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On the Feasibility of an Impulsively Driven Gamma-Ray Laser

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ON THE FEASIBILITY OF AN IMPULSIVELY DRIVEN GAMMA-RAY LASER

by

J. C. Solem

ABSTRACT

We address the feasibility of a gamma-ray laser initiated by the neutron flux from a nuclear explosive and discuss how we might undertake a research program that will culminate in the Nevada test of such a device. We show how such a device is plausible within our understanding of Mössbauer technology and the kinetics of superradiant systems. We speculate on its scientific application as well as its implications for future weaponry.

FOREWORD

This report is the result of an investigation conducted by the author during 1972 of the feasibility of a nuclear explosive-driven gamma-ray laser. Knowledge of the subject has changed significantly since that time. However, because this work provided the impetus for much subsequent research, it has been found necessary to publish it in a referenceable form.

BACKGROUND

Scientists have been toying with the idea of a GRASER since the first lasers were demonstrated in 1961. The notion has been carried through several cycles of popularity and contempt and, until recently, has been continually clouded by a morass of misunderstanding and misconception. We shall avoid signifying those misconceptions by discussing them here.

To understand the problems involved, we must pay a cursory visit to the basic physics. A GRASER would consist of a thin rod of material containing nuclei in some metastable state; the rod, by its large aspect ratio, would be somewhat analogous to a superradiant optical laser. Gamma radiation would emerge from the end of the rod with an intensity

$$I = I_o \frac{\exp[(\beta - \delta)\ell] - 1}{(\beta - \delta)\ell} , \quad (1)$$

where ℓ is the length of the rod, I_o is the intensity of spontaneous radiation, β is the amplification factor, and δ is the absorption coefficient. Nuclear resonant absorption, Compton scattering, and photoelectric effect all contribute to δ, which is a function of the gamma-ray energy. The amplification is given by

$$\beta = \left(\frac{\pi\hbar c}{E_o}\right)^2 \frac{\Gamma_o}{\Gamma} \frac{f}{1 + \alpha} \eta\xi \quad , \quad (2)$$

where E_o is the gamma-ray energy; Γ_o is the natural (homogeneous) line width of the transition determined from the lifetimes of the upper and lower states; Γ is the actual (inhomogeneous) line width resulting from all broadening mechanisms; f is the Mössbauer factor (the fraction of nuclei that radiate into the Mössbauer line, which is near to the natural line width) α is the internal conversion coefficient; η is the density of excited nuclei; and ξ is the population difference between the upper and lower states. The necessary condition for GRASER action is $\beta > \delta$. This gives a critical density for excited nuclei

$$\eta \geqslant \left(\frac{E_o}{2\hbar c}\right)^2 \frac{\Gamma}{\Gamma_o} \frac{1 + \alpha}{f\xi} \delta \, . \quad (3)$$

For the purist, this expression can also be derived by recognizing the condition for collective emission

$$\frac{\eta\xi\Gamma_o}{(1 + \alpha)\, g} \geqslant \frac{c}{\delta} \quad ,$$

where g is the number of normal oscillators per unit volume.

$$g \quad \frac{8\pi E_o{}^2\Gamma}{(2\pi hc)^2} \quad .$$

Plugging a few numbers into Eq. (3) quickly disposes of the straightforward laboratory techniques for engineering a GRASER. If the nuclei are not bound to a lattice, thermal broadening derives (Γ/Γ_o) out of sight. In this case the Mössbauer factor does not apply ($f = 1$) and the inhomogeneous line width is given by $\Gamma \approx \sqrt{R\Theta}$, where R is the recoil energy of the free nucleus in emission of the GRASER gamma ray. The density of excited nuclei required for grasing enters the realm of atrophysical matter.

Using Mössbauer effect, the only laboratory way to get η into the ball park is to chemically separate samples of highly enriched isomer. This turns out tobe possible because certain chemical bonds are broken by the radioactive decays and produce isomer nuclei. However, this sort of "wet-chemistry" separation requires a lot of time and thus necessitates using nuclei of rather long lifetimes. Hence the effect is defeated by a small Γ_o.

$$\Gamma_o = \frac{h}{2\pi}\left(\frac{1}{T_1} + \frac{1}{T_2}\right) ,$$

where T_1 and T_2 are the lifetimes of the upper and lower states. Even under ideal conditions (nearly perfect crystal lattices) the natural line width is swamped by inhomogeneous broadening from gravitational redshift, interactions between magnetic moments of nuclei, and interactions of quadrapole and higher nuclear moments with electric fields.

