A Nuclear Gamma-Ray Laser in the Optical Regime

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The basic problems

L.A. Rivlin.

***Nuclear gamma-ray laser: the evolution of the idea*.** Quantum Electronics **37** (8) 723-744 (2007)

...the key conflict inherent in any conception of the NGL is the antagonism between the necessity to accumulate a sufecient amount of excited nuclei and the requirement to narrow down the emission gamma-ray line to its natural radiative width...

“Never say never”

...Thus, however, will a nuclear gamma-ray laser or any other device emitting stimulated nuclear gamma-ray radiation be created one day (and when)?..

We can overcome now the basic difficulties and develop a unique γ-ray laser working on the magnetic dipole transition in the VUV range between the first excited level $3/2^+$(7.6 eV) and the ground state $5/2^+$(0.0) of the ^{229}Th nucleus!

Let us remember that the first LASERs were MASERs, which operated in the microwave range!

The amplification conditions

The amplification of the 7.6 eV radiation by the stimulated emission of the ensemble of the ^{229m}Th isomeric nuclei in a host dielectric crystal is a result of

1) **the excitation of a large number of ^{229m}Th isomers by the VUV laser radiation (the photoexcitation process),**
2) **the creation of the inverse population of nuclear levels in a cooled sample owing to the interaction**

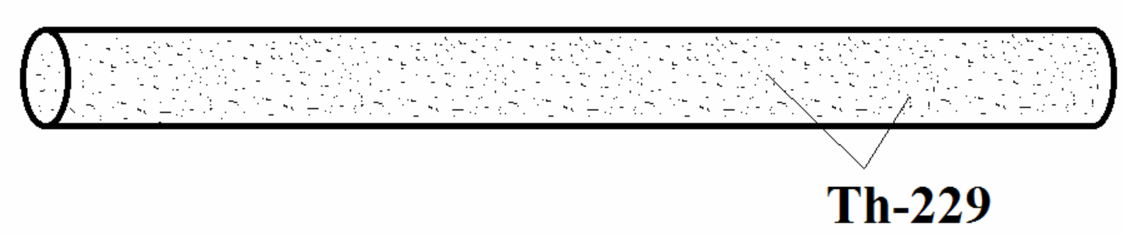
   (a) of the thorium nuclei quadrupole moments with the crystal electric field gradient or

   (b) of the thorium nuclei magnetic moments with an external magnetic field,
3) **the nuclear spin relaxation (achievement of the Boltzmann distribution of the population of nuclear sublevels) through the conduction electrons of the metallic covering,**
4) **the emission or absorption of the optical photons by thorium nuclei in the crystal without recoil (the Mossbauer effect in the optical range).**

The easiest way to develop the ^{229}Th nuclear laser

The first step

Growing a cylindrical shape dielectric crystal doped by the ^{229}Th nuclei. The crystal must have a large band gap.



The sample: dielectric crystal
doped by the Th-229 nuclei

The idea to use a crystal with a large band gap arose in 2000:

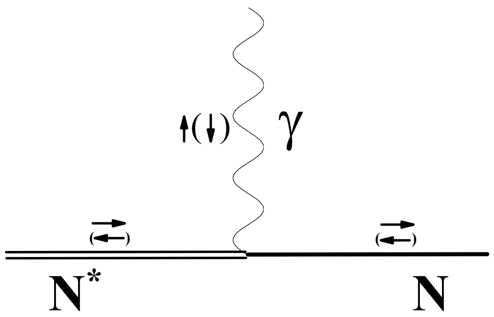
The first step

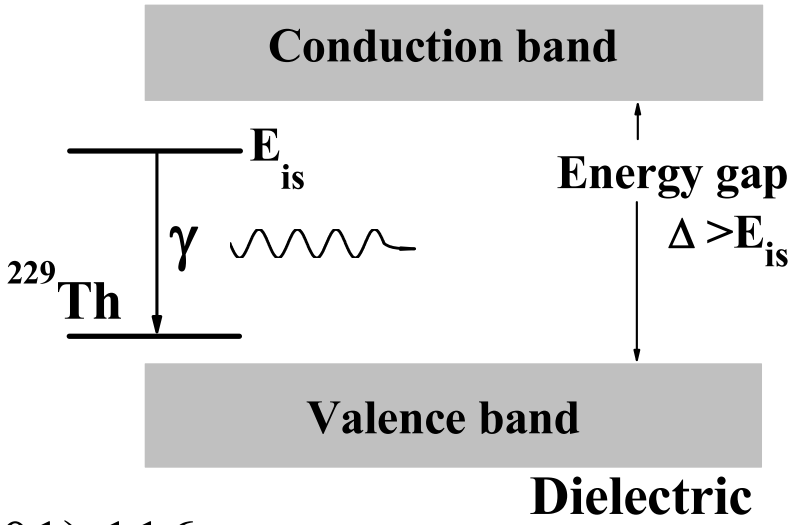
E.V. Tkalya.
Spontaneous Emission Probability for M1 Transition in a Dielectric Medium: ^{229m}Th(3/2+, 3.5 ± 1.0 eV) Decay.
JETP Lett. **71** (2000) 311.

