Dark matter detectors and understanding of glasses

Entangled realities of particle and condensed natter physics

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LLNL-PRES-XXXXXX
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Thesis-plan of the talk

- **Observed features of the excess noise in low-energy-threshold detectors can be explained (not contradicted) by processes of energy accumulation and uneven releases in materials; in-parallel with particles**

- **Glasses are out of equilibrium; dynamic response depends on history and involves energy accumulation and releases**

- **More glass-like properties with temperature decrease: defects motion and relaxation, magnetic impurities and nuclear spins, the motion of charges, surfaces re-organization and charging, etc. Ref.:** S. Pereverzev, "Detecting low-energy interactions and the effects of energy accumulation in materials", Phys. Rev. D 105, 063002 (2022)

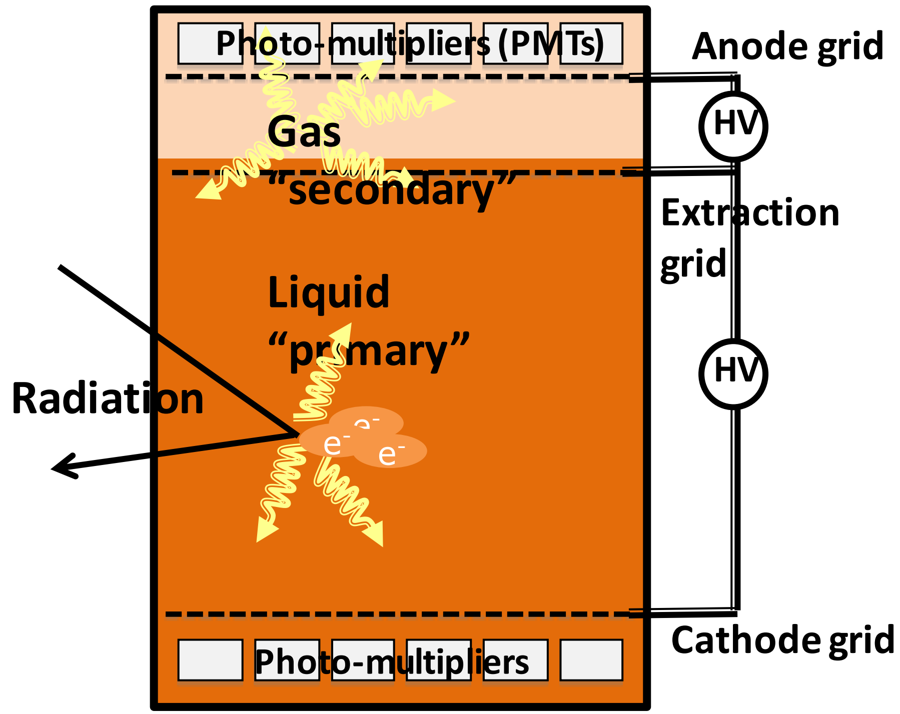
- **Unsettled problem is *the role of interactions between states bearing excess energy:* the dom inant theory is based on non-interacting Tunneling Two-Level Systems model, while internal interactions are essential in other theories**

- **Important, interesting, and difficult to study**
  - Size of efforts: dark matter, CEvNS, AND noise and decoherence in quantum sensors.
  - Emerging phenomena: avalanche relaxations, quantum correlations AND live systems
  - Organization difficulties: HEP, NS, BES; Funding mechanisms & decisions

Posters with new phenomenology observed and expected in NaI(Tl) and Noble Liquid dual-phase TPS at IDM 2022

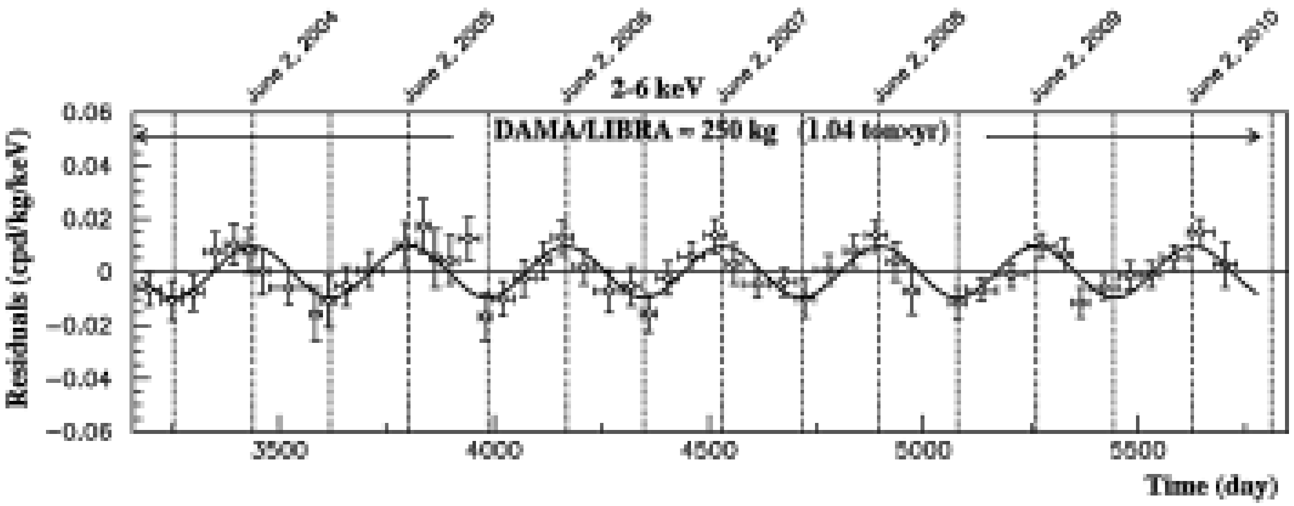
Background in low energy threshold particles detectors

