LIP&LED PROJECT

G. Carugno

Padova,Legnaro,Ferrara,Palermo(LNS)

- Outline :
- Main Physics Areas
- Preliminary Axioma Results
- Low Energy Threshold Cryogenic Detectors
- Conclusions

Main Targeting Areas

- **Axion search & sub-eV scale:**
- **Light Dark matter search: readout via Scintillation, Ionization and phonon**
- **Neutrino coherent scattering**
- **EDM cryogenic doped crystals**
- **Quantum Macroscopic States for 2 neutrinos emission spectroscopy**
- **Medical (MRI/NMR) hyperpolarized 131Xe and Neon Nuclei**

SEE COSMIC VISION & QUANTUM SENSING IN HEP REPORTS

Laser/Matter Approach for New Physics :

- The *neutrino coherent scattering off nuclei*
  [B. Cabrera, L. M. Krauss, F. Wilczek; Phys. Rev. Lett **55,** 25 (1985)]

- *The REMP (Radiative emission of a neutrino pair) atomic process*
  [M.Yoshimura *et al.* Phys. Lett. B **719,** 154 (2013)]

- *Artificial Vacuum* for *T-Violation Experiment*
  [G.Prior , F.Wilczek , Phys. Lett. B194, 137 ,(1987)]

- *Optical Excitation and Decay Dynamics of Ytterbium Atoms Embedded in a Solid Neon Matrix*
  [Z.T.Lu et al. , Phys. Rev. Lett. 107, 093001 (2011)]

- *On the possibility of producing a coherent scintillator*
  [M.I.Ryazanov et al., JTEP Letters 32 , 8 (1980)]

- *The neutrino magnetic moment*
  [H. T. Wong , Hau Bin Li, Shin-Ted Lin; Phys. Rev. Lett **105,** 061801 (2010)]

- *The laser-induced acceleration of forbidden captures of orbital electrons by nuclei*
  [M. Yu Romanovsky, JETP Letters, **94,** 425 (2011)]

AXIOMA RESULTS: 1

www.nature.com/scientificreports

SCIENTIFIC REPORTS

OPEN

Axion dark matter detection by laser induced fluorescence in rare-earth doped materials

Received: 1 September 2017
Accepted: 25 October 2017
Published online: 09 November 2017

Caterina Braggio[1], Giovanni Carugno[1], Federico Chiossi[1], Alberto Di Lieto[2], Marco Guarise[1], Pasquale Maddaloni[3,4], Antonello Ortolan[5], Giuseppe Ruoso[5], Luigi Santamaria[6], Jordanka Tasseva[4] & Mauro Tonelli[2]

We present a detection scheme to search for QCD axion dark matter, that is based on a direct interaction between axions and electrons explicitly predicted by DFSZ axion models. The local axion dark matter field shall drive transitions between Zeeman-split atomic levels separated by the axion rest mass energy $m_a c^2$. Axion-related excitations are then detected with an upconversion scheme involving a pump laser that converts the absorbed axion energy (~hundreds of μeV) to visible or infrared photons, where single photon detection is an established technique. The proposed scheme involves rare-earth ions doped into solid-state crystalline materials, and the optical transitions take place between energy levels of $4f^N$ electron configuration. Beyond discussing theoretical aspects and requirements to achieve

AXIOMA RESULTS 2

REVIEW OF SCIENTIFIC INSTRUMENTS **88**, 113303 (2017)

Experimental setup for the growth of solid crystals of inert gases for particle detection

M. Guarise,[1,2,a)] C. Braggio,[3] R. Calabrese,[1,4] G. Carugno,[3] A. Dainelli,[2] A. Khanbekyan,[1,4] E. Luppi,[1,4] E. Mariotti,[5] M. Poggi,[2] and L. Tomassetti[4,6]
[1]*Dipartimento di Fisica e Scienze della Terra, Via G. Saragat 1, 44122 Ferrara, Italy*
[2]*INFN Laboratori Nazionali Legnaro, Viale dell'Università 2, 35020 Padua, Legnaro, Italy*
[3]*Dipartimento di Fisica e Astronomia and INFN Sezione di Padova, Via F. Marzolo 8, I-35131 Padua, Italy*
[4]*INFN Sezione di Ferrara, Via G. Saragat 1, 44122 Ferrara, Italy*
[5]*Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente and INFN Siena, Via Roma 56, 53100 Siena, Italy*
[6]*Dipartimento di Matematica e Informatica, Via G. Saragat 1, 44122 Ferrara, Italy*

(Received 5 September 2017; accepted 9 October 2017; published online 14 November 2017)

Low energy threshold detectors are necessary in many frontier fields of the experimental physics. In this work, we present a novel detection approach based on pure or doped matrices of inert gases solidified at cryogenic temperatures. The small energy release of the incident particle can be transferred directly (in pure crystals) or through a laser-driven ionization (in doped materials) to the electrons of the medium that are then converted into free electrons. The charge collection process of the electrons that consists in their drift within the crystal and their extraction through the solid–vacuum interface gives rise to an electric signal that we exploit for preliminary tests of charge collection and crystal quality. Such tests are carried out in different matrices of neon and methane using an UV-assisted apparatus for electron injection in crystals. *Published by AIP Publishing.* https://doi.org/10.1063/1.5003296