E.V. Tkalya, A.N. Zherikhin, and V.I. Zhudov.
Decay of the low-energy nuclear isomer ^{229m}Th(3/2+, 3.5+/-1.0 eV) in solids (dielectrics and metals): A new scheme of experimental research.
Phys.Rev.C **61** (2000) 064308.

The first step

The resonance photons with the energy ω = 7.6 eV will interact ***directly*** with the ^{229}Th atomic nucleus in the ground $|5/2^{+},0.0>$ and the isomeric $|3/2^{+},7.6\ \mathrm{eV}>$ states bypassing the interaction with the electron shells inside the dielectric with an energy gap, Δ, between the top of the valence band and the bottom of the conduction band such that $\Delta \approx 10$ eV (i.e. in the case $\Delta > \omega$).



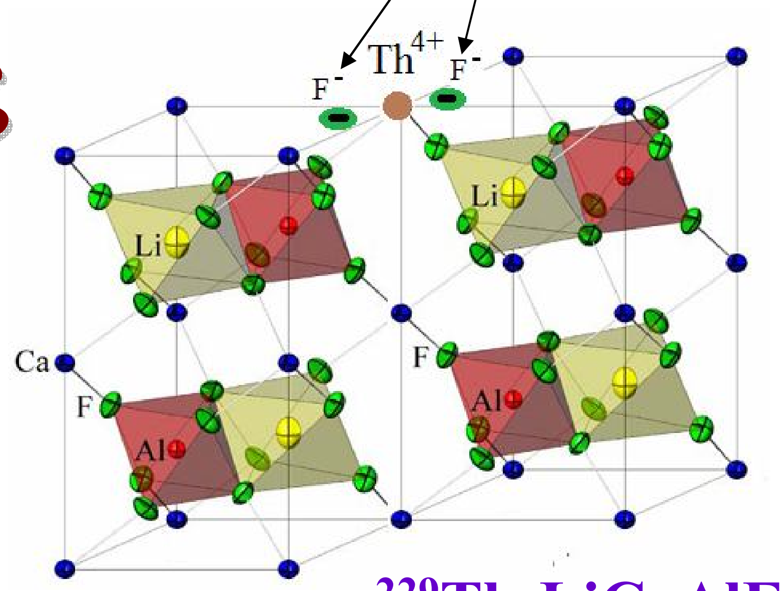


S. Kuck et al. *Laser Phys*. **11** (2001) 116.

$LiCaAlF_6$:	The symmetry:	Trigonal
	The band gap:	110 nm (**11.1 eV**)
	The melting temperature:	825°C

The second step

Achievement the strong Electric Field Gradient at the ^{229}Th nuclei: the thorium atoms should replace atoms with the valence from 1 to 3 in the crystal lattice, and the ***compensative ions*** should placed near the Th^{4+} ions in interstitial sites.



$^{229}Th:LiCaAlF_6$

Structure of LiCAF was taken from the work *S. Kuze et al.* *J. Solid State Chem.* ***177*** *(2004) 3505*.

Possible positions of the additional fluoride ions were calculated in the work *R.A. Jackson et al.* *J. Phys.: Condens. Matter* ***21*** *(2009) 325403*.