Dual-phase detector



Xenon 10, Xenon 100, Xenon 1ton, LUX, LZ, Xenon N ton, …

Scintillator NaI(Tl)



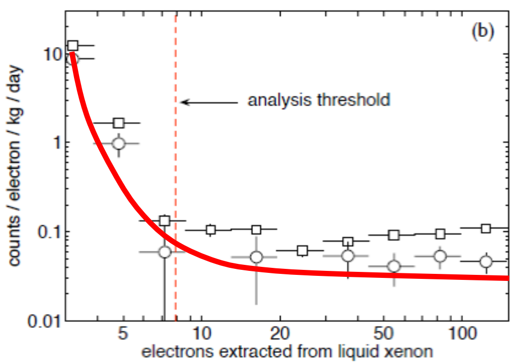
DAMA-LIBRA experiment

Observing yearly oscillation of low energy (1-8 kV) background for two decades; other experiments do not see this

Searches for nuclear recoils: WIMPs, light dark matter particles, coherent elastic neutrino scattering (CEvNS)
What they see at low energies (several electron/ photon signals)?.

Excessive low-energy background in Nobel Liquids dual-phase detectors, NaI(Tl) scintillator

a



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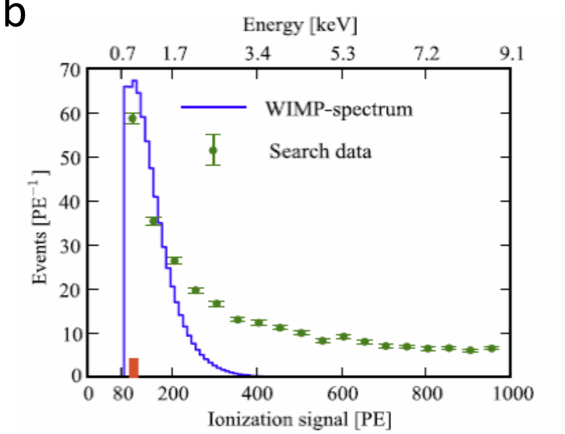

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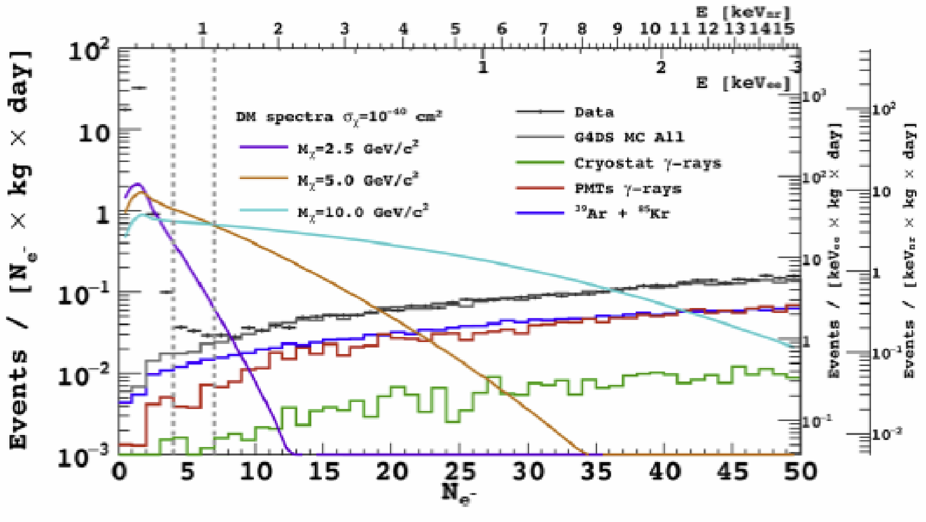

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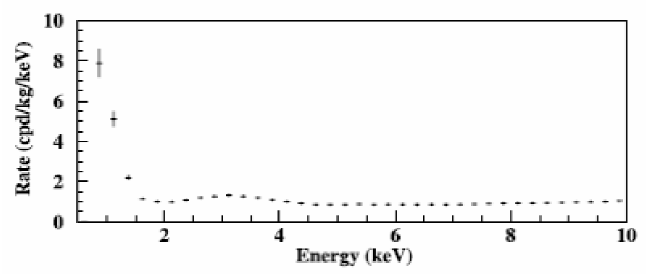


Dark matter particle detectors operating underground (low background).

A: Xenon 10 experiment, 10 kg liquid Xenon TPC

B: Xenon 100,

C: Dark Side 50 experiment, 50 kg liquid Ar TPC;

D: DAMA-LIBRA experiment, NAI(Tl) scintillator, energy deposition of 1 keV results here in registration 5.5-7.5 photons by PMTs; figure from David Nygren paper

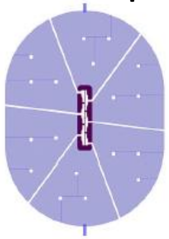
Current experiments are on 1-10 ton scale LUX, LZ, Xenon 1 ton, Xenon n ton

100 to kiloton scale detectors are discussed - b$ cost scale

Common feature- sharp rise in number of low-energy events as energies approaching excitations in materials

Excessive low-energy background in cryogenic solid-state particle detectors (variety of crystals and readout techniques)