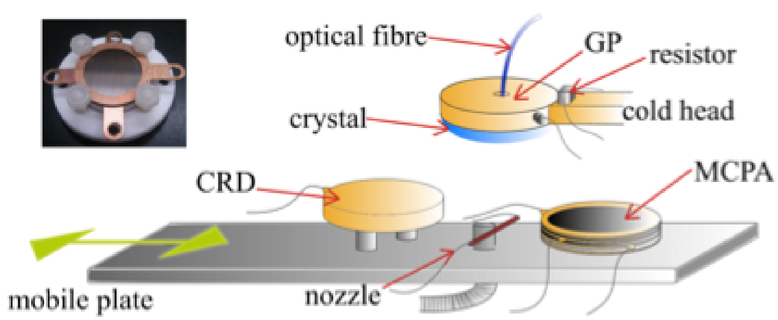
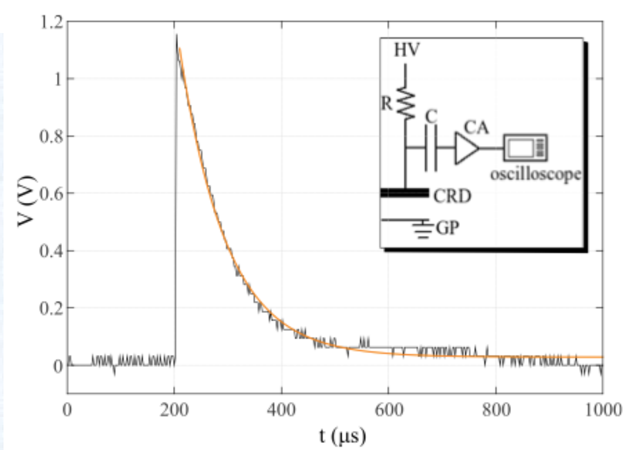


FIG. 2. Sketch of the cold head assembly and the mobile plate. The distance between the growth plate (GP) and the electron detectors is 10 mm. A picture of the microchannel plate assembly (MCPA) is shown in the inset.



AXIOMA RESULTS 3

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A new technique for infrared scintillation measurements

F. Chiossi[a,*], K. Brylew[b], A.F. Borghesani[c], C. Braggio[a], G. Carugno[a], W. Drozdowski[b], M. Guarise[a]

[a] Dip. di Fisica e Astronomia and INFN, University of Padua, Via F. Marzolo 8, I-35131 Padova, Italy
[b] Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziadzka 5, 87-100 Torun, Poland
[c] CNISM Unit and Dip. di Fisica e Astronomia, University of Padua, Via F. Marzolo 8, I-35131 Padova, Italy

ARTICLE INFO

Keywords:
Infrared light yield
Pr:LuYAG
Radioluminescence

ABSTR

We propose a
comparing it t
apply this tecl

Contents lists available at ScienceDirect

Journal of Luminescence

journal homepage: www.elsevier.com/locate/jlumin

Cathodo- and radioluminescence of Tm^{3+}: YAG and Nd^{3+}: YAG in an extended wavelength range

A.F. Borghesani[a,*], C. Braggio[c], G. Carugno[b], F. Chiossi[c], M. Guarise[c]

[a] CNISM Unit, Department of Physics and Astronomy, University of Padua and Istituto Nazionale Fisica Nucleare, sez. Padova via F-Marzolo 8, I-35131 Padua, Italy
[b] Istituto Nazionale Fisica Nucleare, sez. Padova and Department of Physics and Astronomy, University of Padua, via F-Marzolo 8, I-35131 Padua, Italy
[c] Department of Physics and Astronomy, University of Padua and Istituto Nazionale Fisica Nucleare, sez. Padova via F-Marzolo 8, I-35131 Padua, Italy

ARTICLE INFO

Keywords:
Nd:YAG
Tm:YAG
Cathodoluminescence
Radioluminescence
Infrared and visible light yield

ABSTRACT

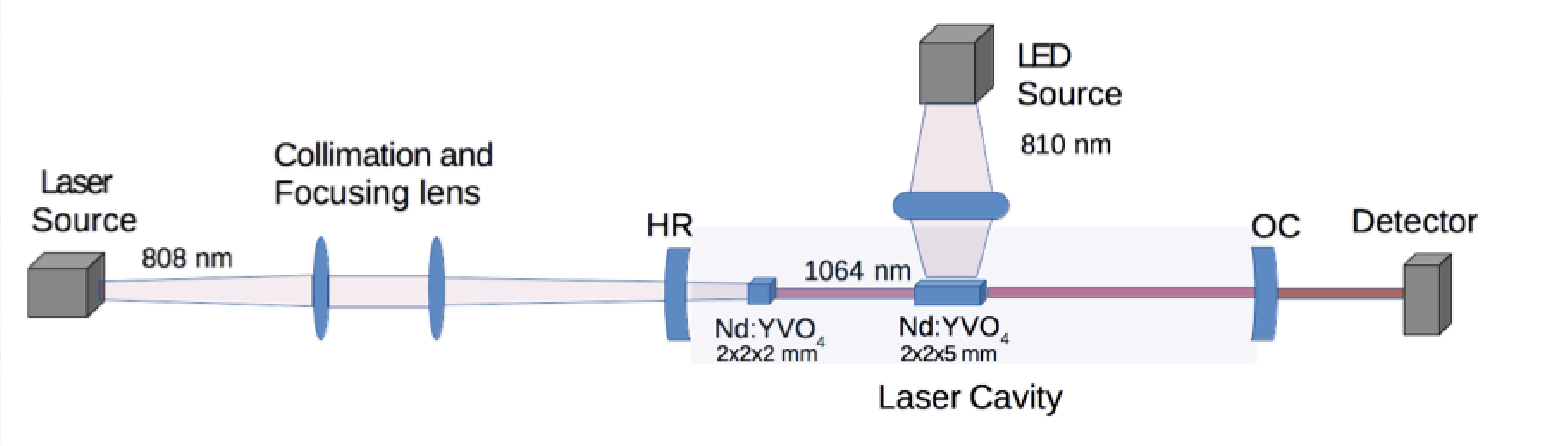
We have studied the cathodo- and radioluminescence of Nd:YAG and of Tm:YAG single crystals in an extended wavelength range up to ≈5 μm in view of developing a new kind of detector for low-energy, low-rate energy deposition events. Whereas the light yield in the visible range is as large as $\approx 10^4$ photons/MeV, in good agreement with literature results, in the infrared range we have found a light yield $\approx 5 \times 10^4$ photons/MeV, thereby proving that ionizing radiation is particularly efficient in populating the low lying levels of rare earth doped crystals.