Structure of ^{229}Th:LiCaAlF$_6$

R.A. Jackson et al. J. Phys.: Condens. Matter **21** (2009) 325403

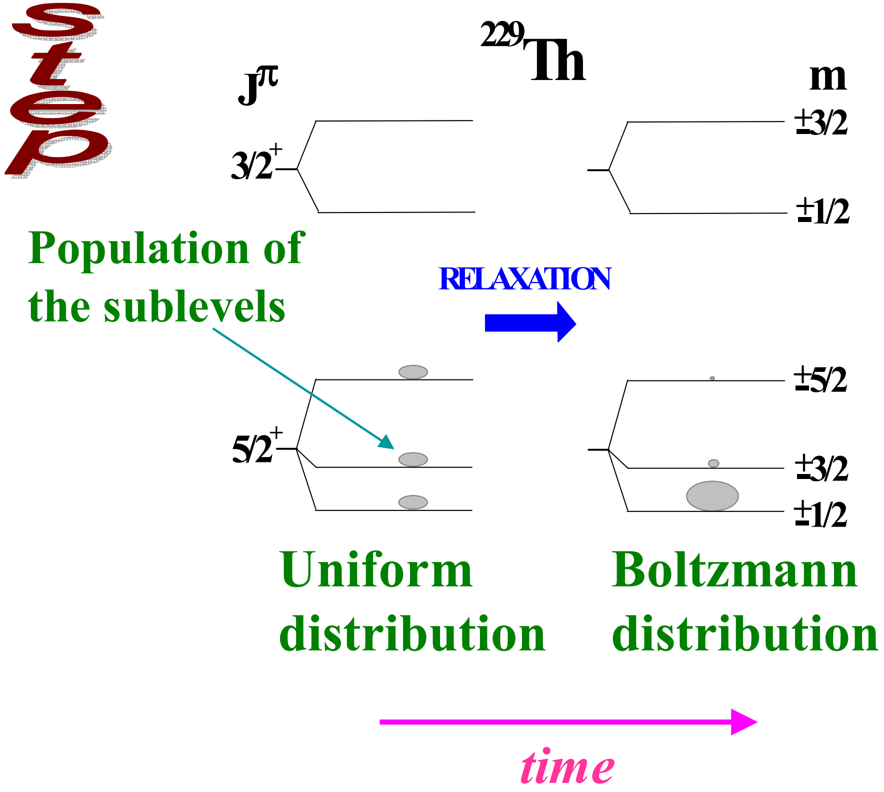
Computer modelling of thorium doping in LiCaAlF$_6$

Site	**Reaction**
Ca^{2+}	$ThF_4 + Ca_{Ca} \rightarrow Th^{\cdot\cdot}_{Ca} + 2F_I^- + CaF_2$

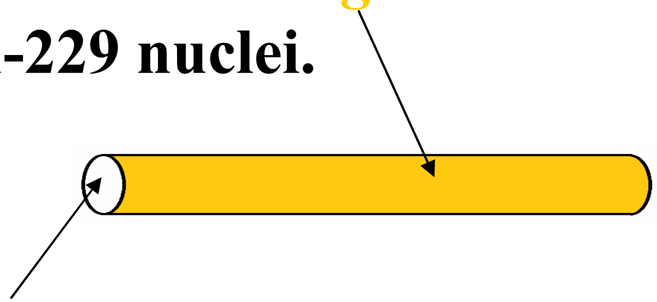
The interstitial positions for the F$^-$ ions in ^{229}Th:LiCAF were calculated. The result is: the F$^-$ ions are placed near the Th^{4+} ion.

The third step

Getting the Boltzmann distribution in the populations of the sublevels in the ground state of the ^{229}Th nuclei by the way of exposition of the specially prepared crystal at low temperature.



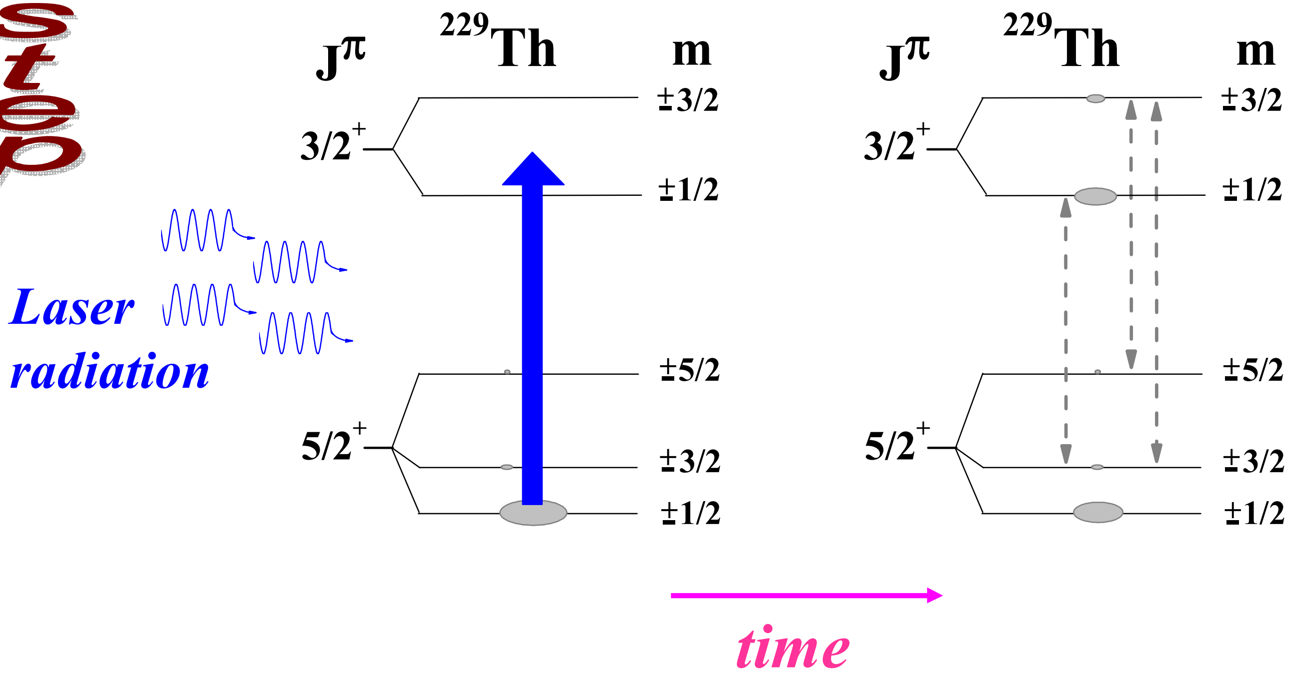
The mechanism of the relaxation process is the inelastic scattering of the conduction electrons of the *metallic covering* from the Th-229 nuclei.



