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NUCLEAR ISOMER SUITABLE FOR GAMMARAY LASER

Shacheenatha Jha
Principal Investigator

University of Cincinnati
Cincinnati, Ohio 45221

Introduction:

The necessary conditions for the successful operation of Gamma-ray Lasers (Gasers) are,

a) population inversion

b) minimum electronic absorption of the gamma ray in the medium

c) recoilless emission of the gamma rays to permit stimulated emission

d) absence of nuclear recoilless absorption to avoid line broadening

e) a sufficiently long medium

Recent review articles(1,2) have described the difficulties which have to be overcome in successfully realizing a gamma-ray laser. The state of our knowledge of nuclear structure and of the interaction of the nucleus with its environment was insufficient to allow the early pioneers to foresee many of the problems[3,4].

Perhaps the most difficult of the originally perceived problems, how to obtain a density of inverted states sufficient to achieve lasing, has not been solved. There is, however, no known fundamental limitation to achieving high densities; and man's continuing effort to make his sources more powerful may someday solve the intensity problem[5].

In this paper we assume that the nuclear isomers mentioned in published papers have inherent limitations. We assume also that the judicious use of Bormann effect or the application of the total external reflection of low-energy gamma radiation at grazing angle of incidence may permit the use of a GASER crystal sufficiently long to achieve observable stimulated emission.

1. V.A. Bush and R.N. Kuzmin, Sor., Phys. Usp 17, 942, (1975).
2. G.C. Baldwin and R.R. Khokhlov, Phys. Today, 28, 32, (1975).
3. B.V. Chirikov, Sov. Physiks JETP 17, 1355, 1963.
4. W. Vali and V. Vale, Proc. IEEE 51, 182, 1963.
5. M.N. Yakimenko, Sov. Phys. 17, 651, 1975.

We suggest that a long-lived 0^+ isomer decaying by low energy gamma-ray emission to a short-lived 2^+ excited nuclear state would be an attractive Gaser candidate. We suggest that the nuclear isomer be incorporated in a matrix of refractory material having an (EFG) electrostatic field gradient whose principal axis lies along the length of the medium. This will result in the preferential transmission of electric quadrupole radiation (some fraction of it, recoil-less) along the length of the medium.

General Consideration of the Nuclear Isomer and the Matrix:

When dealing with atomic nuclei, the achievement of a population inversion is a simple task. ^{114m}In (half-life 50 days, spin and parity 5^+) has been suggested for a long time. The energy of the isomeric transition ($5^+ \rightarrow 1^+$) is 191.6 keV. It may be pointed out that the energy of the transition is especially critical. The parasitic absorption by the atomic electrons falls off as the energy of the gamma ray increases, while the cross-section for the stimulated emission is proportional to the inverse square of the energy of the gamma ray $(E)^{-2}$. The latter consideration leads one to select a low energy isomeric transition. There is another reason for selecting low energy transitions. Success in achieving laser action with atomic nuclei critically hinges on the probability of recoilless emission of the gamma ray. The recoilless fraction f is given by

$$f \propto \exp\left(-\frac{E_\gamma^2/2Mc^2}{k\Theta_D}\right)$$

where $E_\gamma^2/2\,Mc^2$ is the recoil energy and Θ_D is the Debye temperature of the matrix. The recoil-free fraction f is negligible for gamma ray transitions of energy greater than about 150 keV.

Gamma radiation emitted between nuclear level $2^+ \rightarrow 0^+$ or $0^+ \rightarrow 2^+$ actually involves transitions from or to the sublevels $m = \pm 2$, ± 1 and 0. If the matrix in which the nuclear isomer is incorporated is non-cubic and more especially, the electrostatic field gradient q is axially symmetric, then the sublevels split and the three transitions are shifted in energy as shown in figure 1. The angular distribution of the gamma radiation with respect to the symmetry axis is given by

$$W(\theta) = \tfrac{1}{2}(1 - \cos^4\theta) \text{ for } \Delta m = \pm 2$$

$$W(\theta) = \tfrac{1}{2}(1 - 3\cos^2\theta + 4\cos^4\theta) \text{ for } \Delta m = \pm 1$$

$$W(\theta) = 3(\cos^2\theta - \cos^4\theta) \text{ for } \Delta m = 0$$

These radiation patterns are shown in figure 2 and clearly demonstrate that if one has a 0^+ or 2^+ isomer incorporated in a non-cubic crystal, which has a symmetric electrostatic field gradient whose principal axis lies along the long axis of the crystal, then the $\Delta m = \pm 1$ component is preferentially emitted along the crystal axis. The cross section for stimulated emission is likewise greatest along the long axis of the crystal. If the energy of the gamma ray is not too high and the Debye-temperature of the matrix is high enough, there may exist a large fraction of recoilless gamma-ray photons. When one of these photon interacts with another nucleus in the 0^+ or 2^+ isomeric state, then a stimulated emission will occur. However, only the $\Delta m = \pm 1$ photons travelling along the axis of the crystal, will have an energy match with the $\Delta m = \pm 1$ substates. The gamma rays arising from the other two sublevel transitions would emerge preferentially perpendicular to the axis of the crystal.