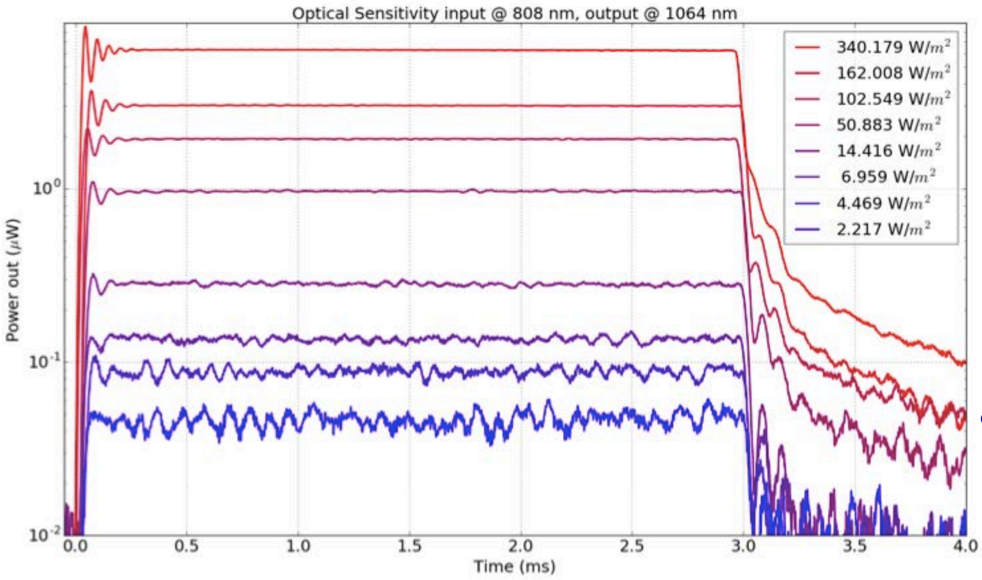
2 more articles already accepted

3 under submissions

AXIOMA RESULTS 4

Laser Based Coherent Scintillator: Radiation Induce Stimulated Emission





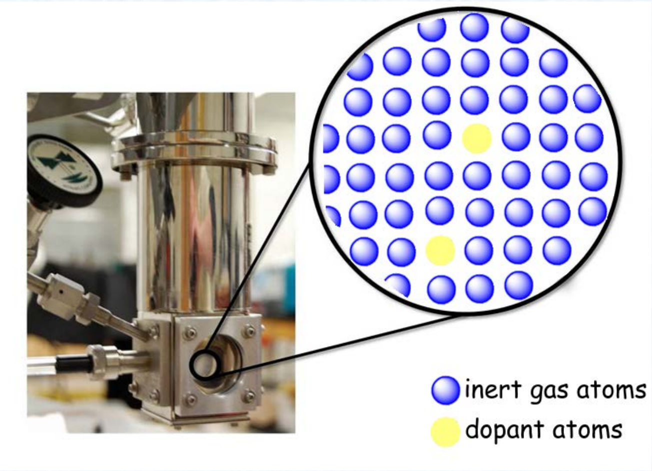
Nd:YVO4 large IR LIGHT SCINTILLATION YIELD

L.Y. = 10^5 IR photon/ MeV

Laser operating near threshold need an extra population on around 10^3 Atoms in Excited States

Low Energy Threshold Cryogenic Detectors

Future efforts on Cryogenics Noble Gases Matrix Isolation detectors:
Undoped & Doped crystals



3 main approaches proposed:

-A) Single Electron Detection promoted without and with laser and Electric Field with a Kg mass detector via Bridgeman's growing technique

-B) Fluorescence Recycling Phenomena in doped cryogenic crystals
-doping atoms: Rare earth, molecular nitrogen or Alkaline atoms

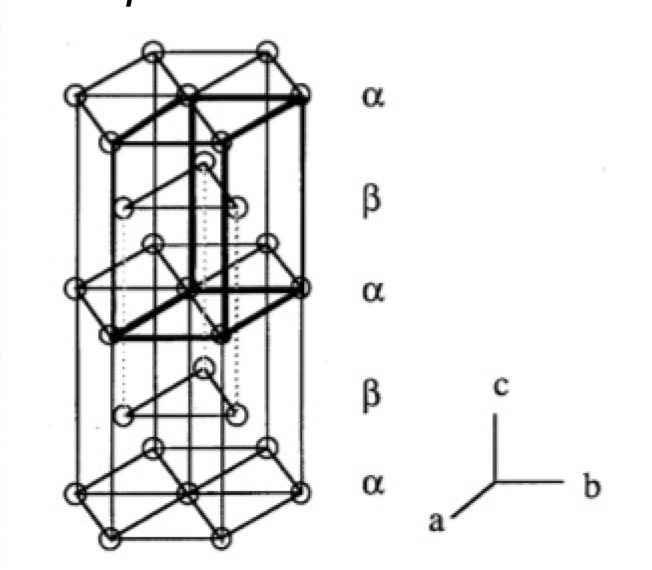
-C) Inverse Bremsstrahlung electron accelleration under Laser Field combination of electron and light multiplication present in high density media