Dielectric crystal doped by the ^{229}Th nuclei

The fourth step

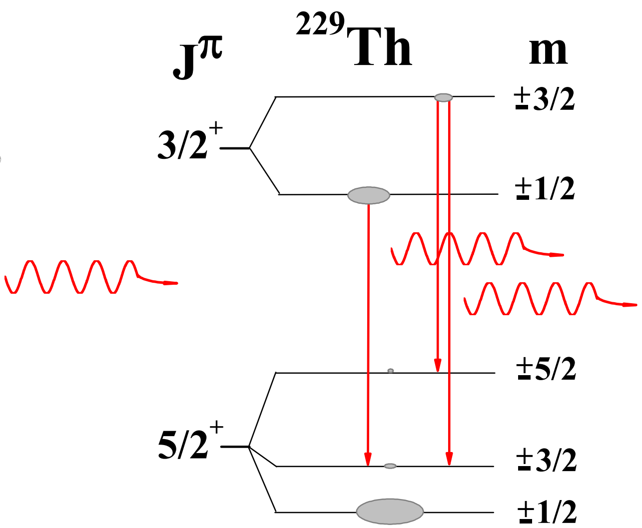
Excitation a considerable number of nuclei on the isomeric level by ***laser radiation*** and creation of the ***inverse population*** in the system of the ^{229}Th nuclei.



The pairs of sublevels with inverse population

The fifth step

Amplification of the 7.6 eV γ-radiation by the stimulated emission of the ensemble of the ^{229m}Th nuclei.



$$\chi = \frac{\lambda_{is}^2}{2\pi}\frac{\Gamma_{rad}}{\Delta\omega_{tot}}\frac{1}{1+\alpha}\left(n_{is} - \frac{n_{gr}}{g}\right) - \kappa$$

$n_{gr}(t=0) = 10^{18}$ $\quad n_{is} \approx 2\times10^{17}$ cm^{-3}

$\lambda_{is} = 2\pi / E_{is} = 163 \pm 11$ nm

$\Gamma_{rad} = \ln 2 / T_{1/2}^{is} \approx 3\times10^{-19}$ eV

$T_{1/2}^{is} \approx 25$ min $\quad \alpha = 0$

W. Rellergert et al., PRL **104** (2010) 200802

$\Delta\omega_{tot} \le 7\times10^{-13}$ eV

$\kappa \approx 1 \quad (\kappa \to 0.01)$ cm^{-1}

(the linear attenuation coefficient)

The overall amplification factor will be $\chi \approx 3$ cm^{-1}

The sixth step

Parameters of the ^{229}Th γ-ray laser.

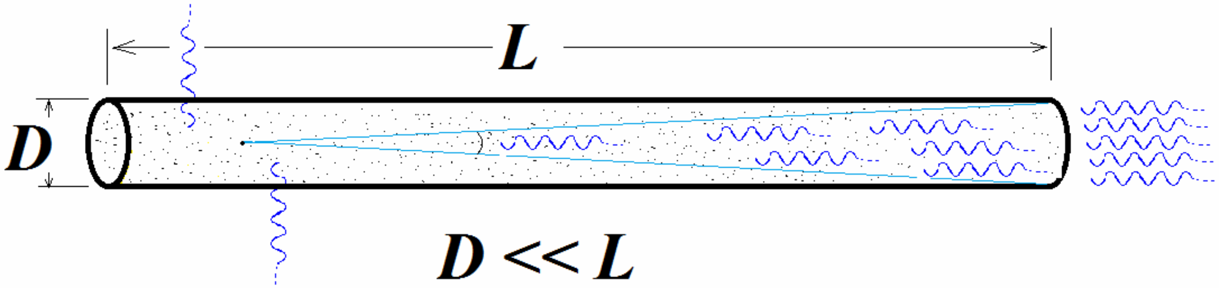
How to detect the effect experimentally?

