Laser techniques for a new class of detectors

- Trends, Wishes and Dreams in Strasbourg -

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KEV−MEV THRESHOLD, ∼CM^3-VOLUME DETECTORS

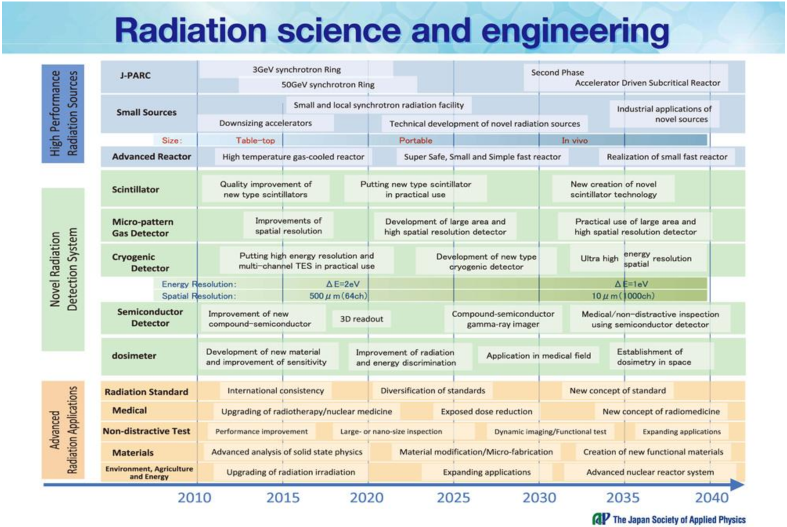
DREAM: to be able to detect down to **tens of meV** energy deposition events in materials without preclusion to significantly **large volume** detectors

NEW CONCEPT: to use LASERS to detect particles in materials
the laser is tuned to a particular atomic/molecular transition

ENVISAGED POSSIBILITIES:

1. upconversion in RE-doped materials
2. upconversion in matrix-isolation
3. anti-Stokes processes
4. the LASER detector
5. Faraday detector (ferromagnetic, paramagnetic materials)

DREAMS:VARIOUS TECHNOLOGIES



Radiation science and engineering

High Performance Radiation Sources	J-PARC	3GeV synchrotron Ring 50GeV synchrotron Ring Second Phase Accelerator Driven Subcritical Reactor
	Small Sources	Small and local synchrotron radiation facility Downsizing accelerators Technical development of novel radiation sources Industrial applications of novel sources
	Size:	Table-top Portable In vivo
	Advanced Reactor	High temperature gas-cooled reactor Super Safe, Small and Simple fast reactor Realization of small fast reactor
Novel Radiation Detection System	Scintillator	Quality improvement of new type scintillators Putting new type scintillator in practical use New creation of novel scintillator technology
	Micro-pattern Gas Detector	Improvements of spatial resolution Development of large area and high spatial resolution detector Practical use of large area and high spatial resolution detector
	Cryogenic Detector	Putting high energy resolution and multi-channel TES in practical use Development of new type cryogenic detector Ultra high energy spatial resolution
	Energy Resolution:	ΔE=2eV ΔE=1eV
	Spatial Resolution:	500μm(64ch) 10μm(1000ch)
	Semiconductor Detector	Improvement of new compound-semiconductor 3D readout Compound-semiconductor gamma-ray imager Medical/non-distractive inspection using semiconductor detector
	dosimeter	Development of new material and improvement of sensitivity Improvement of radiation and energy discrimination Application in medical field Establishment of dosimetry in space
Advanced Radiation Applications	Radiation Standard	International consistency Diversification of standards New concept of standard
	Medical	Upgrading of radiotherapy/nuclear medicine Exposed dose reduction New concept of radiomedicine
	Non-distractive Test	Performance improvement Large- or nano-size inspection Dynamic imaging/Functional test Expanding applications
	Materials	Advanced analysis of solid state physics Material modification/Micro-fabrication Creation of new functional materials
	Environment, Agriculture and Energy	Upgrading of radiation irradiation Expanding applications Advanced nuclear reactor system