Comment on Oxide , Fluoride & Cloride doped Crystals

Matrix isolated crystals

- Noble gases matrices
- Low interacting environment
- Feeble interaction host-host
- Possibility to embed species into the matrices

Example of solid neon structure



Matrices parameters

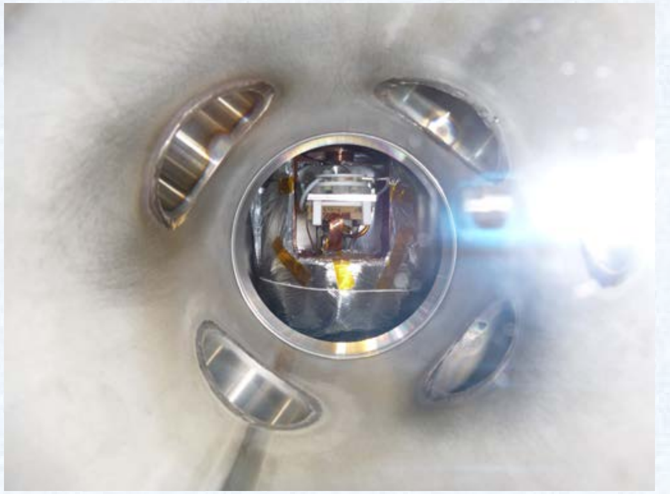
matrix	a (Å)	E_{gap} (eV)	V_0	μ_e(cm^2 V^{-1} s^{-1})
Ne	$\sim$ 4.4	$\sim$13	+1.1	600
CH_4	$\sim$ 8	$\sim$24.5	-0.18	100
$para-H_2$	$\sim$ 3.7		+2	

Axioma receipe:

growing parameters:

- $P_{growth} \sim 2 \cdot 10^{-5}$ mbar
- $t_{growth} \sim 2$ h
- $T_{growth} \sim 9$ K
- $t_{annealing} \sim 15$ min

$\Longrightarrow$ 25 mm diameter, 2 mm thickness crystals

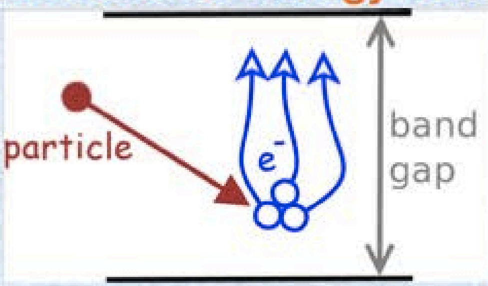


A) Single Electron Detection in undoped or doped matrices

Matrix isolation technique [J. Chem. Phys. 22, 11 (1954)]

a.1)**Direct ionization** in undoped matrices:

Detectable energy **tens eV**

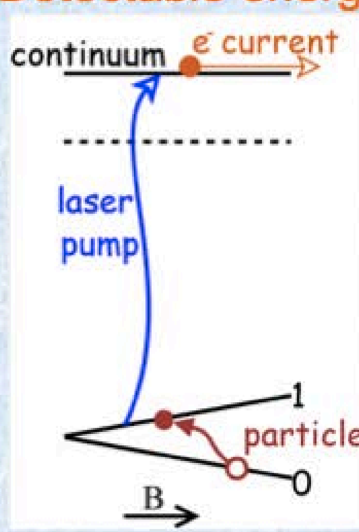


Matrix of inert gas (Ne, paraH, Ar, Xe,…)

- High purity material
- **Positive V_0**
- Band gap of **tens of eV**

a.2)**Energy upconversion** in doped matrices:

Detectable energy **sub eV**

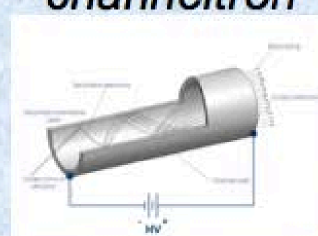


- RE or alkali embedded in
- Firs ionization energy in **eV range**
- Ionization:σ between 10^{-14} and 10^{-10} cm^2
- Detection: 0-1 transition
- **Tunable system**
- Narrow band laser pump