These ideas are based on Mossbauer absorption experiments for $2^+ \to 0^+$ transitions. The absorption of the recoilless photon in a tungsten disulfide ($W\,S_2$) single crystal (hexagonal close packed) which has an EFG with principal axis along the c-axis at each tungsten nucleus gave the results shown in fig. 3a. Only a single component $\Delta m = \pm 1$, is resonantly aborbed when the recoilless photon is incident travelling along the c axis. A similar result is shown in fig. 3b for the $2^+ \rightarrow 0^+$ transition in ^{178}Hf where the gamma ray travelling along the axis of the hafnium metal single crystal was resonantly absorbed. In both cases, the results confirmed that only the $\Delta m = \pm 1$ transition is absorbed parallel to the symmetry axis. So it is inferred that the $\Delta m = \pm 1$ component of the $2^+ \leftrightarrow 0^+$ transition from an isomer incorporated in a matrix with a symmetric electrostatic field gradient along the long axis of the crystal will be emitted preferentially along the long axis of the crystal.

Filamentary Alignment of the Nuclear Isomers:

It was recognized by the inventors of the gamma ray laser concept that the alignment of the active atoms along a single axis could solve the problem of the non-existence of mirrors with which to form a cavity. Whisker crystals were suggested as a possible materials configuration.

The idea of a whisker configuration can be combined with the anisotropic distribution of the $\Delta m = \pm 1$ component of $0^+ \leftrightarrow 2^+$ quadrupole radiation. What is required to do this is an electric field gradient along the whisker filament and the crystal structure of the filament to be symmetric about the whisker axis. The concept is shown in figure 4.

Preferred Level Arrangement for the Nuclear Isomer:

As we have indicated, a long-lived isomer, having a spin sequence of levels $2^+ \rightarrow 0^+$ or $0^+ \rightarrow 2^+$ in a host having an axially symmetric field-gradient, will provide a directed propogation of the gamma radiation. Additional considerations favor the situation $0^+ \rightarrow 2^+$, i.e. the isomeric state should be the 0^+ state, the lower state should be the 2^+ state, and both states should be above the ground state. Whenever the ground state takes part in the isomeric transition, one cannot avoid the recoilless absorption of the gamma ray, causing an excitation from the ground to the isomeric state. This results in the broadening of the gamma-ray width and a loss of gamma-rays from the beam direction. Any broadening of the gamma-ray linewidth reduces the cross-section for the stimulated emission σ_o,

$$\sigma_o = \frac{\lambda^2}{2\pi}\,\frac{f}{\Gamma\tau}\,\frac{\beta}{1+\alpha}$$

Here λ is the wavelength of the radiation.

Γ total width

τ = the effective lifetime of the transition. If the two levels are both unstable, having a mean life $t_{upper} = t_n$ and $t_{lower} = t_\ell$, then $\tau = 1/({}^1/t_u + {}^1/t_\ell)$

β = branching ratio of the isomeric transition

α = internal conversion coefficient

f = recoilless fraction.

When the transition does not involve the ground state, there will be no nuclear absorption of the recoilless gamma rays and consequently no broadening of the linewidth on this account. In addition, there will be no broadening of the 0^+ level due to stochastic field gradients or a distribution of magnetic fields at the nucleus, since the 0^+ state has no moment. The only factor still causing the broadening of the 0^+ state will be the inhomogeneous isomer shift. As pointed out by Baldwin and Khokhlov, the additional broadening, for nuclear lifetimes shorter than 10^{-6} sec., is negligible and the product $(\Gamma\tau)$ is essentially unity.

It may be clearly stated that we have examined only the integral spin possibilities. We do not rule out nuclear isomers involving half-integral spins. The question as to whether 0^+ isomers exist which decay with a mean-life of 10^{-6} sec or less and having a transition energy of tens of keV can only be answered by studies in nuclear isomerism. In what follows a short review is given of the occurrence of isomerism in even A nuclei. It is quite possible that odd-odd nuclei will provide a rich variety of isomers, but our knowledge of such nuclei is rather limited. We shall therefore confine our attention to even-even nuclei.

Isomers in Even-Even Nuclei:

Among the even-even nuclei are to be found some (rare earth and actinide nuclei) which are permanently deformed. The low-lying spectra of such nucleides are given in fig. 5. They consist of a rotational band built on the 0^+ ground state, and higher up, rotational bands built on the beta vibrational 0^+ and gamma-vibrational 2^+ states. The transitions among the levels of these bands are rather fast. The isomers observed in such nuclei are mostly high-spin isomers involving two-quasi-particles, four-quasi-particles and six-quasi-particles. These isomers have all been located in ^{176}Hf whose decay scheme is given in fig. 6. The 9.5 μ sec. 1333.1 keV 6^+ and 9.8 μ sec. 1559.3 keV 8^- states are two-quasi-particle states, the 401 μ sec. 14^- 2866 keV state is a four-quasi-particle state, and the 43 μ sec 22^- 4863.6 keV state is a six-quasi-particle state. Low spin 0^+ isomers among deformed nuclei can only be shape-isomers like the ones which have been found among the transuranic elements*. It may be pointed out that many 0^+ states have been located among the excited states of the rare-earth nucleides by (p,t) reaction. In order for the existence of the shape isomers in trans-rare-earth region to be confirmed, reaction gamma ray spectroscopic studies will have to be carried out.