Super-SDMS-CDP



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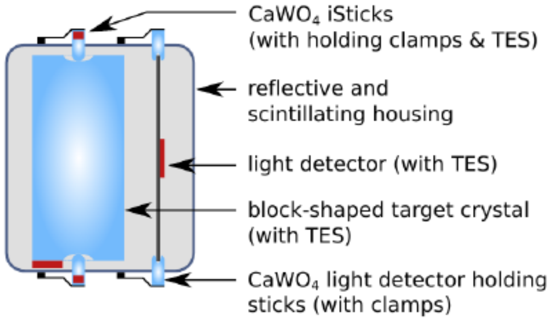
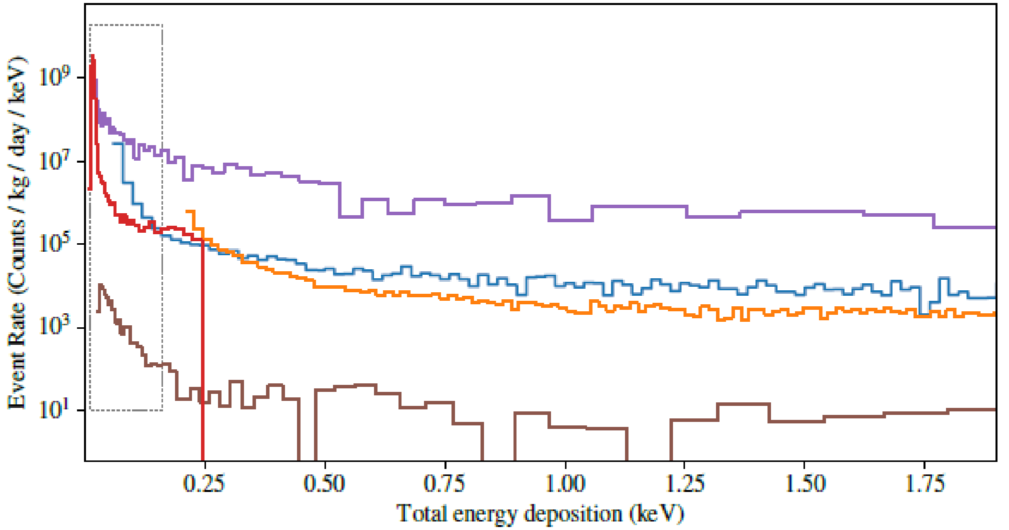
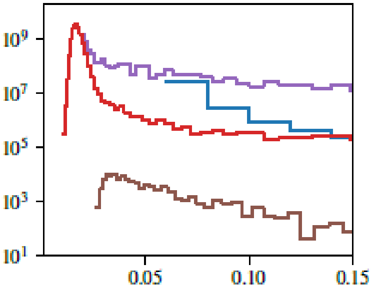




In units of deposited energy



EXCESS workshop report on arXiv

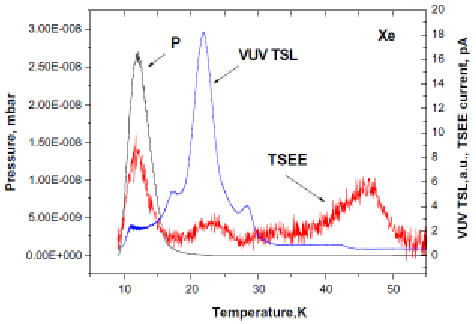
Measurement	Target	Sensor	Exposure (kg days)	Operation Temperature	Depth (m.w.e.)
CRESST III DetA	23.6 g $CaWO_4$	Tungsten TES	5.594	15 mK	3600 (LNGS)
EDELWEISS RED20	33.4 g Ge	NTD	0.033	17 mK	above ground
MINER Sapphire	100 g Al_2O_3	QET	2.72	7 mK	above ground
NUCLEUS 1g prototype	0.49 g Al_2O_3	Tungsten TES	0.0001	15-20 mK	above ground
SuperCDMS CPD	10.6 Si	QET	0.0099	41.5 mK	above ground
DAMIC	40 g Si	CCDs	10.927	140 K	6000 (SNOLAB)
EDELWEISS RED30	33.4 g Ge	NTD, NTL amplification	0.081	20.7 mK	4800 (LSM)
SENSEI	1.926 g Si	Skipper CCD	0.0955	135 K	225 (Fermilab)
Skipper CCD	0.675 g Si	Skipper CCD	0.0022	140 K	above ground
SuperCDMS HVeV Run 1	0.93 g Si	QET, NTL amplification	0.00049	33-36 mK	above ground
SuperCDMS HVeV Run 2	0.93 g Si	QET, NTL amplification	0.0012	50-52 mK	above ground

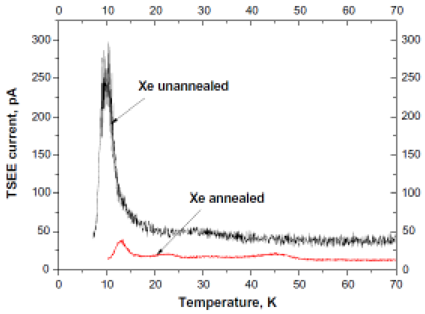
NB: decoherence!

Common features: a sharp rise in the number of low-energy events

SP: Long, (history-dependent, glass-like) relaxation processes after cooling down; background depends on the crystal support, etc.

Energy accumulation in material and delayed release after irradiation, stress, electric breakdown





Radiation effects in atomic cryogenics solids, E.V. Savchenko *et al*, NIM B268, 2010 see also M.E. Fajardo and V.A. Apkarian, J.Chem.Phys. 87, 1988

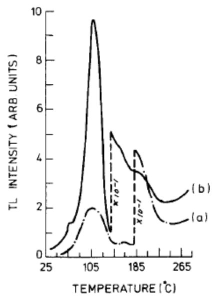


FIG. 1. TL glow curves for NaI crystals containing thallium activator: (a) 0.75 and (b) 1.5 millimolar fractions. Exposure 10^3 R.