Charge signal

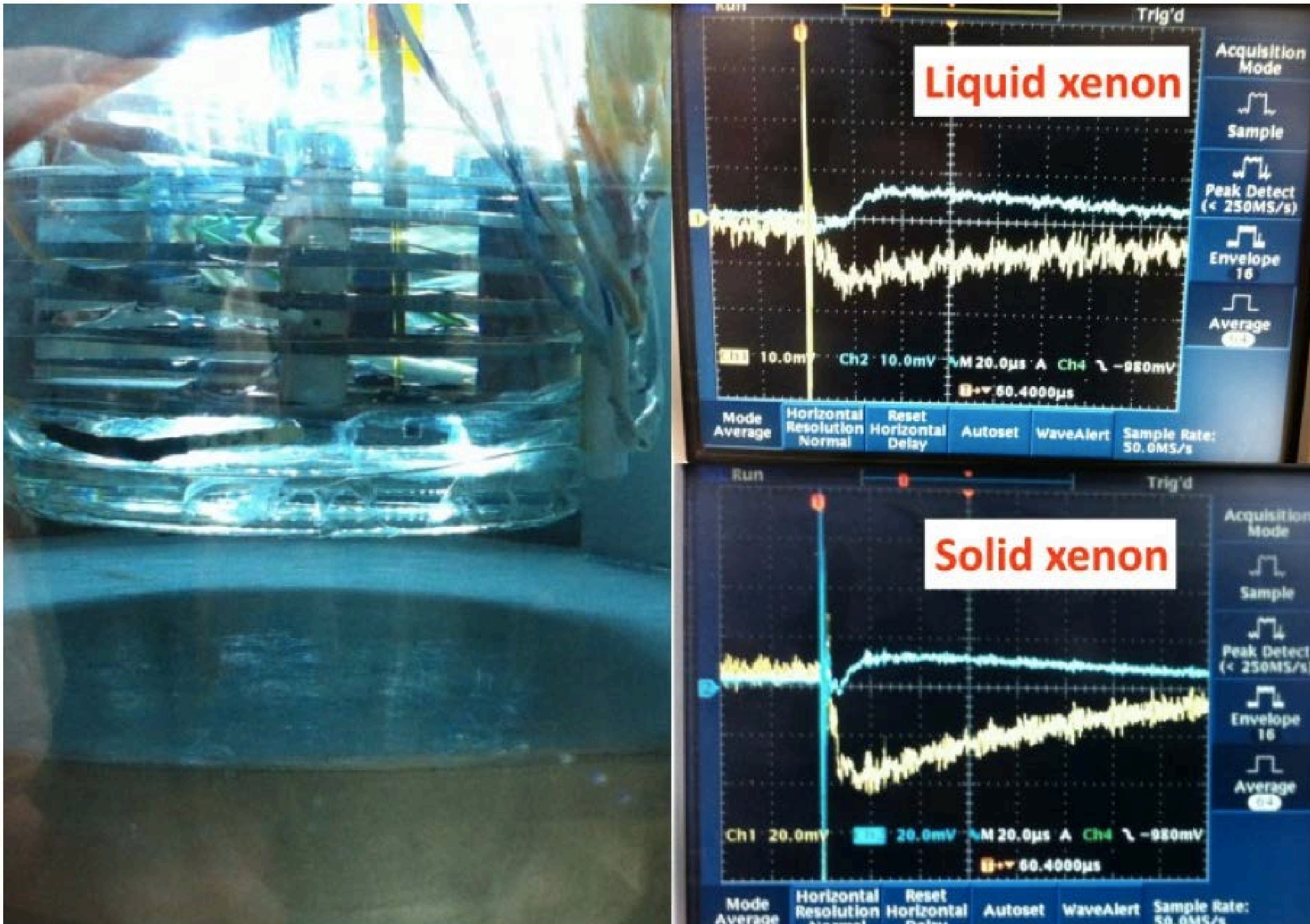
- In vacuum electrons
- High efficiency single electron sensors
- Low dark count rate detector (mHz)

channeltron



MCP

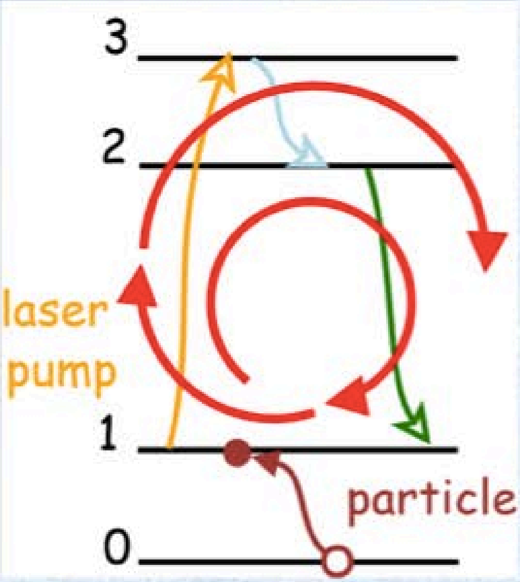
FERMILAB CHAMBER SET-UP



B) Fluorescence Recycling Phenomena in doped cryogenic crystals

Matrix isolated crystals: RE, alkali or nitrogen doped

- Exploit internal energy level scheme
- Narrow bandwidth laser pump probing
- Fluorescence signal emission

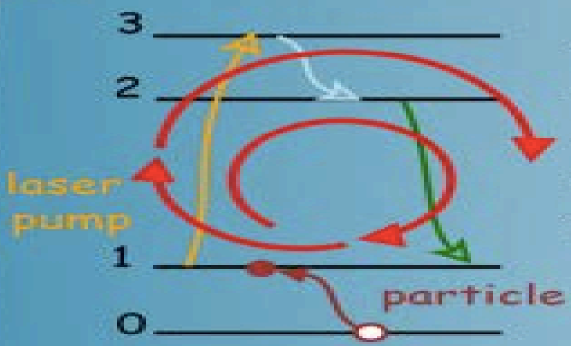


- Particle: transition 0-1
- Laser: transition 1-3
- Non-radiative decay: transition 3-2
- Fluorescence signal: transition 2-1