Among the so-called vibrational nucleides, the low-lying excited states are usually the first 2_1^+, the second 0_2^+, and a 4^+ state as shown in figs. 7 and 8 for even-even molybdenum and ruthenium nucleides. The location of the 0_2^+ level changes from nucleus to nucleus. If the energy difference between the 0_2^+ and 2^+ states is not too large the upper 0_2^+ states become long-lived. The lifetime of such states is still longer if the 0_2^+ state happens to have a nuclear structure very different from that of the 2_1^+ state. Examples of such isomers are given if fig. 9 for ^{70}Ge and ^{42}Ca.

*Nuclear Fission-Vandenbosch and Huizenga-Academic Press (1973), pp. 59-76.

Recent studies of even-even selenium isotopes show a systematic shift of the 0_2^+ state as one goes from ^{76}Se to ^{72}Se as shown in fig. 10. The 0_2^+ state in ^{72}Se at 937 keV is only 75 keV above the 2_1^+ state at 862 keV and is excited in nuclear reactions and also in the radioactive decay of 1.3 min ^{72}Br. Similar states occur in ^{74}Se. The 0_2^+ state is excited in heavy-ion nuclear reactions and in the radioactive decay of 25 min. ^{74}Br.

Low-lying 0_2^+ states have recently been found in heavy ion nuclear reactions and in the radioactive decay in light isotopes of mercury (fig. 11). In the decay of 28-sec. ^{186}Tl and 4.5 sec. ^{186m}Tl, the second 0_2^+ has been located at 522 keV, only 117 keV above the first 2^+ state in ^{186}Hg. In ^{188}Hg the second 0_2^+ state has been found at 824 kev, 57 keV below the second 2^+ state. The state is fed by the decay of 71 sec. ^{188}Tl. The lifetimes have not been measured. Such states have been theoretically predicted by Kolb and Wong in very light even-even mercury isotopes.

These examples illustrate the possibility that further research may reveal an excited 0^+ isomer of suitable lifetime and energy to be suitable for gamma-ray lasers.

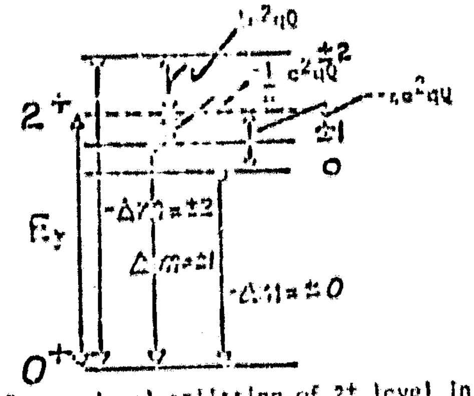

Fig. 1 Energy level splitting of 2^+ level in a field gradient and also showing the three transitions to a 0^+ level.

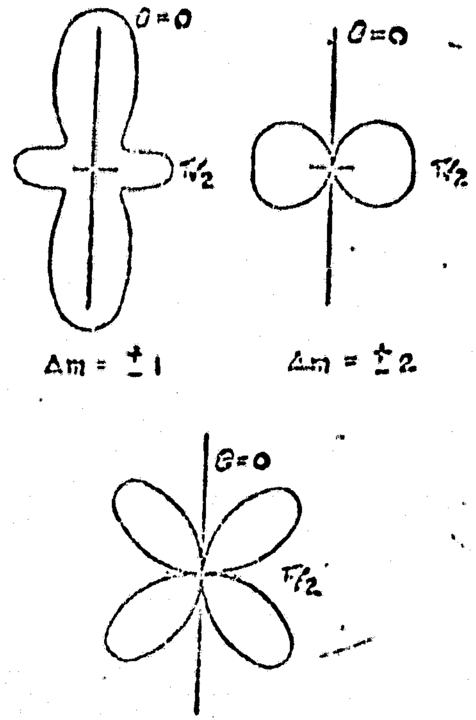

Fig.2 Electric quadrupole angular distributions for the three components of a 2^+ level.

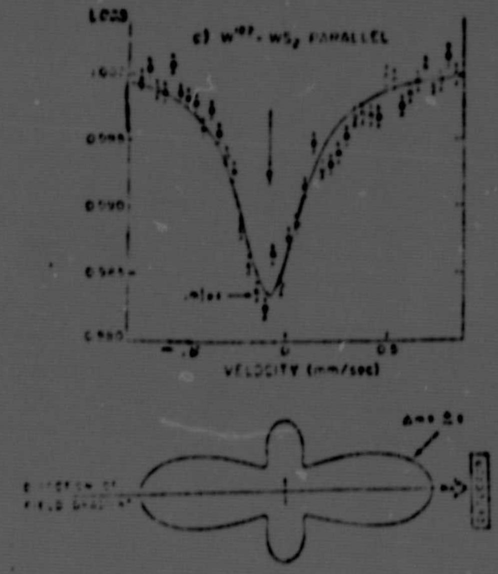

Fig.3a Mossbauer transmission experiment of the $2^+ \rightarrow 0^+$ transition in WS_2 for the case when the incident photon is aligned with c axis of the crystal.