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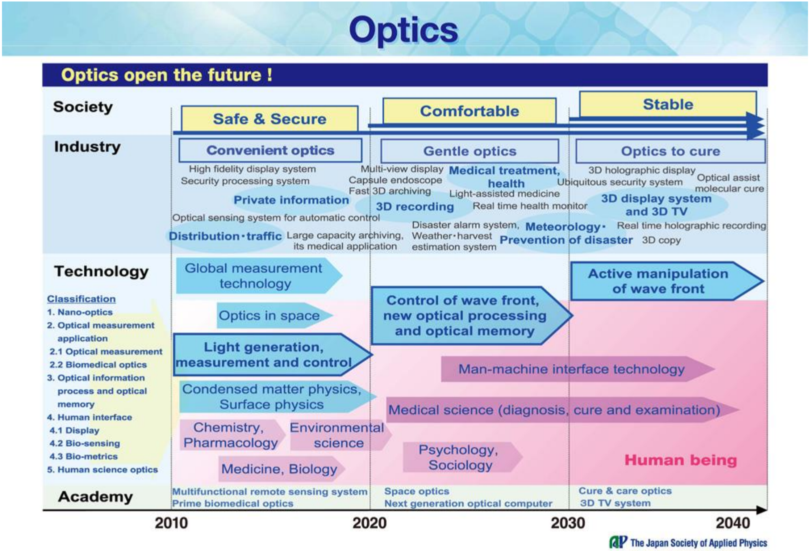
DREAMS:VARIOUS TECHNOLOGIES



Optics

Optics open the future !

Society

Safe & Secure **Comfortable** **Stable**

Industry

Convenient optics

High fidelity display system
Security processing system
Private information
Optical sensing system for automatic control
Distribution・traffic
Large capacity archiving, its medical application

Gentle optics

Multi-view display
Capsule endoscope
Fast 3D archiving
3D recording
Medical treatment, health
Light-assisted medicine
Real time health monitor
Disaster alarm system,
Weather・harvest estimation system
Meteorology・
Prevention of disaster

Optics to cure

3D holographic display
Ubiquitous security system
Optical assist molecular cure
3D display system and 3D TV
Real time holographic recording
3D copy

Technology

Classification
1. Nano-optics
2. Optical measurement application
2.1 Optical measurement
2.2 Biomedical optics
3. Optical information process and optical memory
4. Human interface
4.1 Display
4.2 Bio-sensing
4.3 Bio-metrics
5. Human science optics

Global measurement technology
Optics in space
Light generation, measurement and control
Condensed matter physics, Surface physics
Chemistry, Pharmacology
Environmental science
Medicine, Biology
Control of wave front, new optical processing and optical memory
Man-machine interface technology
Medical science (diagnosis, cure and examination)
Psychology, Sociology
Active manipulation of wave front
Human being

Academy

Multifunctional remote sensing system
Prime biomedical optics
Space optics
Next generation optical computer
Cure & care optics
3D TV system

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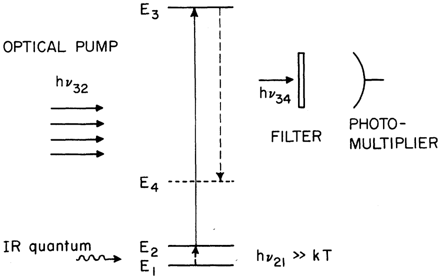
RE-DOPED CRYSTALS

basic idea: **diminish *w*-value** in an **all-optical scheme** based on the IRQC concept

N. Bloembergen, *Phys. Rev. Lett.* **2**, 84 (1959)



- pump laser resonant with transition $2 \rightarrow 3$
- material transparent to the pump until an IR photon is absorbed $(1 \rightarrow 2)$
- level 3 is fluorescent $\Longrightarrow$ detection can be accomplished via conventional detectors (PMT or PD)
- such energy level scheme can be realized in wide bandgap materials doped with trivalent rare-earth ions

the whole field of **upconversion** can be traced back to this idea

(with applications in lasing, laser cooling, up-conversion based weak infrared photon detection, infrared imaging and so on)