In recent years, three techniques have been suggested to overcome the line width and isomer density problem: (1) use chemically separated isomers with techniques developed in nuclear-magnetic-resonance (NMR) research for reducing inhomogeneous broadening; (2) use laser-assisted fast photochemical separation of isomers of intermediate lifetimes, which have much broader homogeneous line widths; and (3) use isomers with very short lifetimes (broad homogeneous line widths) and get the density of isomer nuclei up by manufacturing them in the intense neutron flux of a nuclear explosive. The first scheme would use long-lived isomers and NMR techniques to set nuclear moments in rotation; if the rate of rotation is very fast compared to the lifetime of the isomeric state, the fields of the nuclei average out and the multipole interactions are suppressed. Line width reductions of a factor of a hundred to a thousand have been achieved in analogous NMR experiments. The second technique must be used in conjunction with a fairly intense neutron source because the isomers must be manufactured at the same time they are separated chemically. More imaginative proposals have suggested laser or electron-beam driven microfission capsules as the neutron source for laboratory experiments; in any case, the scheme appears to be very complicated. The third technique, using a bomb in Nevada, is quite straightforward--brute force if you like. We believe it is the most likely to work of the three techniques and offers fantastic possibilities for high-energy laser weapons. The GRASER rod must be exposed to the enormous neutron fluence of a nuclear explosive, and energy densities of megajoules per cubic centimeter are realized in the grasing material. This has the potential of raising the rod to high temperaures, and therein lies the rub. Somehow the energy density must be tolerated without losing Mössbauer effect. I regarded nuclear-explosive pumping as rather difficult until I read the proposal of the Soviet physicists Goldanskii and Kagan, which forms the basis for the experiment described herein.

THE GIMMICK

To build a bomb-powered GRASER we mmust obtain a high enough neutron fluence to create a density of excited nuclei, η, that will satisfy Eq. (3). At the same time, the GRASER rod must be kept cool enough to avoid losing the Mössbauer effect. The sources of heating are (1) recoil from absorption of the neutrons that create the isomer; (2) recoil from the cascade of gamma rays that accompanies transmutation, before the isomer settles to the state from which grasing will occur; (3) heating from absorption of the gamma cascade; and (4) heating by gamma rays from the bomb. In their paper, Goldanskii and Kagan discuss the first three of these heating sources, but deliberately ignore the fourth--probably for classification reasons.

The first gimmick we can use to reduce heating is to dissolve the active nuclei in a matrix of light inactive nuclei for which the gamma path length is long. According to Eq. (3) this reduces the density of excited nuclei required for the system to grase. As long as the dilution is not so complete as to make a critical density unobtainable, this procedure will lead to a system that is less likely to lose Mössbauer effect from heating. It is well known that Mössbauer effect is preserved when active nuclei are dissolved in an inactive lattice and that substantial temperatures can be tolerated if the gamma energy is low enough. For example, the effect is preserved for ^{57}Fe imbedded in glass up to nearly the melting point of the glass.

The best combination we have found so far is ^{180}Ta dissolved in ^{7}Li. The lithium has $\sim$ 1 barn elastic cross section to thermal neutrons and a path length of about 0.5 cm for 10 keV gamma rays. (The next best choice for an inert matrix is ^{9}Be, which has $\sim$ 6 barns cross section ot thermals and a path length of $\sim$ 0.5 cm for 10 keV gammas.) Tantalum-180 can be activated to an isomeric state by absorption of a thermal neutron.

$$n + {}^{180}Ta \rightarrow {}^{181}Ta + \gamma(8\ \text{MeV})$$

There are several properties of ^{180}Ta that make it attractive as the active nucleus for a nuclear-explosive-driven GRASER.

- It has a 1/v-type cross section for absorption of thermal neutrons that drive it to the isomeric state; activation by thermal neutrons minimizes heating of the lattice by neutron recoil. The neutron absorption cross section of ^{180}Ta is not well measured, but is estimated to be $\sigma = 100\ E^{-1/2}$ barns, where E_n is the neutron energy in kiloelectron volts.

- The energy of its first excited state is 6.3 keV, which makes it likely that its Mössbauer factor will be close to unity and will fall off slowly with increasing temperature. This is true for most nuclear species with gamma transitions less than 10 keV; the recoilless emission properties of ^{180}Ta dissolved in a matrix of ^{7}Li will have to be determined experimentally.

- The 6.8 μs lifetime of the first excited state is compatible with the pulse length of thermal neutrons we could create by moderating the output of a fission bomb.