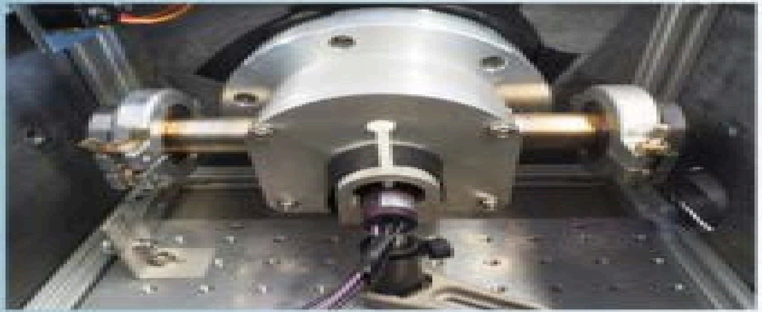
A single particle transition triggers
N fluorescence photons emission

Recycling efficiency $\approx N_{photons}\ \tau_1\ \sigma_{13}\ \beta_{21}$ → high efficiency detector in **eV range!**

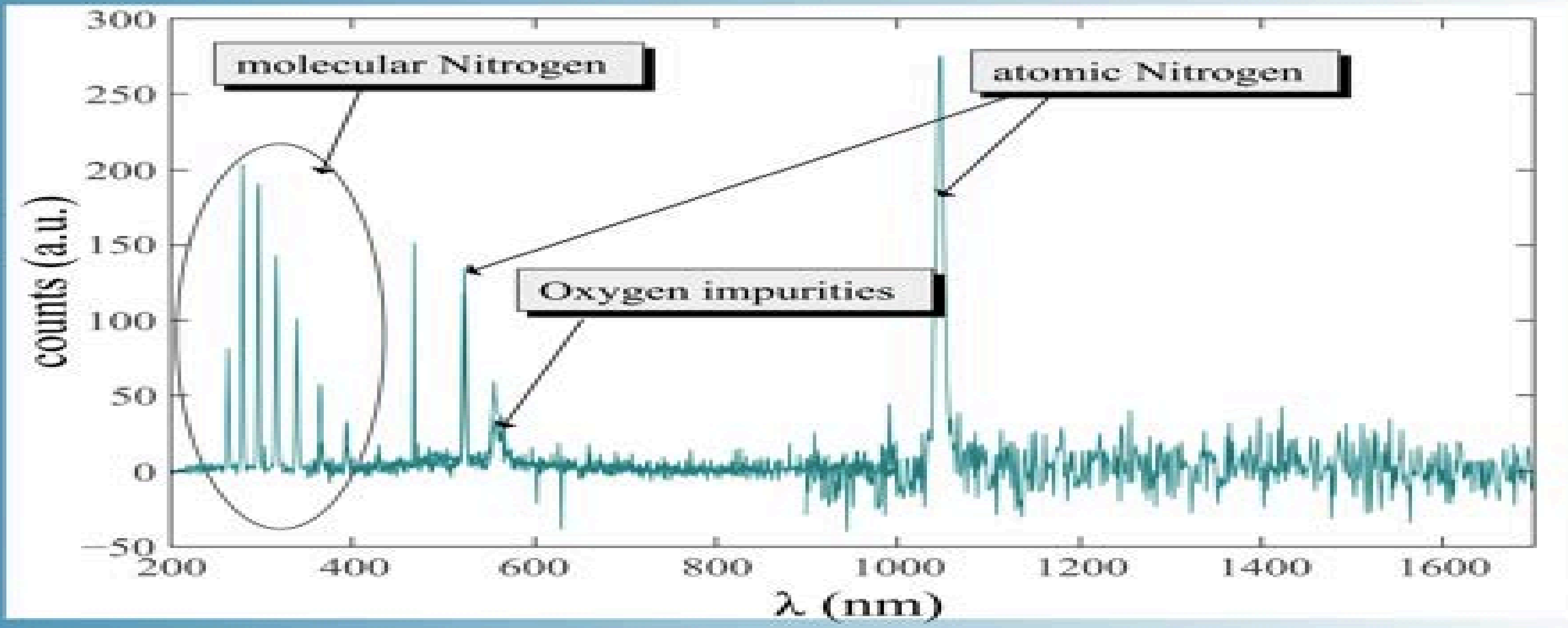
B Recycling scheme



- Laser-assisted transition 1⟶3
- Fluorescence signal 2⟶1
- Recycling mechanism 1⟶3⟶2⟶1
- One single transition 0⟶1 triggers the emission of N photons



We are interested in schemes that involve both the vibrational bands of the undoped matrices [in the figure, the cathodoluminescence emission spectra of solid nitrogen @ 20K], and the energy levels of RE doped crystals.



C) Inverse Bremsstrahlung electron accelleration under Laser Field combination of electron and light multiplication present in high density media

Electrons acceleration-multiplication in **high desity materials**

- High dense gas (Ar, Xe, Kr)
- High power IR Laser light pump
- Charge signal
- Light emission signal

$$\sigma(\varepsilon,\omega)=\frac{8\pi}{3}\frac{(v_i v_f)^2}{\omega^3}NQ(\varepsilon)\frac{e^2}{\hbar c}$$