Thermoluminescence in Gamma-Irradiated NaI(Tl) Crystals
Nucl. Tracs, Vol.10, pp/107-110, 1985

- ○ **Thermally stimulated luminescence, electron emission,**
- • Al_2O_3(I) (personal dosimeters); up to 13% of energy converted to TSL
- • Can be "erased" by sunlight, by microwave exposure.
- • Stress triggers luminescence, electron emission in irradiated materials
- • Thermoluminescence in alkali metal halides (with and without impurities); suppression by red /IR light
- ○ **Thermally stimulated conductivity in semiconductors and dielectrics**
- ○ **Mechanical stress/ deformations lead to delayed photon and exaelectron emissions from metals, semiconductors, dielectrics**
- • Studies of deformations, defect, and dislocation motion in scanning microscopy, electron microscopy
- ○ **Noble liquids, gases: after-luminescence, delayed electron emission**
- • energy comes from long-living excitations, molecular ions, chemical radicals, surfaces of electrodes, **charged liquid surface**

Important: Energy accumulations is possible in practically all common detector materials
Low activation energy for TSL, TSEE (avalanches possible)
Multiple pass ways for interactions and energy exchange between energy- bearing states/defects/configurations

Systems with energy flow & Self-Organized Criticality

Emerging phenomena:

- Formation of dissipative structures
- Emerging of order out of chaos
- Emerging of complexity

- **Polynomial events spectrum (catastrophes possible)**
- **Noise power spectrum close to 1/f (pink noise}**
- **Absence of characteristic time or size of the avalanche**
- **Low energy particles can cause “large events”**
- **Large events suppression by helping “small relaxation”**

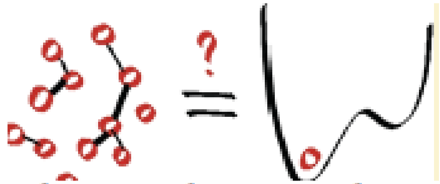
Ilya Prigogine (Noble Price 1977)
Dissipative structures,
irreversibility, **complexity**, order out of chaos, and more

Per Back, Chao Tang and Kurt Wiesenfeld (1991 paper)
Self-Organized Criticality
Another avenue for **complexity;**
1/f noise explained ?

Effects are present in experiments and in simulations of large ensembles of interacting particles, but no “sufficient conditions” can yet be formulated

Non-interacting Tunneling Two-Level Systems in condensed matter (1972-   ) or *Interacting excitations* in chemical physics & biology (1977-   )

TLS introduced to describe glasses around 1972



with ϵ_i as the offset between the potential energy in the two configurations and Δ_i as the matrix element for tunneling between them. Then, we evidently have

$$E_i = (\epsilon_i^2 + \Delta_i^2)^{1/2}$$

Spectrum: $\rho(\epsilon, \Delta) = \dfrac{\text{const}}{\Delta}$

?

Ilya Prigogine

Energy accumulation and releases

Dug Osheroff

Tony Leggett

Noble laureates criticizing TLS model

Still, difficulties with realistic microscopic models for TLS [6]

1. P. W. Anderson , B. I. Halperin & c. M. Varma "Anomalous low-temperature thermal properties of glasses and spin glasses," Phil. Magazine, 25:1, 1-9 (1972).
2. W. A. Phillips, "*Two-level states in glasses*", Rep. Prog. Phys. 50, 165723 (1987).
3. S. Rogge, D, Natelson, and D. Osherof, *Evidence for the Importance of Interactions between Active Defects in Glasses*, Phys. Rev. Lett. 76, 3136, (1996).
4. A.J. Leggett, D.C. Vural, *"Tunneling two-level systems" model of the low-temperature properties of glasses: are "smoking gun" test possible?"*, The Journal of Physical Chemistry B, 117, pp. 12966-12971, (2013).
5. Per Back, Cho Tang, and Kurt Weisenfeld, "*Self-organized criticality: An explanation of 1/f noise*", Phys. Rev. A38, 364 (1988).
6. C. Muller, J.H. Cole, J. Lisenfeld, *"Towards understanding two-level-systems in amorphous solids: Insights from quantum circuits"*, Reports on Progress in Physics, V.82, 124501 (2019).

Excess workshops: excess background resembles SOC-like dynamics.

Energy accumulation and releases in material: history of the problem and possible developement

No theoretical models yet
Physics is experimental science!

?

Tunneling,
Entanglement
Squeezing
In non-equilibrium thermodynamics
& quantum biology

Phenomenology
Experimental studies
Physics of complex systems

?

HEP detectors
Quantum sensors
Condensed Matter

2021 Excess Background and glass-like relaxation in detectors

Chemical physics
Cell biology

~2010 Interacting TLS in Quantum devises
1987 W.A. Phillips
1972 P.W. Anderson et al., Non-interacting tunneling two-level systems

Glasses
stored energy
energy flow

1988 Self-Organized Criticality
1977 Prigogine (Noble prize)
Complex internal interactions

Discussion/Possible coherent picture

- **Interactions of excitations and defects bearing excess energy in materials could lead to new phenomenology in dark matter, CEvNS, photon detectors, and quantum sensors &qubits.**

- Avalanches: bursts in luminescence, exaelectron emission, conductivity, quasiparticle emission, hot phonon emission, and heat spikes. In quantum detectors, “up-conversions” could be possible (transitions to high energy excited state), decoherence, and correlated non-local errors

- Quantum correlations: Interactions of excitations in materials could lead to the emission of photons or particles in entangled or squeezed states, and correlations in energy, directionality, and polarization. Quantum correlations of light produced in atomic cascades are examples.