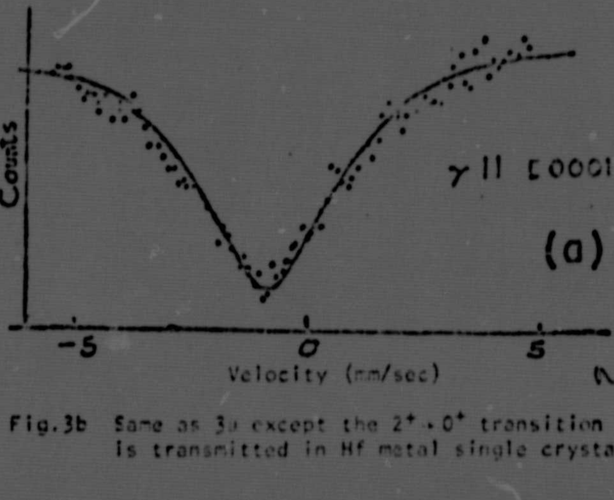

Fig.3b Same as 3a except the $2^+ \rightarrow 0^+$ transition is transmitted in Hf metal single crystal.

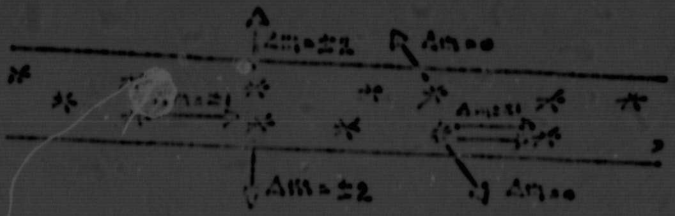

Fig.4 Schematic illustration of nuclei in isomeric states [illegible], aligned in filaments and emitting quadrupole radiation when an electric field gradient is present and is in the filamentary direction.

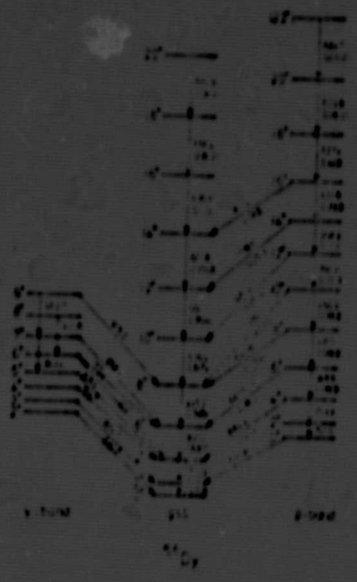

Fig. 14: Excitation energies in ¹⁶⁶Er for the ground states, the s-vibrational and the γ-vibrational bands. The levels are ordered into bands according to the largest reduced E2 transition probabilities. One should remark that the s-vibrational band starts to be the yrast band for all levels with $J^{\pi} = 16^{+}$ and higher. The data have been measured in a collaboration between Jülich and Louvain-la-Neuve [32].

Fressler: Reactions between
complex nuclei.
Ed. Rh Robinson et al
North Holland Publishing Co (1974)
p 450

Fig 5

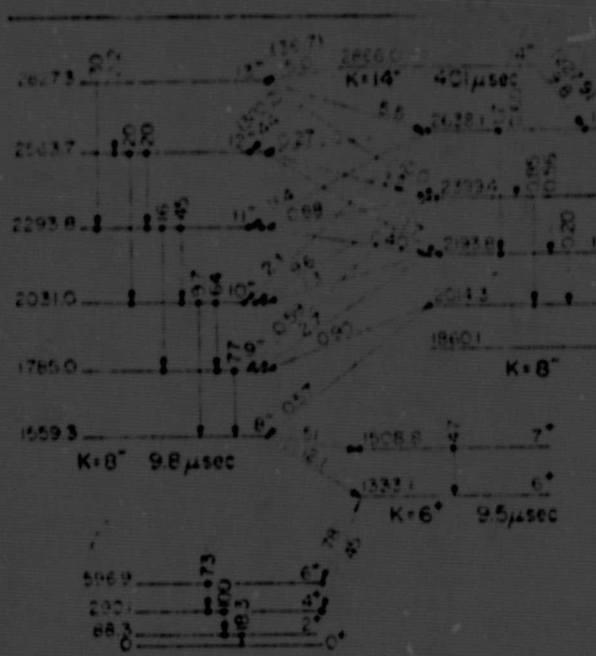

FIG. 1. Decay scheme of 4-qp $K^{\pi} = 14^{+}$ isomer in ^{178}Hf. The γ-ray relative intensities of all transitions are indicated; the energies of the transitions directly de-exciting the isomer are given in parentheses. Filled circles indicate γ rays entering and leaving a level in prompt coincidence.