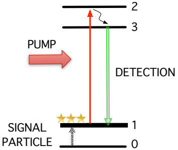
RE-DOPED CRYSTALS

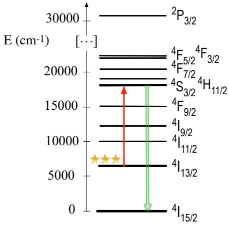
$\mathcal{H}p$: the particle interaction causes an increase of the population in the level just above the GS

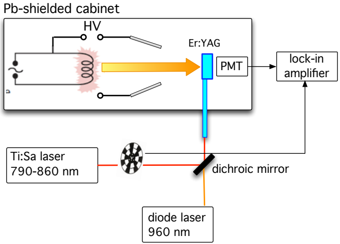
related to previous works on infrared scintillation

W. Moses *et al*, IEEE Trans. Nucl. Sci. 45 (1998).

P. Antonini *et al*, Nucl. Instrum. Meth. A 486, 799802 (2002).

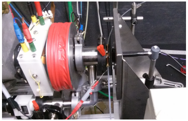


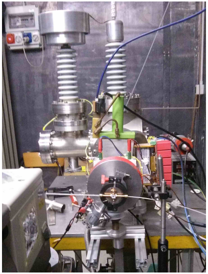


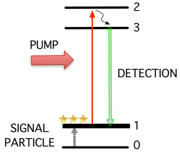


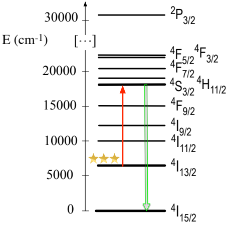
THE IRQC IDEA APPLIED TO PARTICLE DETECTION:

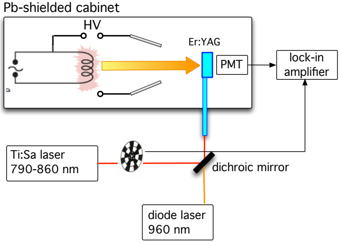
- an **electron gun** as a signal source (wideband)
- YAG:Er^{3+}, $E_1 = 0.74\,\text{eV}$ ($^4\text{I}_{15/2} \longrightarrow {}^4\text{I}_{13/2}$ transition)
- **room temperature** $\rightarrow N_1/N_0 \sim 10^{-14}$
- **lock-in detection** to select fluorescent photons originated only from double resonance



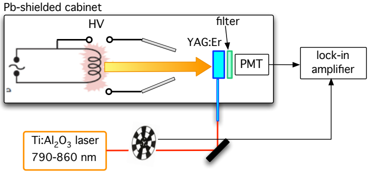


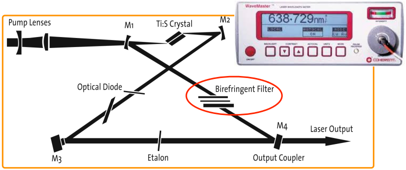




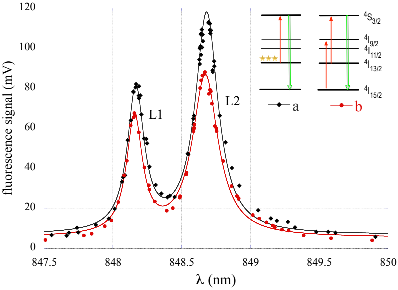


Appl. Phys. Lett. **107** (2015)





L1, L2 transitions between sublevels in the $^4I_{13/2}$ and $^4S_{3/2}$ manifolds