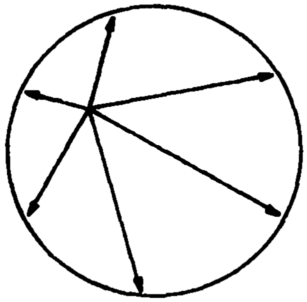
Los Alamos Scientific Laboratory's Group J-14 can build gamma-ray detectors that narrow the band around 6.3 keV by using the window between K edges of differing elements. This would not be true for gamma rays in the 100-keV regime. Much of the technology for appropriate detection and measurement already exists.

- It is expected that the dynamics of the gamma cascade are such that there will be a reasonably large inversion of the first excited state. However, because there are hundreds of states above those shown in the energy level diagrams, it is difficult to get an estimate of this parameter theoretically. Like the other Mössbauer properties of ^{180}Ta, this parameter will have to be determined experimentally.

In general, a good deal of laboratory work will have to be done before we know whether ^{180}Ta dissolved in ^{7}Li would have all of the desirable properties that we ascribe to it out of partial ignorance. Two possible alternatives for the active nucleus are ^{109}Co and ^{99}Mo; research may reveal that they have advantages ofer ^{182}Ta. Perhaps the only deleterious feature of ^{180}Ta is its low natural abundance. At present, the price tag for 5.1% pure ^{180}Ta is $1175 per milligram. This is by no means prohibitive, but we hope that we can get higher purity and that demand for the isotope will bring the price down--an interesting but precedented reversal of economics.

The second gimmick we can use to reduce heating is to form our GRASER out of thin rods or "needles." This will be necessary in the normal course of designing a high aspect ratio superfluorescent GRASER, but by optimal adjustment of the size and density of active nuclei, much of the heating from the gamma cascade can be eliminated. There are two reasons: (1) if the gamma-ray path length is long compared to the cylinder diameter, many gamma rays escape with few or no collisions; and (2) most of the energy from the megaelectron volt gammma rays from the cascade is deposited indirectly by

Rutherford scattering of electrons that are Compton scattered by the cascade gamma rays; so if the electron path length is large compared to the cylinder diameter, energy deposition is further mitigated. The average path length to the surface of a cylinder from a random point within the cylinder is approximately $\pi d/4$. The energy density transferred to electrons can be estimated at



Average distance to surface of cylinder is approximately $\frac{\pi}{4}$ d

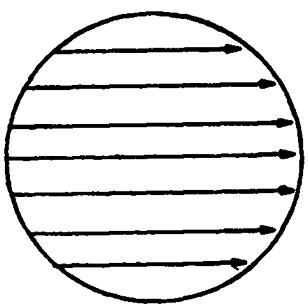
$$\frac{\pi}{8} d \, \bar{\sigma}_c \, (n_1 z_1 + n_2 z_2) \, n \, E_\gamma \, , \tag{4}$$

where $\bar{\sigma}_c$ is the average Compton cross section, n is the density of excited nuclei, E_γ is the cascade energy, and n_1, z_1, etc., are the densities and charges of the active and inactive nuclei; a factor of 1/2 appears because about half the gamma energy is deposited per collision. The fraction of electron energy retained in the cylinder is

$$d/\lambda \quad , \tag{5}$$

where λ is the average electron path length.

The third gimmick is similar to the second: we reduce heating by gamma rays from the nuclear explosive by making the GRASER from thin rods and orienting the GRASER axis perpendicular to the line of sight. This way the heating is mitigated by the escape of Compton electrons to the extent specified by Eq. (5). Because the gamma-ray spectrum from the cascade is similar (for most interesting nuclear species) to the gamma-ray spectrum from a fission bomb, an optimal selection of diameter and active-nuclei density for reducing one heating source will be close to optimum for the other. The average path length through a cylinder, perpendicular to its axis, is $\pi d/4$,



Average distance across cylinder is $\frac{\pi}{4}$ d.

so the energy density transferred to the electrons by a gamma-ray fluence F_γ (MeV cm^{-3}) is

$$\frac{1}{2}\bar{\sigma}_c\,(\eta_1 z_1 + \eta_2 z_2)\,F_\gamma \tag{6}$$

and the factor of Eq. (5) applies to this heating term as well as it does to Eq. (4).