Khoo et al
Phys Rev letters 35, 1256, 1975

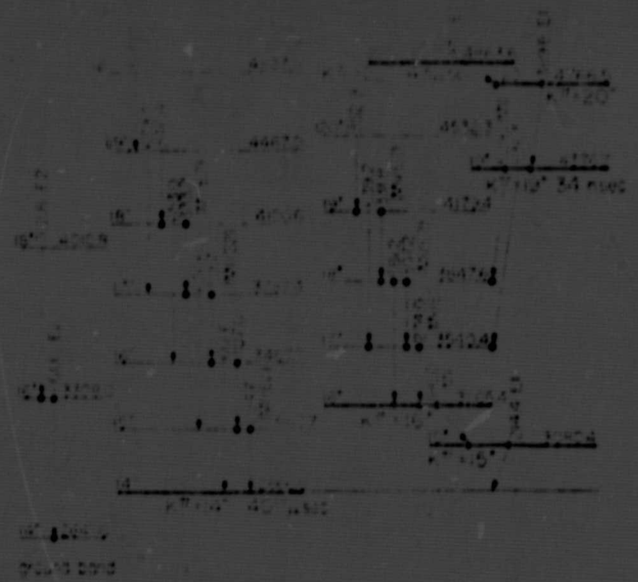

FIG. 1. Partial level scheme for ^{178}Hf showing four- and six-qp excitations and upper portion of ground band. Assignments in parentheses are tentative. Filled circles indicate γ rays entering and leaving a level in prompt coincidence.