a) **The amplifier**. The amplification factor $\chi \approx 3$ cm^{-1} provides the gain $\exp(\chi L) \approx 10^4$ in the sample with the length of 3 cm.

One can detect the effect using an external source.

The sixth step

b) **The simplest laser**, which will generate the pulses by himself.



$\chi = 3$ cm^{-1} , $D = 0.1$ mm , $L = 5$ cm, the gain $\exp(\chi L) \approx 10^6$

^{229}Th : $m = 1$ μg $n_{gr}(0) = 10^{18} \div 10^{19}$ cm^{-3} $n_{is} = 2\times10^{17}$ cm^{-3}

The emission will be a sequence of pulses with the repetition frequency

$$f_{rep} = Q_{is}(D/L)^2 \approx 10^4 \div 10^5 \text{ s}^{-1}, \text{ where } Q_{is} = \frac{\ln 2}{T_{1/2}^{is}} N_{is} \approx 2\times10^{10} \text{ s}^{-1}$$

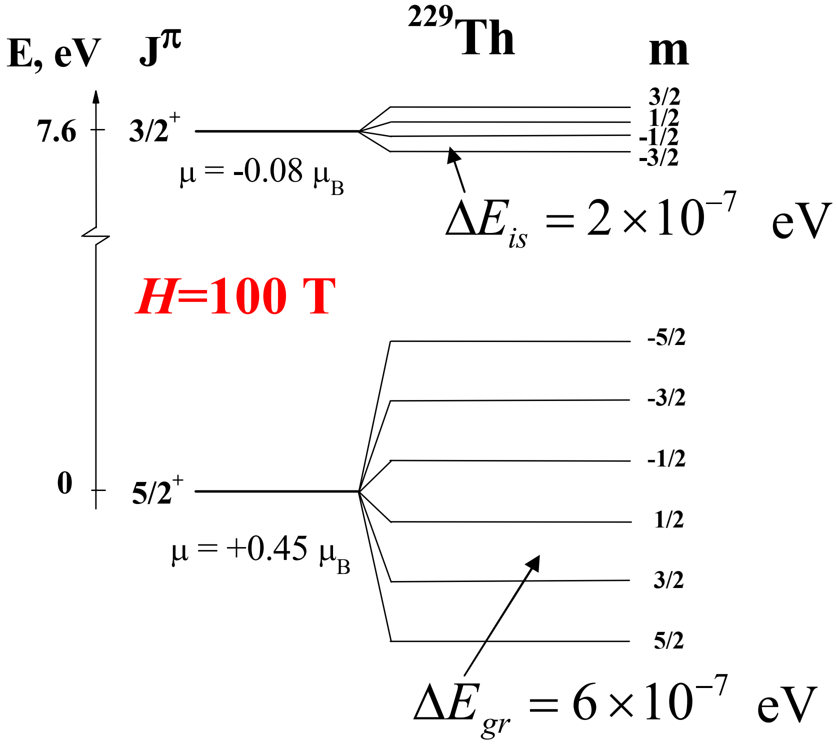
Duration of the γ-ray laser emission

$$\tau \approx T_{1/2}^{is}(L/D)^2 \exp(-\chi L) \approx 100 \text{ s}$$

The mean power of this γ-ray laser will be $P \approx 10^{-6} \div 10^{-7}$ W.