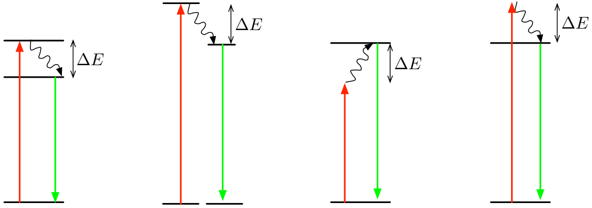


		λ_{max} (nm)	*area*
L1	p.l.	848.16 ± 0.01	12.8 ± 0.8
	p.l. + e^-	848.17 ± 0.02	16.5 ± 1.1
L2	p.l.	848.67 ± 0.01	28.8 ± 1.1
	p.l. + e^-	848.68 ± 0.01	34.8 ± 1.1

- the fluorescence signal is greater when the electron gun excites the crystal
- a significant fraction of the fluorescence is determined by the pump laser double resonance
- e^- excitation geometrically unfavorite as compared to pump laser double resonance
- host crystal (YAG) has a weak IRQC output

THE PUMP LASER DOUBLE RESONANCE

A MULTIPHONON EXCITATION PROCESS



de-excitation of one RE^{3+} ion

energy transfer between two RE^{3+} ions S and A

Anti-Stokes

Stokes

W_{NA} W_T W_{AS} W_S

$$\Delta E > \hbar\omega_m$$

- $W_{NA} = W_{NA}(0)\, e^{-\alpha\Delta E}$
- $W_T = W_T(0)\, e^{-\beta\Delta E}$
- $W_{AS} = W_{NA}\,(0) e^{-\alpha_{AS}\Delta E}$
- $W_S = W_{NA}\,(0) e^{-\alpha_S\Delta E}$

$$\alpha_S = (\hbar\omega_m)^{-1} \cdot \ln[\bar{N}/S_0(\bar{n}+1) - 1]$$
$$\alpha_{AS} = \alpha_S + 1/kT$$

$\omega_m =$ highest phonon frequency of the host

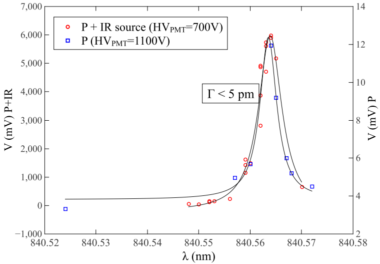
$\bar{N} = \Delta E/\hbar\omega_m$ average phonon number

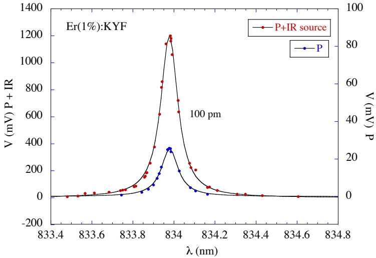
Host	$\hbar\omega_m$ [cm^{-1}]
YAG	700
KYF	350-400
YLF	400-560
KPB	140

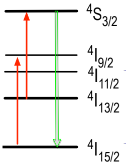
T [K]	kT [meV]	R(350)
300	25	$\sim$ 1.7
77	6.4	$\sim$ 6.8
10	0.83	$\sim$ 52
5	0.42	$\sim$ 104

THE PUMP LASER DOUBLE RESONANCE

IRQC MEASUREMENTS AT $T = 10\,\mathrm{K}$







$$E_P = 11897\,\mathrm{cm}^{-1}$$

$$^4I_{11/2} = 10400\,\mathrm{cm}^{-1} \rightarrow \Delta E = 1497\,\mathrm{cm}^{-1}$$

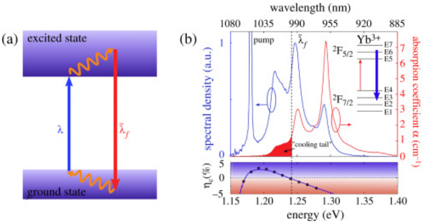
Host	$\hbar\omega_m$ [cm^{-1}]	IR/PDR	order
Er(0.5%)YAG	700	$\sim 1:10$	2
Er(1%)YLF	400-560	$\sim 1:5000$	3