Khoo et al
Phys Rev letters 37, 823, 1976

Fig 6

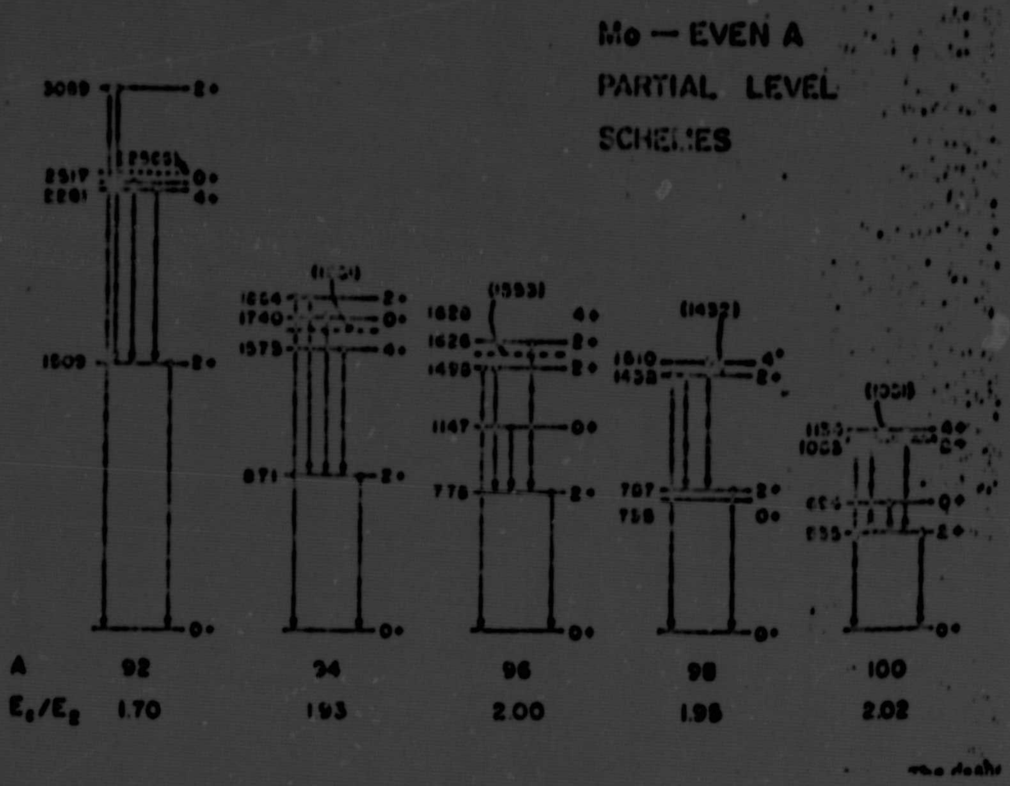

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fig 7

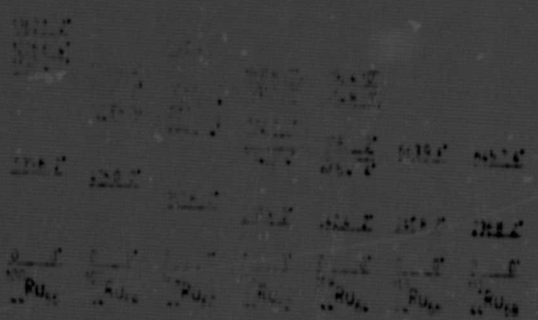

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fig 8

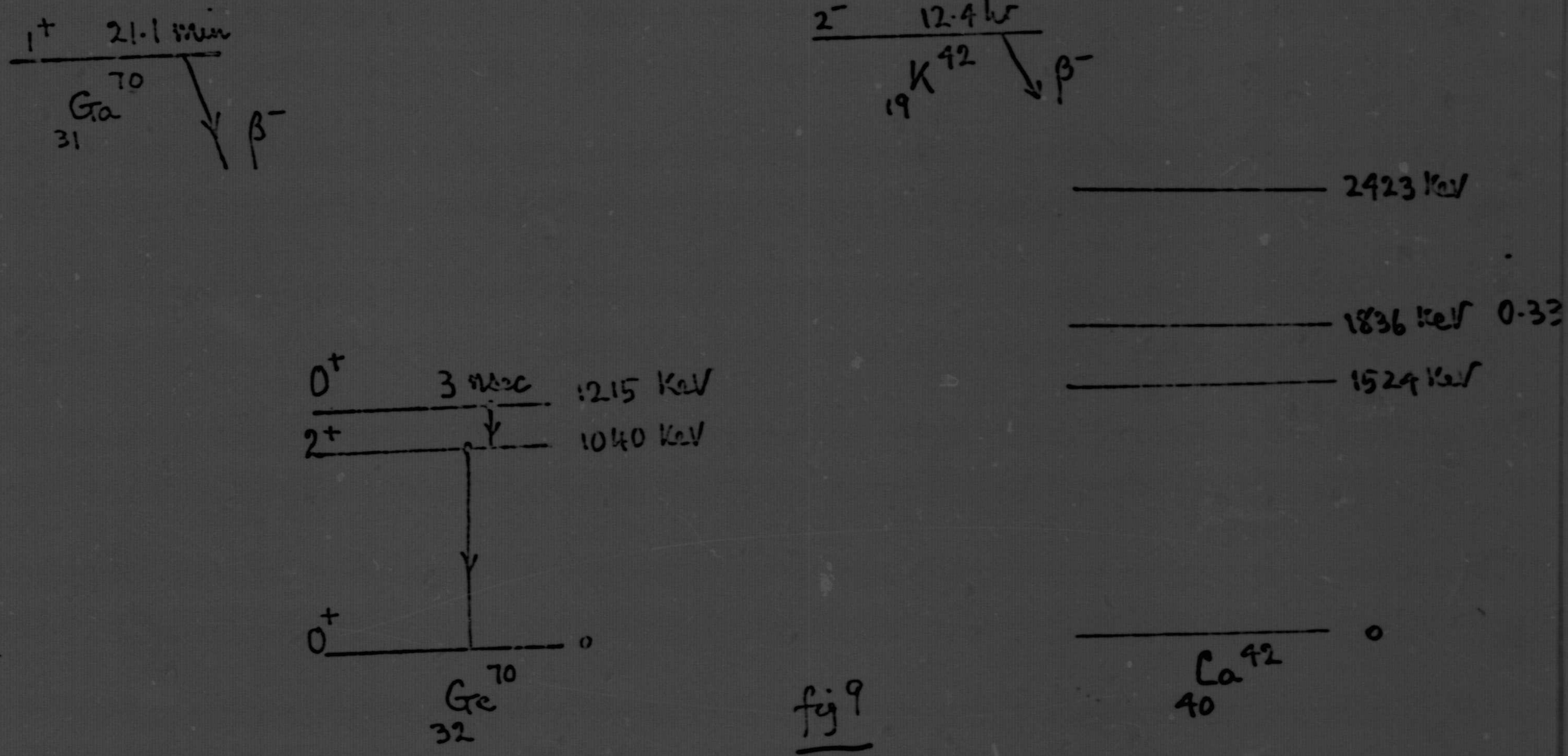

fig 9

Table of Isotopes: Lederer et al

L Nolte et al
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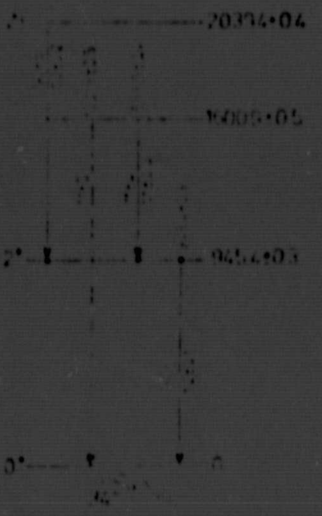
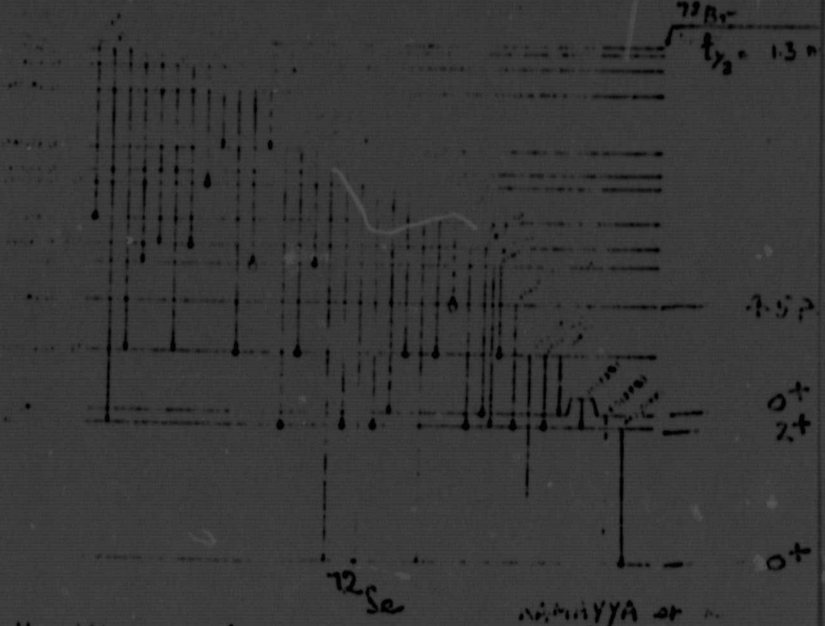