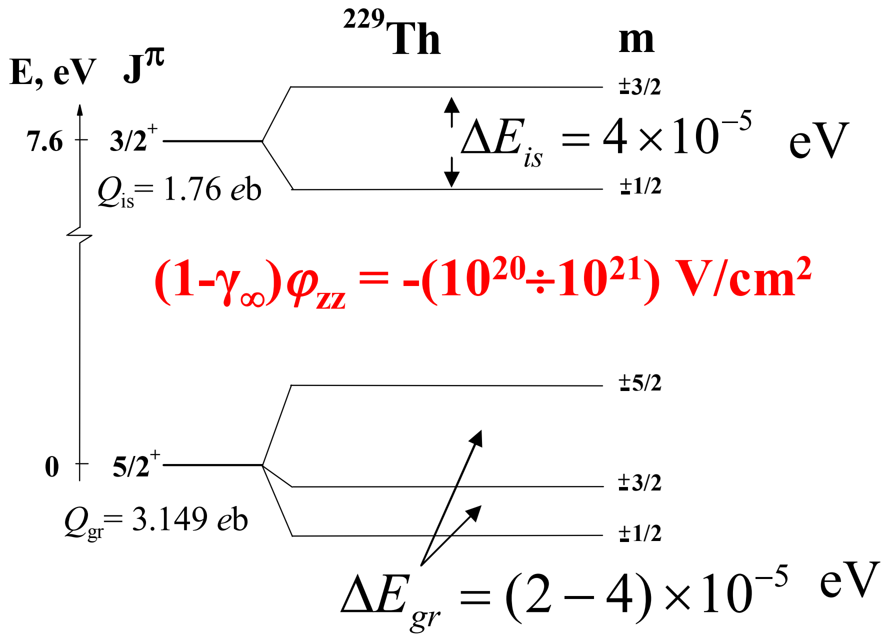
What scheme should we choose?

Quadrupole or Zeeman splitting?



$$\Delta E_{gr(is)} = \frac{\mu_{gr(is)} H}{J_{gr(is)}}$$

The ^{229}Th:LiCaAlF$_6$ crystal:



$$E_m = eQ_{gr(is)}(1-\gamma_\infty)\varphi_{zz}\frac{3m^2 - J_{gr(is)}(J_{gr(is)}+1)}{4J_{gr(is)}(2J_{gr(is)}-1)}$$

The extremely low temperature
***T* = 0.01 K is needed ($kT = 8.6\times10^{-7}$ eV)**

The experiment is possible
at the temperature *T* = 0.1 K

Quadrupole splitting in $LiCaAlF_6$

The Electric Field Gradient (EFG)

"Wien2k": EFG at the Ca^{2+} ion site in LiCAF is

$$\varphi_{zz} = -\,1.2\times10^{17}\ \mathrm{V/cm^2}$$

In the $^{229}Th{:}LiCaAlF_6$ crystal the leading contribution to EFG at the Th^{4+} ion site comes from $\mathbf{F^-}$ ions, which compensate the extra charge 2+.

These ions are located in interstitial sites in the vicinity of Th^{4+}. Estimations of the EFG at the Th^{4+} site for the ***point*** ions give

$$\varphi_{zz} \approx -\,2\times10^{18}\ \mathrm{V/cm^2}\ .$$

The Sternheimer antishielding factor $\gamma_\infty \approx -\,(100\div200)$

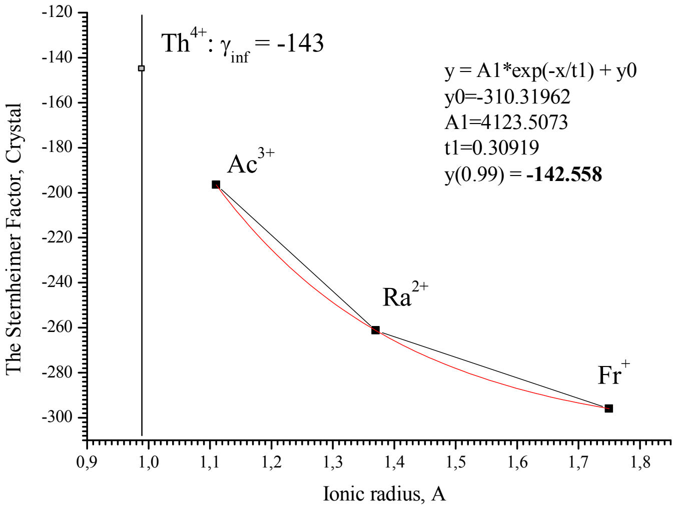
$$\mathbf{EFG} = (1-\gamma_\infty)\,\varphi_{zz} \approx -5\times10^{20}\ \mathrm{V/cm^2}$$

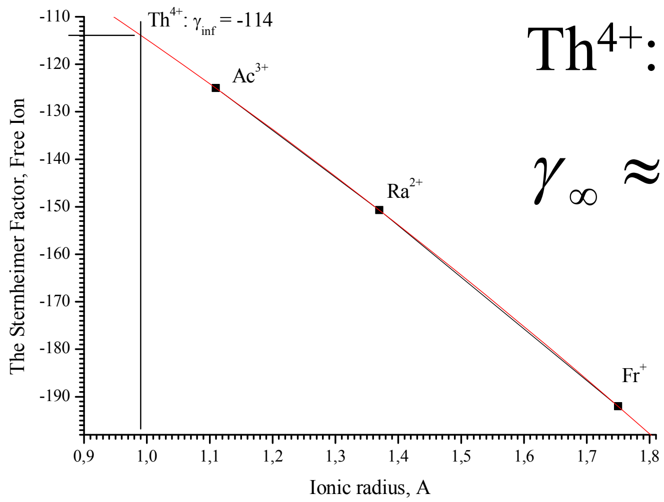
!