The heating due to scatter and absorption of neutrons is mitigated by moderating the neutron output of the bomb and using an active nucleus with a 1/v-type absorption cross section--not much of a gimmick. The heating due to emission of gamma rays in the nγ reaction is unavoidable--no gimmick applies. The energy density from recoil in neutron capture is approximately

$$\left[\frac{\eta_1}{A_1}\left(1 - e^{-F_n\sigma_1}\right) + \frac{\eta_2}{A_2}\left(1 - e^{-F_n\sigma_2}\right)\right]E_n \tag{7}$$

where E_n is the neutron fluence (cm^{-2}), E_n is the neutron energy, and σ_1 and σ_2 are the nγ cross sections of the active and inactive nuclei. Similarly the energy density from gamma recoil is approximately

$$\left[\frac{\eta_1}{A_1}\left(1 - e^{-F_n\sigma_1}\right) + \frac{\eta_2}{A_2}\left(1 - e^{-F_n\sigma_2}\right)\right]E_R \tag{8}$$

where E_R is the recoil energy. The energy density due to scattering of neutrons is

$$F_n\left(\eta_1\sigma_1^s x_1 + \eta_2\sigma_1^s x_2\right)E_n \tag{9}$$

where σ_1^s and σ_2^s are the scattering cross sections and x_1 and x_2 are the average energy fractions lost per scatter.

THE EXPERIMENT

A good deal of intensive local laboratory work will precede actual design of a GRASER for Nevada test. Assuming that we proceed with ^{180}Ta dissolved in a ^{7}Li matrix, we will have to measure; (1) the ratio of

Mössbauer to natural line width (Γ/Γ_o) as a function of temperature, (2) the Mössbauer factor (f) as a function of temperature, and (3) the population inversion (ξ). It will also be important to get a good measurement of the $n\gamma$ cross section for ^{180}Ta. If the results of this local experimental work are consistent with our estimates, we can proceed to design the Nevada test; if they are not good we may look at other combinations of active and matrix nuclei. In reality, it is probably most reasonable to measure several different combinations at the same time.

We assume the following estimates for the vital parameters involved:

- Mössbauer factor $f = 1$, good up to 100°C (reasonable)
- Internal conversion coefficient: $\alpha = 45$ (measured)
- Population inversion parameter: $\xi = 0.2$ (pure guestimation)
- Line width ratio: $\Gamma/\Gamma_o = 1$ (very optimistic)
- Cross sections for absorption of gamma rays at 6.3 keV

  ^{181}Ta: 9×10^4 barns

  ^{7}Li: 24 barns

Cross sections for the $n\gamma$ reaction

  ^{180}Ta: $100\ E_n^{-\frac{1}{2}}$ barns (reasonable estimate

  ^{7}Li: $5 \times 10\text{-}5\ E_n^{-\frac{1}{2}}$ barns (not very important)

where E_n is the neutron energy in keV.

Cross section for thermal neutron scattering

  $^{180,181}Ta$: 10 barns

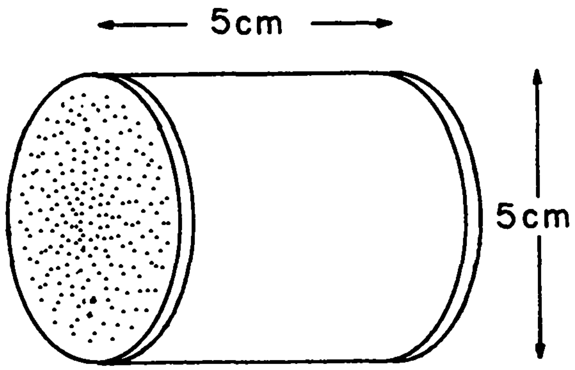
  ^{7}Li: 1 barn

Average fraction of energy lost in neutron scatter

  $^{180,181}Ta$: 0.1

  ^{7}Li: 0.25

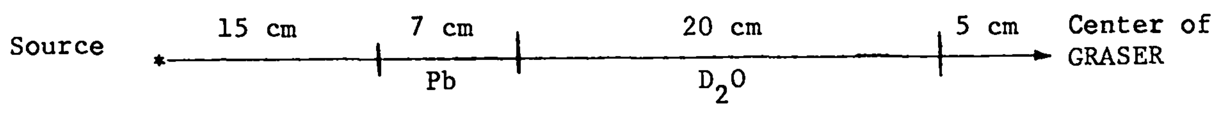
The optimal mixture of ^{180}Ta in ^{7}Li is not obvious; here we will take one part in four thousand as a reasonable guess. This will make the specific heat of the GRASER material very close to that of pure ^{7}Li.