Nolte [illegible]
Zeits f Physik 268, 267, 1974



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Phys Rev 12[illegible]
J. H. Hamilton
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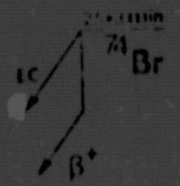
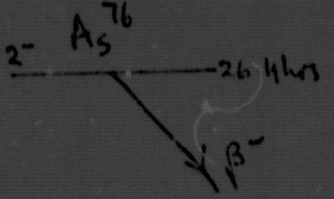
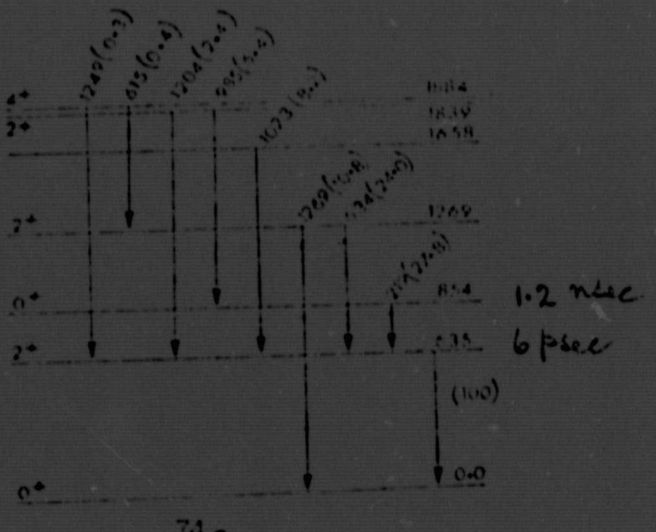
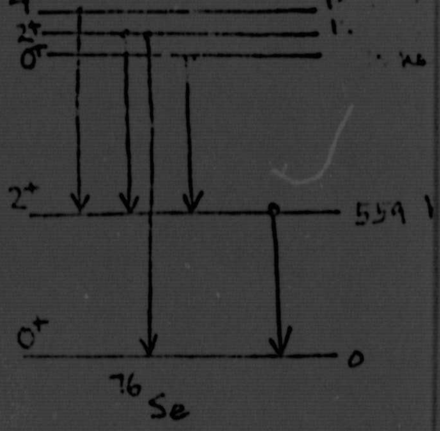