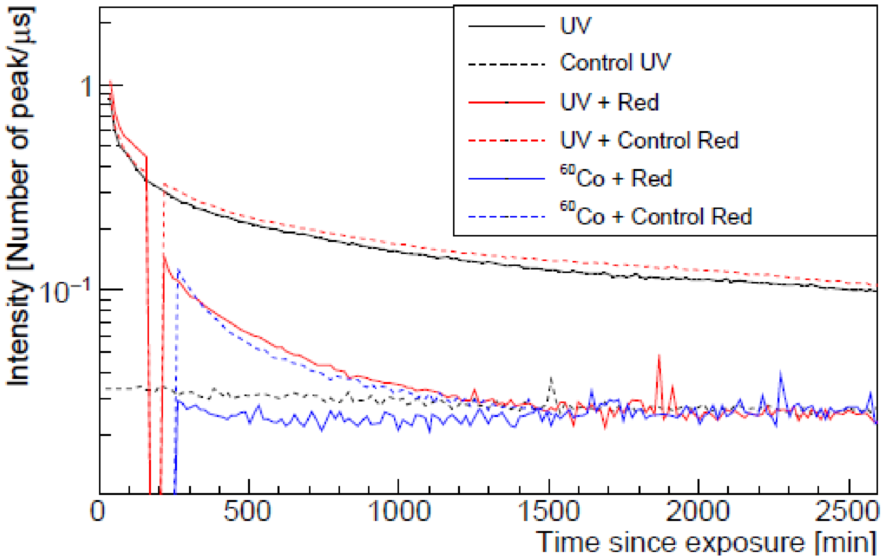
- Hypothesis: Live cell IR luminescence: interactions of metabolic processes in live-cell should lead to process-specific spectral & intensity variation of IR luminescence and quantum correlations in luminescence

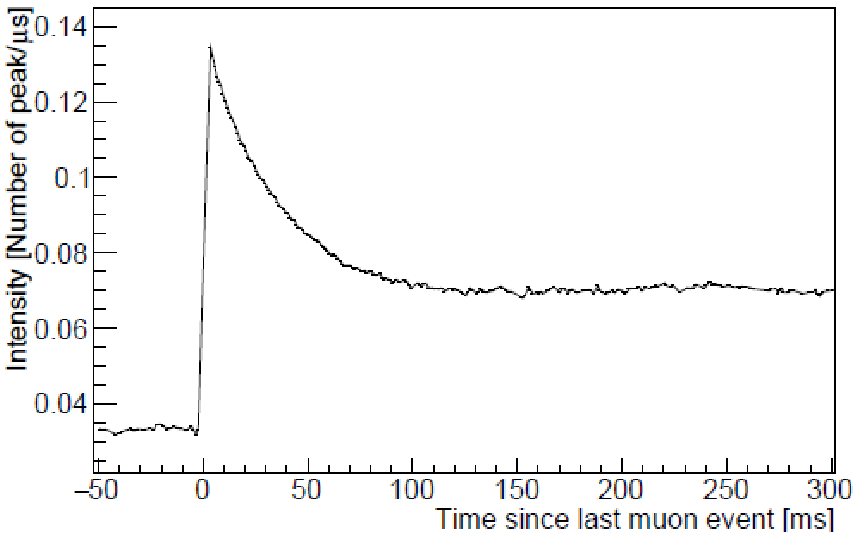
- Experiments with NaI(Tl) scintillators, superconducting photon detectors noble liquids detectors (next few slides)

Collaboration, using theoretical and experimental approaches of particle physics and condensed matter are required

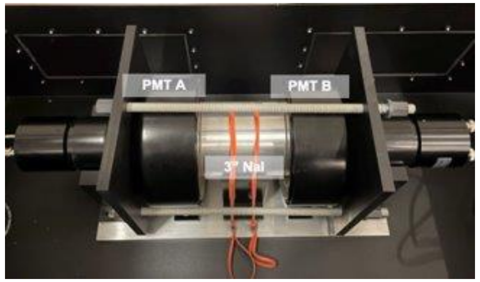
Energy accumulation and releases in NaI(Tl), quenching by red light

F. Sutanto, J. Xu, A. Bernstein, S. Pereverzev (LLNL)





With mild UV exposure, several pulses per second can be seen in the 6-10~keV region of a spectrum. If the crystal is stored in a dark area, this mild UV exposure will eventually disappear, although it may take from several hours to several days for the effects to stop --Saint-Gobain company technical note



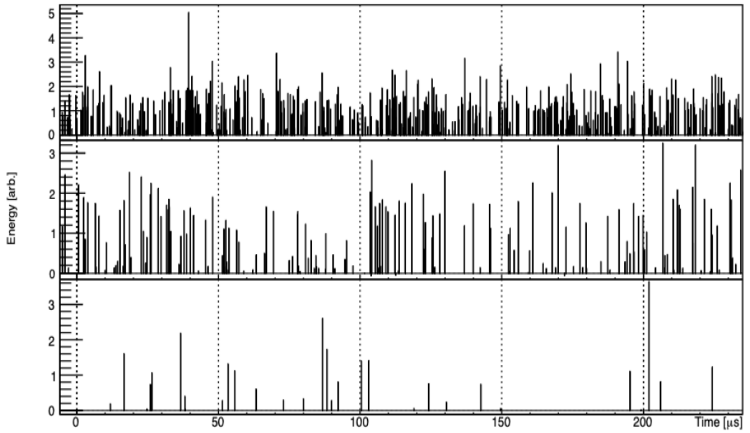
Set-up to reproduce Saint-Gobain observations

Random triggering (from external generator) and photon counting in 1 us interval
We can see lasting delayed luminescence days after UV exposure, hours after Co60 exposure, and also after muons.
Like suppression of thermally stimulated luminescence in Nai(Tl) by red / IR light exposure, we see suppression of delayed luminescence by red light exposure after UV exposure, or simultaneous Co60 and red-light exposure.
Proving Particle-like delayed events (Saint-Gobain claim) required a more delicate analysis

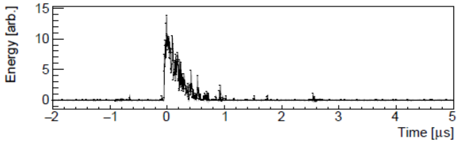
Effect of red light exposure was expected ; other environmental factor also can affect delayed luminescence