The Sternheimer antishielding factor

K.D. Sen and P.T. Narasimhan. *Quadrupole antishielding factors and polarizabilities in ionic crystals*. Phys.Rev.B (Solid State) **15**, 95 (1977)

Ion	Free ion: Present	Free ion: Feiock and Johnson	Free ion: Others	Crystal ion: Present	Crystal ion: Others	Experimental
Fr^{+}	−192.035		−193.01[w]	−295.958		
Ra^{2+}	−150.746		−151.60[w]	−261.234		
Ac^{3+}	−126.049		−126.06[w]	−196.517		





Th^{4+}:

$$\gamma_\infty \approx -(100 \div 200)$$

Promising crystals for the researches

W.G. Rellergert et al. *Phys.Rev.Lett.* **104**, 200802 (2010)

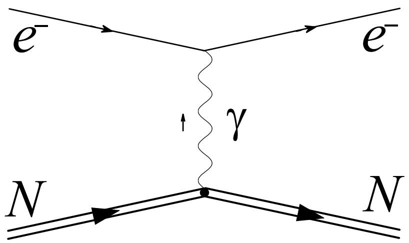
Na_2ThF_6 –	**(?)** The energy of the electric quadrupole interaction is probably too small in the Na_2ThF_6 crystal. There are no additional (compensative) negative ions in the vicinity of the Th^{4+} ions.
$LiCaAlF_6$ (LiCAF)	$Ca^{2+} \rightarrow Th^{4+} + 2F^-$
$LiSrAlF_6$ (LiSAF)	$Sr^{2+} \rightarrow Th^{4+} + 2F^-$
$LiYF_4$ (YLF)	$Y^{3+} \rightarrow Th^{4+} + F^-$
CaF_2	$Ca^{2+} \rightarrow Th^{4+} + 2F^-$

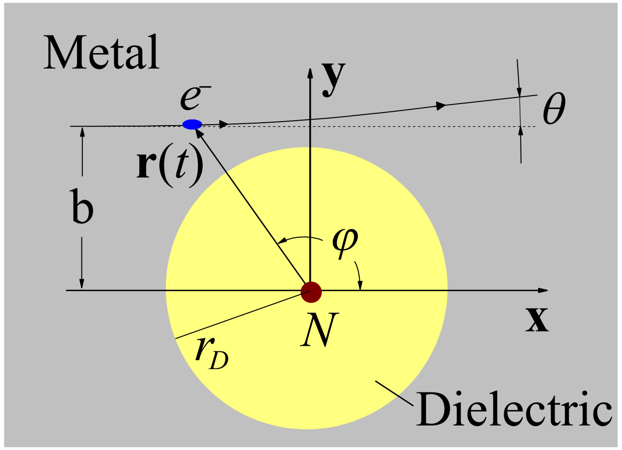
A. Ritucci et al. *LLNL Preprint* UCRL-JRNL-219656 (2006)

LiF – 13.6-14.5 eV, BaF_2 – 9.1 eV, SiO_2 – 8.9 eV

Inelastic scattering of the conduction electron from the nuclei

"Internal" conversion on the conduction electrons



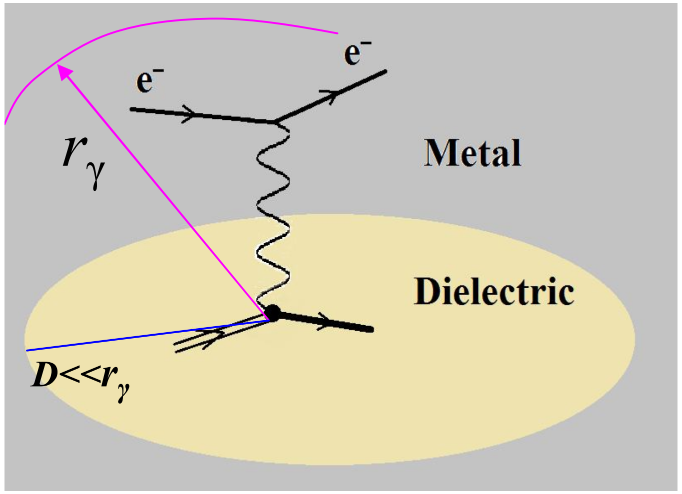


A new method of obtaining of aligned nuclei in ***a crystal of ionic insulator***, which is cooled to cryogenic temperatures. Orientation is a result of inelastic scattering of the conduction electrons (***e⁻***) of the ***metallic covering*** of ***sample*** from the nuclei (*N*). **(E.Tkalya, *Submitted to* PRC)**

$$\sigma_{M1} = \frac{32\pi^2}{9} e^2 \xi \left(K_0(\xi) K_1(\xi) + \frac{\xi}{2}[K_0^2(\xi) - K_1^2(\xi)] \right) B(M1; I_i \to I_f)$$