GRASER ROD-ASSEMBLY PACKAGE
100,000 25m needles ^{7}Li + 0.025% ^{180}Ta

Here is one possible design for the GRASER we might test in Nevada. It would consist of a package of tiny needles separated from the bomb by shielding and moderating material. The needles would be 25 μ (about one mil) in diameter and 5 centimeters long. They would be aligned in parallel with a 100 μ spacing between their axes, and arranged so the centers of no three needles would be in a straight line. This would minimize the possibility of cross talk between the needles and potential superfluorescent grasing in the radial direction--such an arrangement is geometrically possible. The diameter and length of the package would be 5 cm, and it would contain approximately 20,000 needles. To minimize heating of the needles by Compton electrons knocked out of neighboring needles, we might make every seventh or so needle out of an inert material and impose potential difference so that Compton electrons would be collected; this procedure has its difficulties and there may be other approaches.

The beam divergence would be determined by the aspect ratio, which gives on the order of 1/2 milliradian. This is far above the diffraction limit, which is about 8 milliradian. The planned configuration of the experiment is displayed above, this arrangement is shown schematically below.



The lead serves the triple purpose of attenuating the gamma radiation from the bomb, slowing debris motion, and blocking x-radiation that will destroy the GRASER. It is hoped that the system will remain intact for a few microseconds required for the GRASER to operate. Assuming motions on the order of a millimeter per shake, the GRASER should be unaffected. If this estimate is in error, redesign to accommodate greater durations should be straightforward. The heavy water is used to moderate the neutron output. Here we are designing for a 6-μs pulse of 10 eV neutrons; needless to say, this idealization cannot be realized. A detailed calculation of the time-dependent neutron spectrum and flux is not too difficult with present codes, but requires the investment of some computer time. A detailed calculation of the debris motion is also simple to obtain if we are willing to pay for it.

Assuming a 1-kiloton device, the gamma-ray fluence at the center of the GRASER is approximately

$$F \sim 3.5 \times 10^{15} \text{ MeV cm}^{-2} \tag{10}$$

The neutron fluence at the center of the GRASER is approximately

$$F_n \sim 2.1 \times 10^{21} \text{ cm}^{-2} . \tag{11}$$

(We have consistently used the confusing, but standard, definitions for gamma-ray and neutron fluences.)

The density of $^{180}Ta(n,\gamma)^{181}Ta$ reactions caused by fluence in Eq. (9) is

$$\eta = \eta_1 \left(1 - e^{-\sigma_1 F_n}\right)$$

Assuming that the baseline design characteristic of $E_n \approx 0.01$ keV is met, we have a converted-nucleus number density of

$$\eta \approx 1.02 \times 10^{19} \text{ cm}^{-3} \tag{12}$$

The absorption length for a 6.3-MeV gamma ray in this mixture is 0.46 cm, so Eq. (10) satisfies the inequality in Eq. (3). The amplification is given by Eq. (2) as

$$\beta \sim 4.9 \text{ cm}^{-1} .$$

From Eq. (1), this implies a gain of about 2×10^4 for our five-centimeter needles. Because of the short pathlength for 6.3 keV gammas, only about 9%

of the nuclear energy in the grasing transition will actually escape the needles. The energy available is 7.30 x 10^{16} MeV cm^{-3}, which means the GRASER should deliver about 2.6 kilojoules to the detectors (an equal suze pulse will be emitted in the opposite direction). Detectors should cover a range from 3000 to 30 joules.

To preserve Mössbauer effect the GRASER needles must be reasonably cool. Here are the components of GRASER-needle heating.

Cascade Heating

In Eq. (4) we have $\sigma_c(\eta_1 z_1 + \eta_2 z_2) = 9.3 \times 10^{-2}$ cm^{-1}, and the average energy for the cascade is 8 MeV. This gives 7.47 x 10^{15} MeV cm^{-3} for Eq. (4). The pathlength for a 1-MeV electron in the GRASER material is about 1 cm. Assuming that this is the average energy of Compton electrons from the cascade, multiplying Eqs. (4) and (5) gives a net heating of

$$1.87 \times 10^{13} \text{ MeV cm}^{-3}, \tag{13}$$

assuming that electrons knocked out of one needle do not heat other needles.

Bomb Gamma-Ray Heating

The net heating from gamma rays emitted by the bomb is obtained by using the fluence at the center of the GRASER [Eq. (10)] in Eq. (6) and multiplying by Eq. (5). The result is

$$4.08 \times 10^{11} \text{ MeV cm}^{-3}, \tag{14}$$

again assuming no cross-heating between needles.