ANTI-STOKES PROCESS

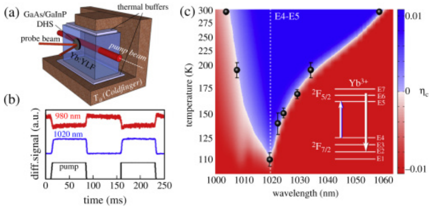
EXPLOIT THE PHONON CHANNEL FOR DETECTION

a dominant process is the **thermalization** of the secondary electrons produced in the particle interaction, which takes place through optical *phonon scattering*
$\Rightarrow$ **thermal upconversion**

Example: optical refrigeration/laser cooling of solids
(from D. V. Seletskiy *et al* Nat. Photonics **4**(3), 161164 (2010))



anti-Stokes fluorescence
luminescence upconversion cooling

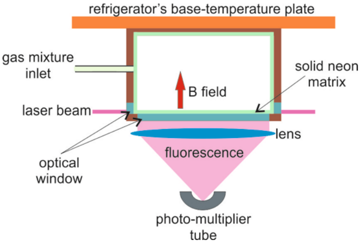


phonon absorption followed by blueshifted fluorescence λ that carries away heat λ_f

SOLID NEON MATRIX

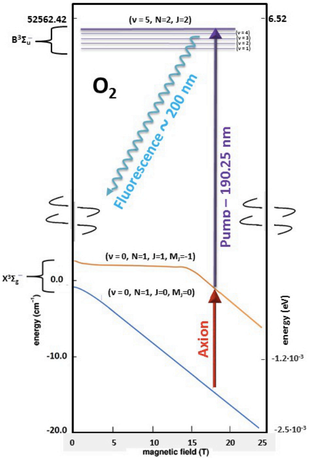
Alkali atom or molecular oxygen embedded in a condensed phase according to the matrix-isolation spectroscopy technique (MIS).

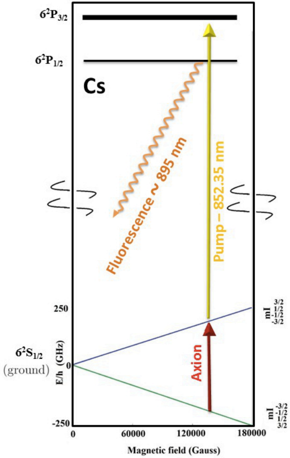
- 80 mK in **B** up to 18 T
- copper cell $1 \times 3 \times 3\,\mathrm{cm}^3$
- inject noble gas N and atomic/molecular species D (1:100 to 1:1000)



After a few hours of deposition, a 1-mm-thick noble gas matrix, incorporating species D is grown on each side of the walls.

SOLID NEON MATRIX: DOPANT SPECIES





Number of axion-induced absorption events:

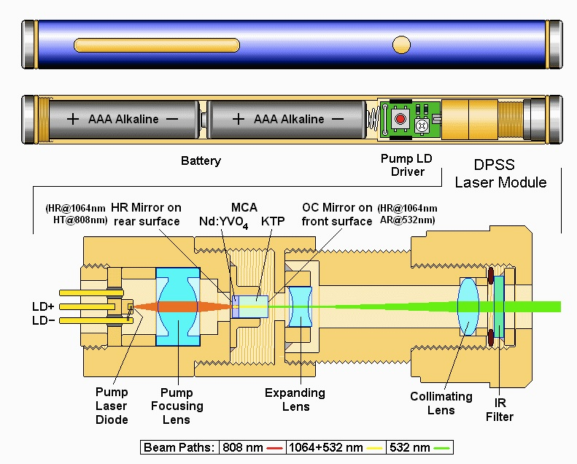
$$N \cdot N_A = \mathcal{R}_{ab}\, n_{\mathrm{Ne}}\, V_c\, d\, (3600\,\mathrm{s}) n_h$$

