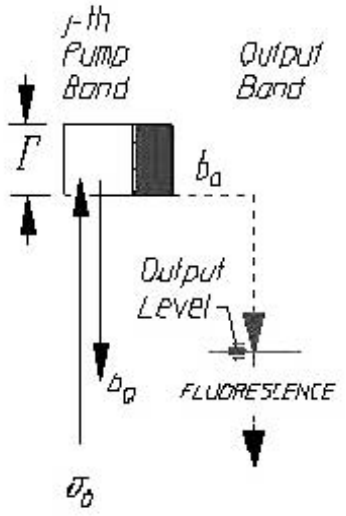

Fig. 5: Energy release from an isomeric state with the (γ, γ') reaction.

Population can be accumulated in the output level by continuing to run the pump cycle for a time comparable to the lifetime of the output state much like charging a capacitor.

All (γ, γ') reactions occurring at energies below the threshold for particle evaporation excite discrete pump bands, or gateways. Although only one gateway is shown, there could be more. Each would be excited at a different pump energy but all would branch to some extent into the same fluorescence level.

DEFORMED NUCLEI

In experimental work the bremsstrahlung from five accelerators in different experimental environments was used to verify the model for the triggering of exawatt materials and to cross-check the accelerator intensities. During these experiments samples with typical masses of grams were exposed to the bremsstrahlung from the five accelerators for times ranging from seconds to hours for the continuously operating machines and to single flashes from the pulsed devices. Results were in agreement with the predictions of the model used with literature values of the parameters. The most detailed confirmation of theory was obtained with the reaction Sr^{87} (γ, γ')Sr^{87m} as shown in Fig. 6.

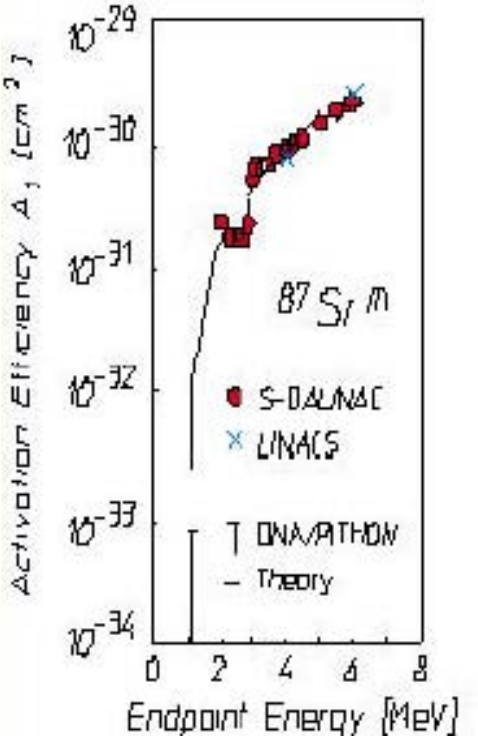

Fig. 6: The activation energy of the $Sr^{87}(\gamma, \gamma')Sr^{87m}$ reaction.

The isomers of many of the exawatt materials belong to the class of nuclei deformed from the normally spherical shape. For those systems there is a quantum number of dominant importance, K which is the projection of individual nucleonic angular momenta upon the axis of elongation. To this is added the collective rotation of the nucleus to obtain the total angular momentum J. The resulting system of energy levels resembles that of a diatomic molecule.

In most cases an isomeric state has a large lifetime because its value of K differs considerably from those of lower levels to which it would otherwise be radiatively connected. As a consequence, bandwidth funneling processes that start from isomeric levels must span substantial changes in K and component transitions have been expected to have large, and hence unlikely multipolarities.

From this perspective the isomer, $_{73}Ta^{180m}$ was initially unattractive as it had one of the largest changes of angular momentum between isomer and ground state, 8 units. However, because a macroscopic sample was readily available, $_{73}Ta^{180m}$ became the first isomeric material to be optically pumped with x rays to a fluorescent level (Fig. 7).

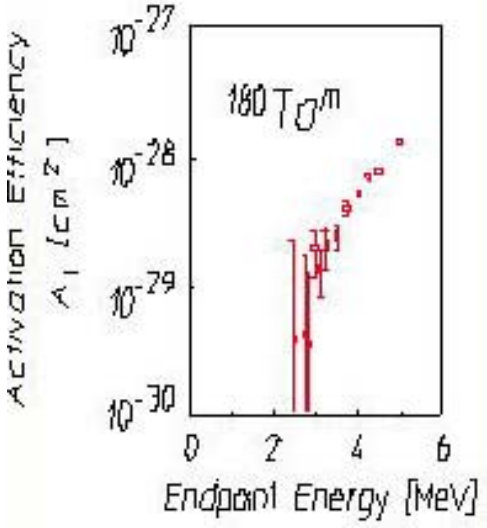

Fig. 7: Activation energy for Ta^{180m}.