Questions to answer: "excess" photon bunching, leakage into "particle domain", modulation by environmental factors

F. Sutanto, J. Xu, A. Bernstein, S. Pereverzev (LLNL)

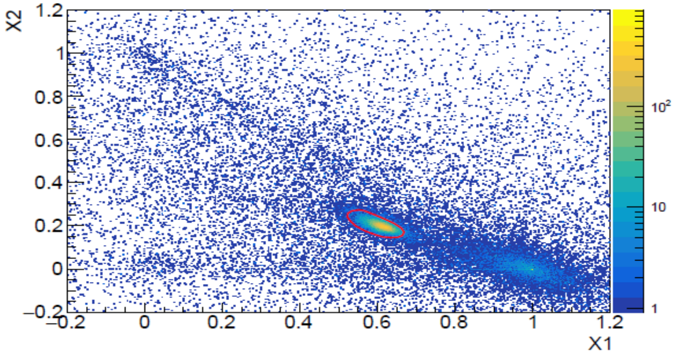


flux in 250 us data taking intervals right after UV exposure, at the middle of relaxation and close to equilibrium background; Example of particle

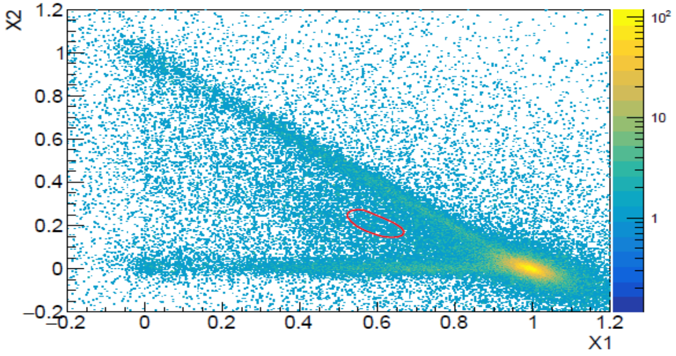


Ba^{133} data reveals the position of traditional NaI(Tl) pulse in the X1-X2 parameter space (a). UV-induced delayed light emission has the potential to leak into the X1-X2 region of genuine NaI(Tl) pulse (b).

$$X_1 = \frac{A[100, 600]\ ns}{A[0, 600]\ ns}, X_2 = \frac{A[0, 50]\ ns}{A[0, 600]\ ns}$$



(a)



(b)

The ratio of energy in "immediate light response" and in "delayed luminescence" can be modulated by environmental factors: Temperature, pressure, electric and magnetic fields, AC modulation (Schuman resonances), microwave background, mechanical stress, and vibrations; bunching also can be modulated- so, accurate accounting of energy in&out fluxes is required.

SOC dynamics and superconducting detectors & qubits

- At low temperatures systems of interacting charges (in bulk and on interfaces), spins (localized electrons, impurities, nuclei), nuclear quadrupole moments, etc., **<u>are in glass-like state</u>**, so one can define a 'generalized excitation' as any non-equilibrium configurations of these systems.
- Time-varying electric or magnetic **fields applied** to materials or **signals leaking from hot environment** can produce generalized hot excitations, as well as mechanical stress and ionizing radiation.

Energy pumping in materials and sensitivity of CMB and IR photon detectors:

<<< AC field 'drive' intensity <<< Noise equivalent power "energy sensitivity">>>

MKIDs	TES with SQUID array readout	Superconducting nanowire
Sensors are integrated into microwave resonant circuits	TES are DC-coupled to an array of SQUIDs. Frequency multiplexing readout	DC supercurrent in sensors while waiting for "click"; RSFQ -compatible*
Continuous Dissipation in sensors by microwave readout signals	Some leakage of SQUIDs signals to sensors, dissipation by DC current in TES	No dissipation by readout in sensor while waiting for photon

SOC –type dynamics provide possible explanation or the "superiority" of SPSPD technology for IR photon detectors

Improving SNSPD & studying SOC-like effects

G. Carosi, S. Pereverzev (LLNL)

- **Increasing Energy sensitivity:**

Decrease of temperature and decrease of Tc/critical current by:

- Materials/ impurities
- Suppression by magnetic field
- **Suppression by electric field in thin films**
- Removing low-lying states including nuclear spins)*

* Ultra low noise materials and devices for cryogenic superconductors and quantum bitts- US patent 10,318,880, S. Pereverzev

- **Looking for SOC-type effects:**

- Pumping energy with photons below superconducting gap energy
- Look for a change in the dark counts as a function of wavelength-

"dark counts" spectroscopy of sub-gap excitations

- Looking for up-conversion event

Effect of red light exposure was expected ; other environmental factor also can affect delayed luminescence

WHAT SURFACES IN NOBLE LIQUID DARK MATTER DETECTORS OPERATION

SERGEY PEREVERZEV
LLNL

Poster number

- DM searches with Noble Liquid detectors move toward lower energies and non-elastic interactions /multi-vertex events analysis (ELBEKA, DARWIN, use of Migdal effect)
- Inconsistencies in responses are paling up
- Comparison with HELIUM physics Pointing on advanced electron-Noble-liquid surface effects: electron trapping, accumulation, interacting with waves, Wigner crystallization- leading to the *distortion of the measured event energy spectrum*
- A complex "parallel reality" of energy and charges accumulation and delayed releases needs to be studied in collaboration with material & condensed matter scientists

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Lawrence Livermore National Laboratory