some reasonable values:
$\mathcal{R}_{ab} = 1\,\mathrm{Hz}$;
$n_{\mathrm{Ne}} = 4.6 \cdot 10^{22}\,\mathrm{cm}^{-3}$ neon density;
$V_c \sim 1\,\mathrm{cm}^3$ crystal volume;
$d = 1\%$ doping ratio;
n_h acquisition time [hours]=4

$$\Longrightarrow N \cdot N_A = 10$$

THE LASER DETECTOR

GREEN LASER POINTER

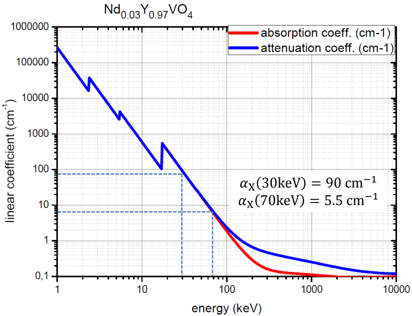


THE LASER DETECTOR

X RAYS DETECTION

Nd:YVO$_4$ (a-cut):

$$1\ \%\ \text{at.} \equiv 1.26 \times 10^{20}\ \text{cm}^{-3}$$
$$\sigma_A = 2.8 \times 10^{-19}\ \text{cm}^2$$
$$\sigma_E = 25 \times 10^{-19}\ \text{cm}^2$$
$$\tau_{sp}(3\%\ \text{at.}) \approx 30 \times 10^{-6}\ \text{s}$$



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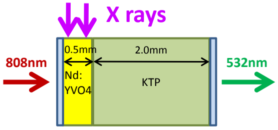
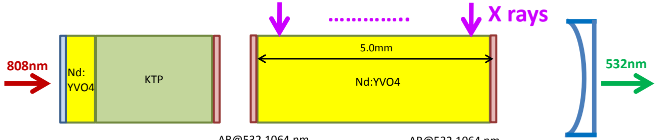


HT@808 nm
HR@532,1064 nm

HT@532 nm
HR@1064 nm

2)



AR@532,1064 nm

AR@532,1064 nm

THE LASER DETECTOR

X RAYS DETECTION

Pump/laser beam parameters: $w_0\,(808\text{ nm}) = w_0\,(1064\text{ nm}) = 100\ \mu\text{m}$

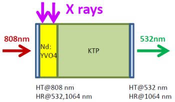
$M^2(808\text{ nm}) = 20 \quad M^2(1064\text{ nm}) = 1.5$

Cavity parameters: $L = 0.5\text{ mm}, L_c = 2.5\text{ mm}\ (+5\text{ mm} + \cdots), \text{Loss} = 3\%$

Nd sensitization efficiency: $\eta_{\text{X}-\text{Nd}}(30\text{ keV}, 3\%\text{ at.}) \approx 4500$

Pump noise: $\sigma_{\text{noise}}(808\text{ nm}) = 0.5\%\text{ rms}$

1)

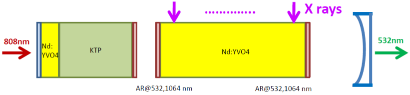


$P_{\text{th}} = 32\text{ mW}$

$\phi_{\text{X,min}} = 2.7 \times 10^{14}\text{ ph s}^{-1}\text{cm}^{-2}\ (1.3\text{ W cm}^{-2})$ cw

$F_{\text{X,min}} = 8.2 \times 10^{9}\text{ ph cm}^{-2}\ (39\ \mu\text{J cm}^{-2})$ short pulse

2)



$P_{\text{th}} = 32\text{ mW}$

$\phi_{\text{X,min}} = 2.7 \times 10^{13}\text{ ph s}^{-1}\text{cm}^{-2}\ (0.13\text{ W cm}^{-2})$ cw

$F_{\text{X,min}} = 8.2 \times 10^{8}\text{ ph cm}^{-2}\ (3.9\ \mu\text{J cm}^{-2})$ short pulse