This particular isomer, $_{73}Ta^{180m}$ carries a dual distinction. It is the rarest stable isotope occurring in nature and it is the only naturally occurring exawatt material. The actual ground state of $_{73}Ta^{180}$ is 1+ with a half life of 8.1 hours while the tantalum nucleus of mass 180 occurring with 0.012% natural abundance is the 9- isomer, $_{73}Ta^{180m}$. It has an excitation energy of 75.3 keV and a half life in excess of 1.2×10^{15} years.

In an experiment conducted in 1987, 1.2 mg of $_{73}Ta^{180m}$ was exposed to the bremsstrahlung from a 6 MeV linac accelerator and a large fluorescence yield was obtained. This was the first time a (γ, γ') reaction had been excited from an isomeric target as needed for triggering the release of exawatt materials and was the first evidence of the existence of giant pumping resonances. The observation of fluorescence from a milligram sized target implied that an unexpected reaction channel had opened. Usually grams of material have been required in this type of experiment. Analyses of the data indicated that the partial width for the dumping of $_{73}Ta^{180m}$ was around 0.5 eV.

To determine the transition energy, Ej from the $_{73}Ta^{180m}$ isomer to the gateway level, a series of irradiations was made at the S-DALINAC facility using fourteen different endpoints in the range from 2.0 to 6.0 MeV. The existence of an activation edge was seen in the data shown in Fig. 7. The fitting of such data to the model by adjusting trial values of parameters provided the integrated cross sections for the dumping of $_{73}Ta^{180m}$ isomeric populations into freely radiating states. Reported values were 12,000 and 35,000 in the usual units of 10^{-29} cm^2 keV for gateways at 2.8 and 3.6 MeV, respectively. These are significant values exceeding anything previously reported for transfer through a gateway by two orders of magnitude. They are 10,000 times larger than the values usually measured for nuclei.

INDUCED GAMMA EMISSION, IGE

A survey of 19 isotopes conducted with four USA accelerators over a fairly coarse mesh of bremsstrahlung endpoints confirmed the existence of giant resonances for transferring K in the region of atomic masses near A=180 as shown in Fig. 8. Activation edges continued to support the identifications of integrated cross sections for pumping and dumping of isomers that were of the order of 10,000 times greater than usual values.

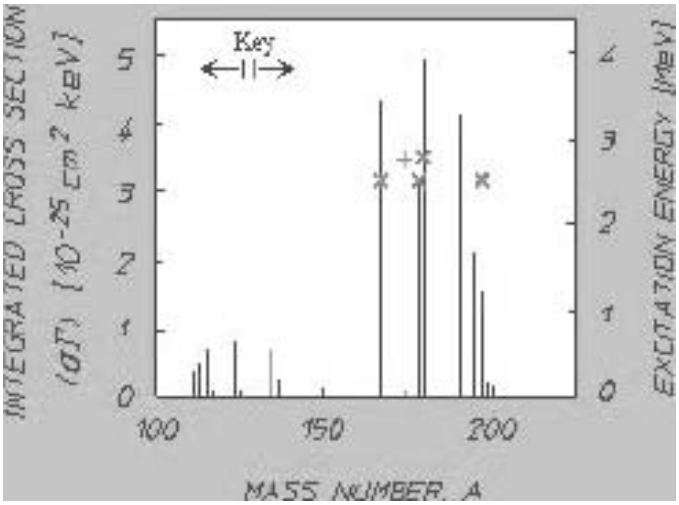

Fig. 8: Integrated cross section and excitation energy of isotopes in the mass number A= 180 region.

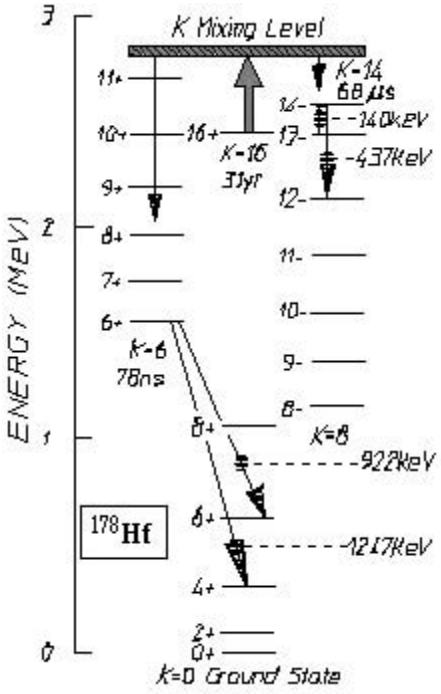

Fig. 9: Energy diagram for the $_{72}$Hafnium^{187m} isomer.

The conclusion of studies at the Center for Quantum Electronics is that the best material for Induced Gamma Emission (IGE) is the 31 year half life isomer of $_{72}$Hafnium^{178} because it should be the easiest to trigger.

The energy level diagram for $_{72}Hf^{178}$ is shown in Fig. 9 with prominent fluorescent transitions indicated. The transfer band for dumping is plotted where the systematics of Fig. 4 would indicate. The remaining physics issues being resolved by research at the state of the art in various institutions are:

1) The energy of the trigger photon,

2) The cross section for triggering with those photons,

3) The precise nature of the output spectra of x-rays.