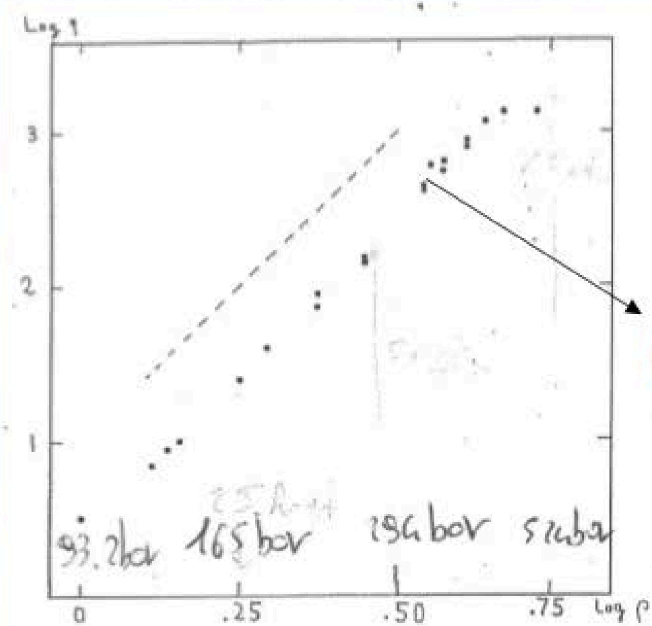


Fig. 2. Effect of density on electron integrated signal q at constant pulse energy. Abscissas: Logarithm of density expressed in hundreds of Amagsts. Ordinates: Logarithm of q. The

High amplification!
1000 times gain

- G. Hauchecorne, et al, *Photoionization experiments in dense argon gas*, Opt. Comm., 38, 3, (1981)
- G. Mayer, *Laser indued multiplication and visualization of free electrons in dense monoatomic gases*, Nucl. Instrum. Meth A, A254 (1987)

LIP&LED: 3 ANNI (19-21)

Sezioni INFN partecipanti all'esperimento: **LNL, Padova, LNS (Palermo), Ferrara**

Resp. Naz.: **Giovanni Carugno**

Partecipazione PD:

G.Carugno	50%
C.Braggio	50%
F.Borghesani	100%
F.Chiossi	100%
B.Baboussinov	50%
M.Pegoraro	20% TBC
L.Ricci	50%
Totale	**4.2 FTE**

Richieste 2019 PD : 60 Keuro

Richieste Servizi Sezione : 10 M/U O.M , 8 M/U O.E., 2 M/U U.T

Laser Driven Particle Detector = Sistema a 3/+ livelli

$$\rho_{ij} = Densita'\ EnergiaEM$$

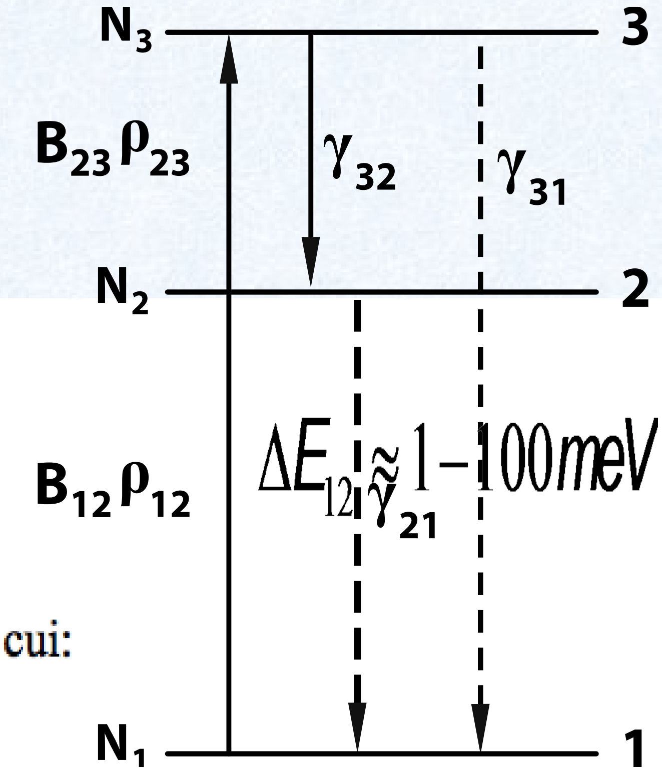
$$B_{ij} = Coeff.Einstein$$

$$\gamma_{ij} = Rate - TransizioneRad + NonRad.$$

$$\dot{N}_1 = -B_{12}\rho_{12}N_1 + N_2\gamma_{21} + N_3\gamma_{31}$$

$$\dot{N}_2 = B_{12}\rho_{12}N_1 - B_{23}\rho_{23}N_2 + N_3\gamma_{32} - N_2\gamma_{21}$$

$$\dot{N}_3 = B_{23}\rho_{23}N_2 / N_3\gamma_{32} - N_3\gamma_{31}$$



Questa serie di equazioni si può semplificare nel caso in cui:

a) $\Delta E_{21} > kT$ (T cristallo < 4 K)

b) Pompa Laser ν_{23} CONTINUA $\dot{N}_i = 0$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{T_1 \alpha_p I_p P_p}{\Delta E_{12} V_{cristallo}}$$

c) V = Volume del cristallo illuminato

d) il cristallo sia poco irragiato il che significa poca popolazione nel primo stato eccitato

Stato Attuale Rivelatori Alle Basse Soglie

$$Segnale \propto E_{rilasciata} / w_{detector}$$ (Fano Factor , Quenching Factor,…)

$$W \approx 2,5 E_{gap}$$ **Shockley**

Scintillatori : Kev (40 ph/KeV) Q.F. elevato alle basse energie , Fano Factor alto

Semiconduttori : 400 eV (1 e/h /3,6 eV Si ,100 elettroni rumore a bassa Capacita'