Neutron Capture Heating

The net heating due to neutron capture in the nγ reaction is given by Eq. (7). Using the neutron fluence given in Eq. (11) and assuming our baseline energy for the average of the moderated neutrons, $E_n \backsim 0.01$ keV, we obtain a neutron capture heating of

$$6.31 \times 10^{11} \text{ MeV cm}^{-3}. \tag{15}$$

Gamma-Ray Recoil Heating

The net heating by recoil from gamma rays emitted in the cascade is given by Eq. (8). Assuming $E_R \approx 20$ keV the energy density is

$$1.26 \times 10^{15} \text{ MeV cm}^{-3} . \tag{16}$$

Neutron Scatter Heating

The net heating from neutrons being scattered by the active and inactive nuclei is given by Eq. (9) as

$$2.44 \times 10^{14} . \tag{17}$$

The heating sources are dominated by the gamma-ray recoil. Adding up the energy densities (13), (14), (15), (16), and (17) gives a total heating of

$$1.52 \times 10^{15} \text{ MeV cm}^{-3} .$$

This means that if the GRASER were cooled with dry ice to -75° before the nuclear detonation, the total heating would bring it to about $+57^{\circ}$, well below the melting point and in a region where Mössbauer effect should be preserved. Further insurance could be bought by cooling it with liquid nitrogen to -181°C. In this analysis, we have ignored possible damaging of the GRASER medium by the few fast neutrons from the bomb that will pass through the moderator without scattering. Radiation damage of this sort could alter the host lattice so Mössbauer effect is lost.

THE PAYOFF

This program will require a substantial investment of effort to make the laboratory measurements that are a necessary prelude to an actual experiment. When we actually go to Nevada, the cost will be even greater. However, it seems to me that the product of the size of the payoff (huge) and the probability of success (moderate) justifies a substantial investment.

As a scientific achievement, demonstration of a gamma-ray laser, even in the awkward environment of a Nevada test, would likely cause a minor revolution in technology. It would certainly stimulate world-wide interest in pursuing means of duplicating such effects in the laboratory, and probably usher in an era of new instrumentation and measurement techniques. While it is not the kind of achievement that is likely to buy anyone a ticket to Stockholm, it certainly would be a feather in the Laboratory's collective cap.

Here are some of the applications that have been mentioned if the GRASER were to develop into a well-controlled instrument.

- Power Transmission. Because of its great penetrating power and narrow divergence, the GRASER could be used to transmit power from earth to objects in space--satellites, interplanetary probes, etc. The beam could also be used to transmit impulses for propulsion, orbital corrections, etc.
- Microholography. Because of the short wavelength, a gamma-ray laser might be used to obtain holograms of molecular structure, if one had a way to record the proper information.
- Precision Measurement. The short wavelength may allow a sweeping extension of the measurement technology that has developed around lasers; perhaps to the point where the uncertainty principle renders further refinement meaningless.
- Medicine. The penetrating power of a GRASER might revolutionize radiotherapy techniques.

Of more immediate interest, even if the GRASER could only be pumped by a nuclear explosive, it would make one hellava weapon. In the illustrative example of a Gedanken Nevada Test described in the previous paragraphs, grasing transition energy densities of tens of kilojoules per cubic centimeter were calculated. Even with its complicated and space-consuming needle-bundle-structure, a megajoule GRASER would fit in a breadbox--sans bomb, of course.

Gamma rays might provide an effective kill mechanism if used against reentry vehicles. Neutrons produced in (γ,n) reactions could melt the pit of a weapon and high-energy Compton-scattered electrons are sure to produce an enormous EMP, which might tear up electronics--the warhead electrical system, fusing and firing, etc. Its potential effectiveness against softer targets--personnel (in tanks, for example), satellites, unmanned aircraft, etc.--is an exercise for the reader.

A particular advantage is the great penetrating power of gamma rays. A GRASER-bomb weapon might be used quite successfully within the atmosphere. Unlike "conventional" laser weapons, its effectiveness would be unaltered by meteorological conditions (clouds, fog, smoke, rain, etc.) and by the surface reflectivity of the target. Gamma radiation is also particularly lethal to personnel, the weakest link of most military systems.

I think even the most cynical of critics would agree that if we demonstrated a gadget with a grasing transition energy density within an order of magnitude of the device described in this proposal, it would open new vistas for the future of weaponry. Frankly, it makes my skin crawl to see so much hard evidence in the open literature that the Soviets are carrying on an intensive research program in this area, and to realize that we are doing nothing.

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