Isotopes from Er^{167} to Ir^{191} have proven the pervasive occurrence, location and structure of the important nuclear states. The confidence in finding them for the best material, the 31 year half life isomer of $_{72}Hf^{178m}$, rests on interpolations of data solidly established for neighboring nuclei on both sides of its mass value; as opposed to the alternative of requiring the success of long extrapolations from remote points of reference, poorly established.

EXPERIMENTAL RESULTS

C. B. Collins et al. of the University of Texas at Dallas, reported that irradiating samples of $_{72}Hf^{178}$ with x-rays produces a several percent enhancement of gamma rays emission from the isomer. This experiment therefore suggested that the isomer could be triggered to release its energy by irradiating it with a much lower-energy beam.

However, using a very intense x-ray source at Argonne National Laboratory (ANL) did not reproduce the phenomenon reported by the Texas group. The experiment at ANL sets limits on the effect more than a thousand times below the magnitudes reported in the Texas work. There are certain differences between the experiments that might have prevented the experiment at ANL from detecting the effect reported by the Texas group. On the other hand, the results reported by the ANL experiment are consistent with established knowledge about nuclear structure and processes, whereas those from the Texas group are in disagreement with such knowledge.

A collaborative effort between The Lawrence Livermore National Laboratory (LLNL), the Los Alamos National Laboratory (LANL) and Argonne National Laboratory (ANL) was undertaken. They used the Argonne Advanced Photon Source (APS), an electron accelerator designed to produce very intense x-ray beams, as a trigger for the energy release from the isomer.

This x ray source is 100, 000 times more intense than the dental x ray machine used in the earlier experiments. The logic is that such a powerful source should easily lead to the triggering of the isomer's stored energy. A white beam of broad band x rays was also used, not knowing the precise x ray energy required to induce the isomeric hafnium decay. Another aspect of the reasoning is that the white beam would contain all the energies that could induce enhanced decay, with the hope that the decay time would decrease from 31 years to less than a second. The experiment's cross section limits representing the probability of an interaction event between the x rays and the hafnium

isomer were lower by five orders of magnitudes in the relevant energy ranges than the previously reported results. No evidence of triggered decay was observed.

If the Texas result were to be confirmed, putting it to use would require overcoming a series of hurdles, the first being the cost of generating significant amounts of the isomer.

The hafnium nucleus has an ellipsoidal shape and, as a consequence, its excitation spectrum is similar to that of molecules. Below the isomer at 2.5 MeV, which has a rather large angular momentum of 16, there are two rotational bands. The undisturbed isomer decays spontaneously by first de-exciting to the higher rotational band with the half-life of 31 years, then cascading rapidly to the bottom of this band, from where it de-excites to the ground state band with a half-life of four seconds. The Texas researchers suggest that irradiation by x rays excites the isomer to one or more somewhat higher states whose decay is not suppressed by the stringent selection rules associated with very high angular momentum states. These selection rules account for the very long lifetime of the isomer. Moreover, and of importance for applications, the Texas group reports that the transitions from the states they excite above the isomer do not all pass through the state with the four seconds half-life.

The spectrum of $_{72}Hf^{178}$ showing the 31-year isomer, and the state at the bottom of the second rotational band with the four-second half-life, also called an isomer, is shown in Fig. 1. The heavy arrows are the transitions that Collins et al. report as enhanced; the numbers on the transitions are gamma ray energies in keV. The states above the 31 year isomer, which it populates by x-ray absorption, are reported to decay rapidly to the ground state band.

The Texas approach sounds simple enough, and one asks why it was not used earlier. If the phenomenon proves to be real, the reason would be that the reaction rate for x ray photons to resonantly jiggle the isomer into higher states is far larger than what would be expected on the basis of well-established knowledge about nuclei. In contrast, the lower bounds reported by the ANL experiment are consistent with such expectations. The original Texas experiments used a dental x-ray source, but their more recent experiments have also used far more intense x-ray sources. The experiments at ANL have all been done with the Advanced Photon Source, a state-of-the-art electron accelerator designed to produce very intense x-ray beams. The Texas group argues that these intense beams damage the target and produce backgrounds that mask the effect, but the authors of the experiment at ANL have stated that their measurements produce results that are still valid.

DISCUSSION

Given the difficulty of triggering the simultaneous decay of most nuclei in a large sample of $_{72}Hf^{178}$, assuming that the stimulated decay exists; some speculate that it may be possible to achieve release of the energy stored in the whole sample by means of a chain reaction initiated by triggering a small fraction of such a sample. This appears to some as a far-fetched concept. In contrast to a neutron chain reaction in fissile materials, where the neutrons are not lost as they travel from their place of birth to where they induce a fission reaction, the gamma ray photons emitted by any nucleus have a high

probability of quickly disappearing by knocking electrons out of their atoms. Thus processes that do not loose the gamma photons such as Compton scattering should be encouraged to happen. In addition, a chain reaction would require each isomer decay cascade to promptly emit, on average, more than one photon in the energy band required by the triggering mechanism. If all the cascades pass through the four seconds isomer, a chain reaction may not be feasible.

Nuclear physicists in the USA and the rest of the world continue investigating such curious nuclear phenomena.

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