Additional slides

Energy accumulation and releases in materials: general case and NaI(Tl)results

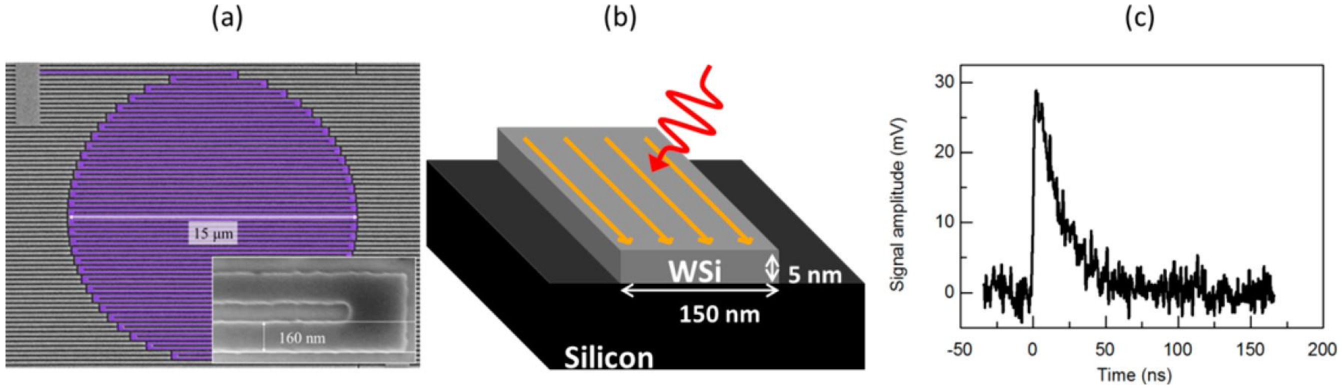
Sergey PEREVERZEV
LLNL

Poster number

- There are multiple mechanisms for excess energy accumulation in materials by defects, citations, and trapped ions with delayed releases. Interactions between energy-bearing states could lead to new emerging phenomena- relaxation avalanches like in self-organized criticality, and quantum correlations in emitted light or electrons, like in atomic cascades.
- These phenomena connect properties of glasses (disordered solids), dynamical effects in systems with energy flow (Prigogine ideas on non-equilibrium thermodynamics), and related mechanisms of noise and decoherence in quantum sensors
- WE DEMONSTRATED LONG-LASTING DELAYED LUMINISCECNE IN nai(Tl) after exposure to UV light, electrons (C060), and after muons. The stored energy can be manipulated by exposure to red light
- delayed photon emission in NAI(tl) can potentially produce signals leaking into the domain of particle luminescence signals; environmental factors can modulate the ratio of fast and delayed luminescence; moreover, stored energy releases could produce correlated light and hot phonons emission bursts at cryogenic temperatures.
- a complex "parallel reality" of energy accumulation and delayed-release processes required joined efforts between the Particle Physics community and Condensed matter physics to study emerging non-equilibrium thermodynamics effects.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Progress in superconducting photon detectors
why SNSPD outperforms other superconducting IR photon counters?



Inventor:
Professor Gregory Goltsman
Moscow Pedagogical University

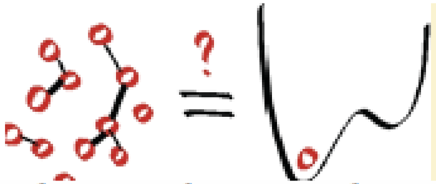
Detection of a single 5 µm photon with Superconducting Nano-Wire Photon Detector (SNSPD).
(a) SEM image of an SNSPD with false color for clarity;
(b) (b) Absorption of a photon produces a hotspot in a superconducting nanowire. This event destroys superconductivity across the entire width of the nanowire and can be detected as a voltage pulse -(c)
Thermal time constant = ~30 ns; Working temperature = ~250 mK-1.5 K

Li Chen et al., Accounts of Chemical Research, V. 50 pp1400-1409 (2017)
Detection of weak IR luminescence is demonstrated in this paper

nanowire detectors outperform PMTs in response time and quantum efficiency,
have macroscopic sensor (pixel) areas, require cooling to 250- 300 mK, (1.5 K for Near-IR) ;
In development: large arrays, working temperature 1.5- 2 K

Non-interacting Tunneling Two-Level Systems in condensed matter (1972-) or *Interacting excitations* in chemical physics & biology (1977-)

TLS introduced to describe glasses around 1972



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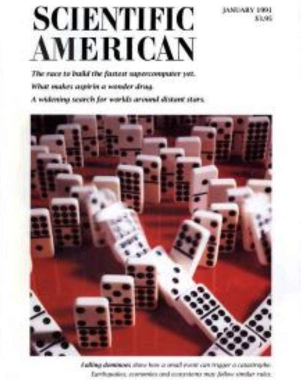
Spectrum: $\rho(\epsilon, \Delta) = \frac{\text{const}}{\Delta}$

P. w. Anderson , B. I. Halperin & c. M. Varma "Anomalous low-temperature thermal properties of glasses and spin glasses," Philosophical Magazine, 25:1, 1-9 (1972),
W. A. Phillips, "*Two-level states in glasses*", Rep. Prog. Phys. 50, 165723 (1987).

Still, no realistic microscopic models for TLS [4]

Ilya Prigogine



Energy accumulation and releases [3]

Dug Osheroff [1]

Tony Leggett[2]

Noble laureates criticizing TLS model

Systems with energy flow (Prigogine): dissipative structures, irreversibility, complexity, order out of chaos (Noble prize 1977)
Self-Organized Criticality: complexity, 1/f noise explained 1(988)

Excess workshops: excess background resembles SOC-like dynamics

1. S. Rogge, D, Natelson, and D. Osherof, *Evidence for the Importance of Interactions between Active Defects in Glasses*, Phys. Rev. Lett. 76, 3136, (1996).
2. A.J. Leggett, D.C. Vural, *"Tunneling two-level systems" model of the low-temperature properties of glasses: are "smoking gun" test possible?"*, The Journal of Physical Chemistry B, 117, pp. 12966-12971, (2013).
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4. C. Muller, J.H. Cole, J. Lisenfeld, *"Towards understanding two-level-systems in amorphous solids: Insights from quantum circuits"*, Reports on Progress in Physics, V.82, 124501 (2019).