Bolometri : less than eV **MA** Risoluzione $\delta E = \sqrt{K_b T^2 C_0 M_{DET}}$

(Basse Soglie = microgrammi @ milli Kelvin)

PROBING THE MATTER WITH LASER :

- **Soglia Energia = Singolo Atomo Eccitato (SATURAZIONE)**
- **Volume/Masse = 1 Lt / Kg seems possible**
- **Amplificazione ottica : Geiger mode + Em. Stimolata,**

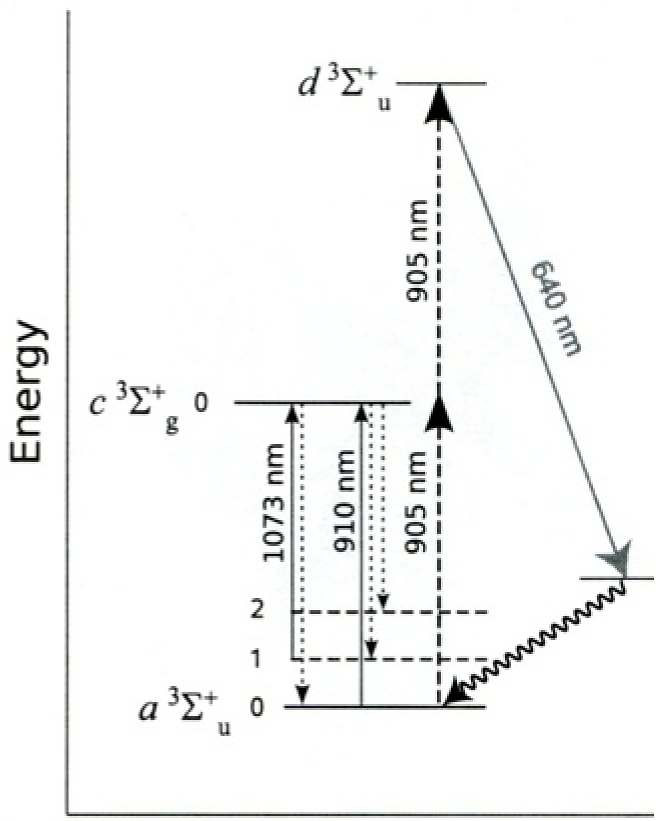
PRL **100**, 025301 (2008) PHYSICAL REVIEW LETTERS week ending 18 JANUARY 2008

Detection and Imaging of He_2 Molecules in Superfluid Helium

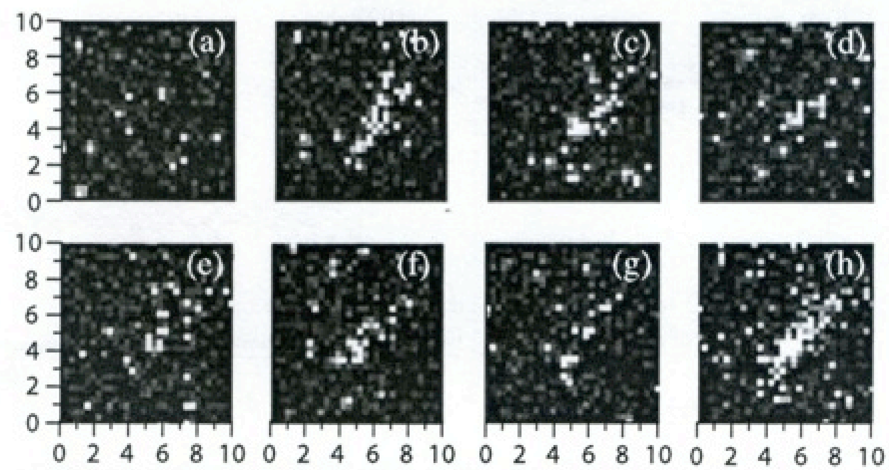
W. G. Rellergert, S. B. Cahn, A. Garvan, J. C. Hanson, W. H. Lippincott, J. A. Nikkel, and D. N. McKinsey*
Department of Physics, Yale University, New Haven, Connecticut 06520, USA
(Received 10 September 2007; revised manuscript received 15 November 2007; published 15 January 2008)

We present data that show a cycling transition can be used to detect and image metastable He_2 triplet molecules in superfluid helium. We demonstrate that limitations on the cycling efficiency due to the vibrational structure of the molecule can be mitigated by the use of repumping lasers. Images of the molecules obtained using the method are also shown. This technique gives rise to a new kind of ionizing radiation detector. The use of He_2 triplet molecules as tracer particles in the superfluid promises to be a powerful tool for visualization of both quantum and classical turbulence in liquid helium.

PACS numbers: 67.25.D−, 29.40.Gx, 67.25.dk



Tracce Elettrone Compton in Elio Liquido CCD



Low Energy Threshold Cryogenic Detectors

Future efforts on Cryogenics Noble Gases Matrix Isolation Detectors:

Undoped & Doped

3 main approaches proposed:

- **A) Single Electron Detection promoted without and with laser and Electric Field with a Kg mass detector via Bridgeman's growing technique**

- **B) Fluorescence Recycling Phenomena in doped cryogenic crystals doping atoms: Rare earth, molecular nitrogen or Alkaline atoms**

- **C) Inverse Bremsstrahlung electron accelleration under Laser Field combination of electron and light multiplication present in high density media**

Comment on Oxide , Fluoride & Cloride doped Crystals