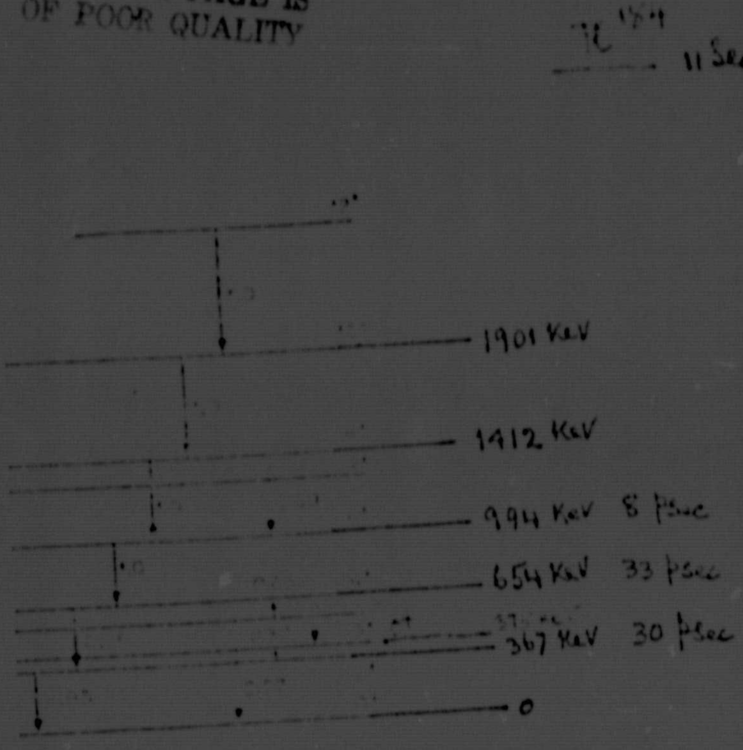


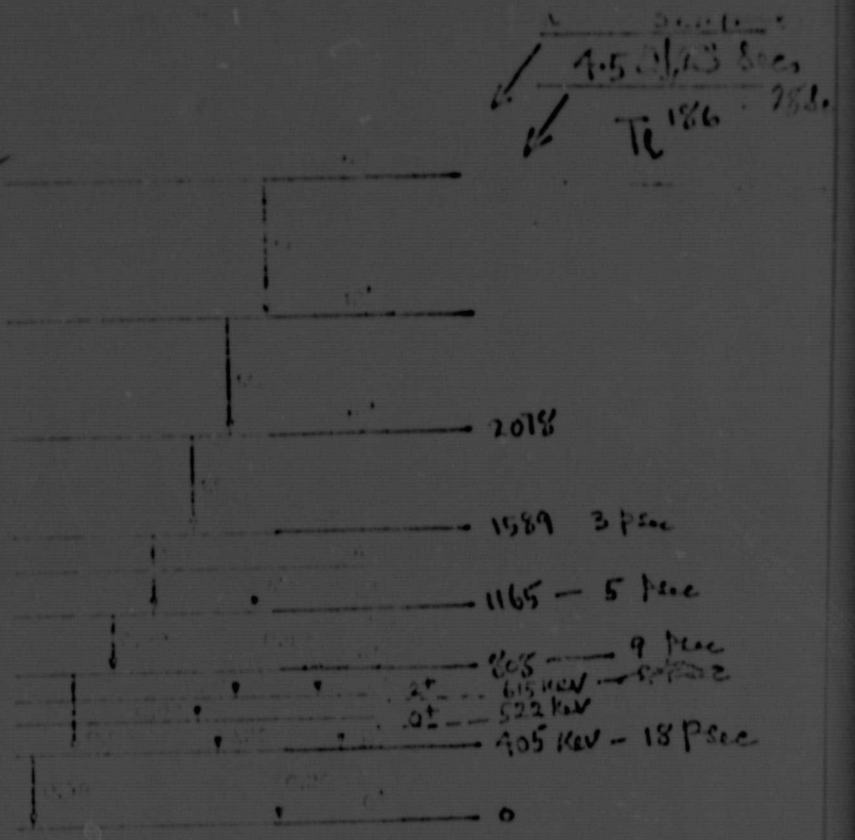
Ronningen et al
[illegible] A261 [illegible], 1976

Fig 10



Lieder et al
Table of Isotopes





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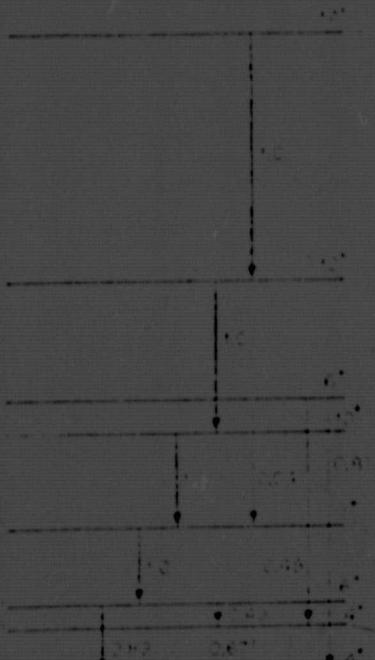

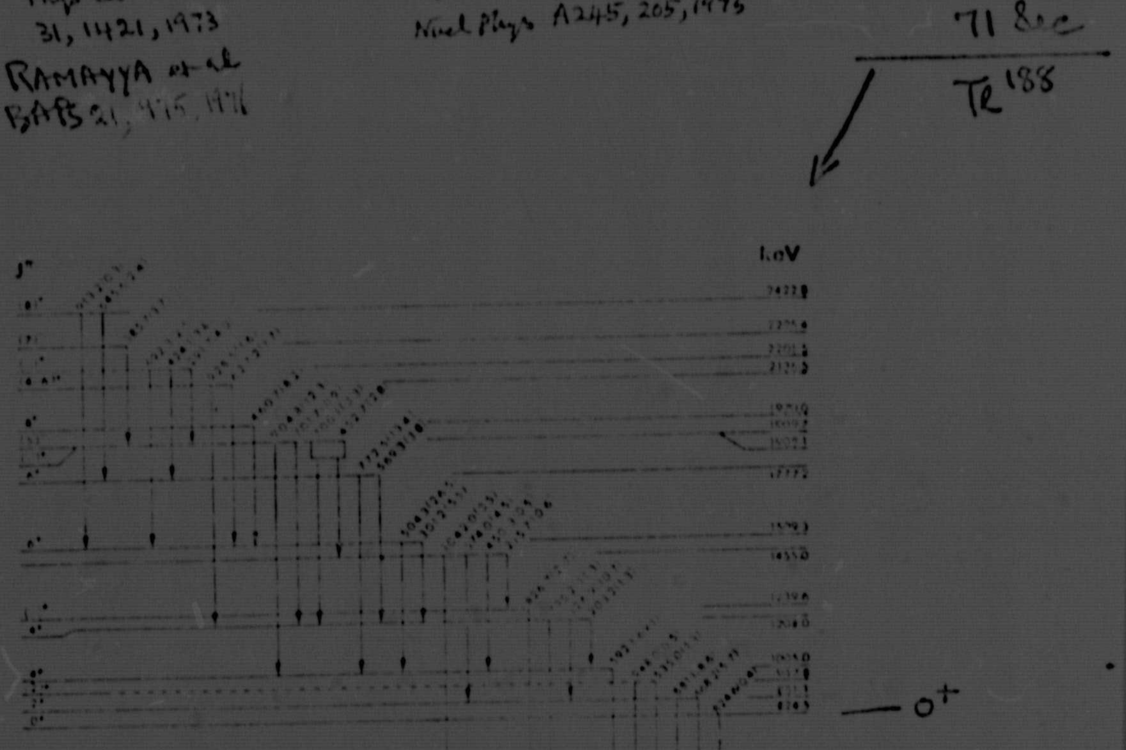

FIG. 2. The decay scheme of 71-sec, principally high-spin ^{188}Tl to ^{188}Hg.

Fig 11