$K_n(\xi)$ is the modified Bessel function of the second kind, $\xi = \frac{r_D \Delta E}{\upsilon}$

Kinematics of the process



Energy of the quadrupole splitting

$$\Delta E = 10^{-5} \quad \text{eV}$$

Energy of the conduction electrons

$$E_e = E_F \approx 5.5 \quad \text{eV}$$

Momentums of the electron

$$p_i = \sqrt{2m_e E_F} \quad , \qquad p_f = \sqrt{2m_e (E_F + \Delta E)}$$

Properties of the virtual photon

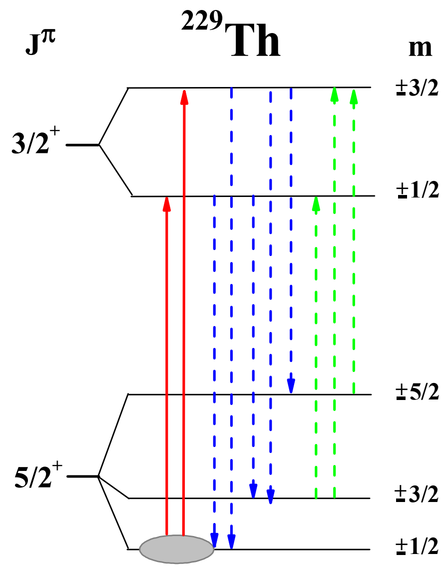
$$\omega_\gamma = \Delta E \ , \quad q_\gamma^{\min} = p_f - p_i = \Delta E \sqrt{m_e / 2E_F} \ , \quad \lambdabar_\gamma = 1 / q_\gamma^{\min} \approx 0.01 \ \text{cm}$$

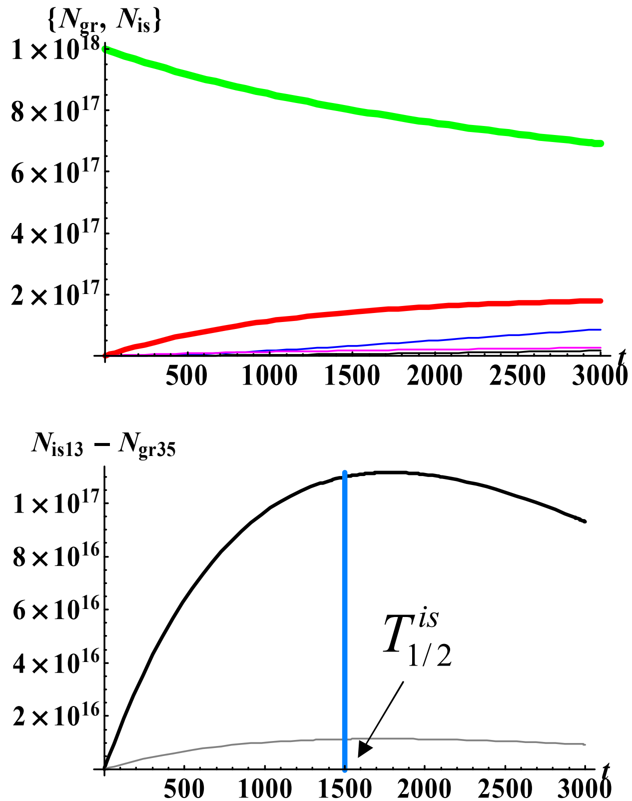
The photon exists in the time $\Delta t \approx \hbar / m_\gamma^*$ **, where** $m_\gamma^* = \sqrt{q_\gamma^2 - \omega_\gamma^2} \approx q_\gamma^{\min}$

The finite range of the photon is $\boxed{r_\gamma = c\Delta t \approx 1 / m_\gamma^* \approx 10^{-2} \quad \text{cm} \ !}$

Photoexcitation of the ^{229}Th nuclei

Excitation of the isomeric state by the wide beam: taking into account the ***anti-Stokes*** transitions





Optimal pumping (excitation) time is $T_{1/2}^{is}$