Additional slides

Importance of sociological factor, pear presure
How goals are formulated:

"Looking for Dark Matter"

Or

"***Resolving the dark matter problem***"

Summary box has a full-width bleed.
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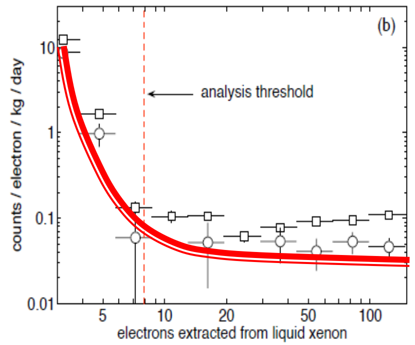
SOC model (hypothesis) main features

- Polynomial (not exponential) events spectrum- applicable to particles detectors; probability of a catastrophic event not negligible.
- Absence of characteristic time or size of avalanche region (a-la phase transition)
- Noise power spectrum close to 1/f (pink noise)- applicable to superconducting detectors (SQUIDs, TES, etc., qubits)
- Low energy particles/ events can cause "large events"
- Suppression of "large events" by reinforcing relaxation at small scale-

(put sand pile on vibrating platform…)

Looks familiar?



EXAMPLES

"soft condensed matter" - grows of the sand pile, when more material is added to the top and spreads horizontally by avalanches.

"hardcore condensed matter"- crack formation, a motion of quantized vortexes in the superconductor.

Results of computer modeling of system with known interactions in between particles
SOC may be or may be not present; no "sufficient conditions" criteria for the presence

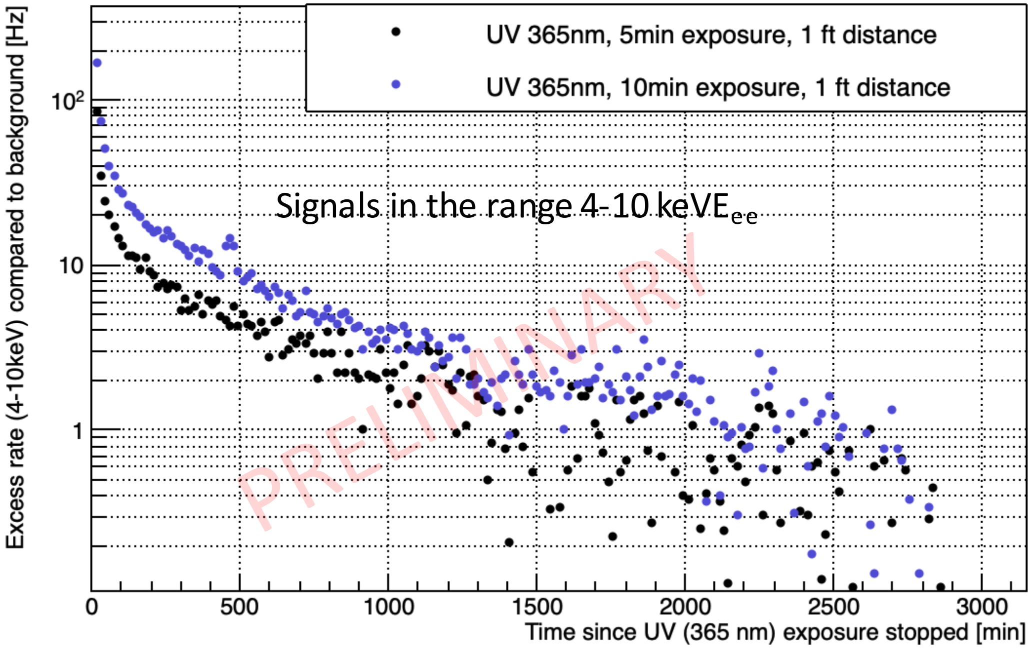
Excess of the low-energy background was observed after NaI crystal was exposed to UV light

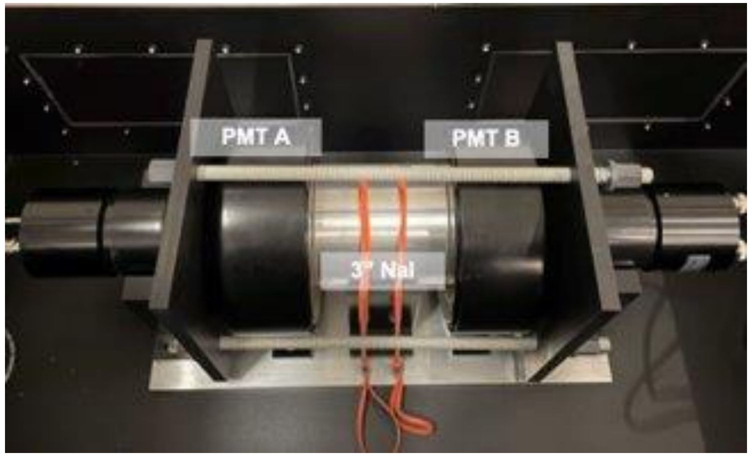
Professor
David Nygren.

With mild UV exposure, several pulses per second can be seen in the 6-10~keV region of a spectrum. If the crystal is stored in a dark area, this mild UV exposure will eventually disappear, although it may take from several hours to several days for the effects to stop --Saint-Gobain company technical note

Dr. Felicia Sutanto

Left-right coincidence trigger
Traditional way
of signal detection/triggering
can cause confusion





Red light (625 nm) exposure may force quenching of energy-bearing states