

Advancements in the LTD Science and Technology at LTD -10

Genova 11. July 2003 Klaus Pretzl

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1967 first bolometer used in molecular beam experiment in the second sec

für Group of Prof.G.Gallinaro:

M.Cavallini, G.Gallinaro, G.Scoles

Zeitschrift Naturforschung Band 22a, Heft 3, 1967



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LTD developments

- Bolometers
- Tunnel Junctions
- Superheated superconducting granules (SSG)
- Magnetic micro-calorimeters
- Cryogenic tracking detectors
- Developments are physics driven
- Unprecedented energy resolutions obtained

LTD opened new roads in experimental physics 10. genuted

- Direct dark matter (WIMP) searches
- Double beta decay and direct neutrino mass det.
- Nuclear and atomic physics
- X-ray astrophysics
- Infrared astronomy
- Cosmic microwave background radiation (CMB)
- Single photon detection
- Particle tracking detectors
- **Biological and medical applications**
- Material science

Cryogenic WIMP Detectors



Collaboration	Site (m.w.e.)	Eff. Absorber Mass (kg)	Exposure (kg d)
CDMS	Stanford (17)	Ge (1.0) Si (0.2)	28.3
CRESST	Gran Sasso (3800)	Al ₂ O ₃ (0.262)	1.5
EDELWEISS	Frejus (4800)	Ge (1.0)	30.5
MIBETA	Gran Sasso (3800)	TeO ₂ (0.68)	60
ORPHEUS	Bern (70)	Sn (0.206)	0.68
ROSEBUD	Canfranc (2450)	CaWO ₄ (0.054) BGO (0.046) Ge (0.067) Al ₂ O ₃ (0.050)	0.034 0.034
Tokyo group	Kamioka Ob- servatory(2700)	LiF (0.168)	4.1

Conventional WIMP Detectors



Collaboration	Collaboration Site (m.w.e.)		Exposure (kg d)	
DAMA	Gran Sasso (3800)	NaI (100)	57986	
LSM Saclay	Frejus (4800)	NaI (10)	805	
UKDMC	Boulby Mine (2530)	NaI (6)	709	
ELEGANT	Kamioka (2700)	NaI (662)	241630	
Heidelberg-Moscow	Gran Sasso (3800)	Ge (2.7)	252	
IGEX	Canfranc (2450)	Ge (2.2)	60	
ZEPLIN I	Boulby Mine (2530)	Liquid Xe (3.1)	230	
SIMPLE	Rustrel (63)	Superheated Droplets (15 10 ⁻³)	0.19	
PICASSO	SNO (4755)	Superheated Droplets (21.7 10 ⁻³)	0.35	

Active background rejection

counts





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CRESST and ROSEBUD



• Measure light and heat simultaneously to discriminate nuclear recoils from background.

Pioneered by

L.Gonzales-Mestres and D. Perret-Gallix NIM A279 (1989) 382-387

- High rejection:99.7% E>15keV 99.9% E>20keV
- Eliminates problem of surface electrons (Ge,Si bolometers).
- CRESST uses CaWO₄ crystals.
- ROSEBUD uses CaWO₄ and BGO crystals.



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- A strong light emission is detected (~ BGO) !
- a very good γ/recoils separation is achieved

→very good news for ROSEBUD & CRESST !

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Alpha particles from the radioactive decay of natura Bismuth (²⁰⁹Bi)

Inst. Astr. Spatial CNRS Paris Sud



- Detection of ²⁰⁹Bi α –decay in emulsions failed so far
- First detection in 46 g BGO scintillating bolometer $T_{1/2}=(1.9\pm0.2)\ 10^{19}$ y Pierre de Marcillac et al. Nature/ Vol 422/ 24. April/ 2003
- High quenching factor allows to separate α particles.

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Double beta decay of 130 TE

- The use of LTD for the search of DBD was suggested by E. Fiorini and T.Niinikoski NIM 224 (1984) 83
- Excellent energy resolution of the bolometer
- Wide choice of DBD candidates
- ¹³⁰Te a good candidate due to

high transition energy 2528 keV

large isotopic abundance (33.8%)

- Experimental results competitive with Ge results (Heidelberg Moskow)
- Mi-DBD->CUORICINO->CUORE











A SINGLE HIGH GRANULARITY DETECTOR

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Neutrino Mass Measurements

- Genova group pioneered neutrino mass measurements using ¹⁸⁷Re β-decay Fontanelli et al.NIM A 370 (1996)247
- Early developments continued by the Milano and Lisbon groups
- Advantages of Re:

high natural abundance (62%)

low endpoint energy (2.64 keV)

- Calorimetric measurement of end point energy
- No negative values of m²_v due to final state interactions (tritium decay spectroscopy)
- However, limited counting rate capability due to slow bolometer signals.

Milano neutrino mass experiment



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Beta Environment Fine Structure in ¹⁸⁷R

F. Gatti (Univ. Genova), C.Maurizio (Univ. Padova), F.Gonella (Univ. Venezia), F. d'Acapito (INFM- Grenoble), S.Mobilio(Univ Roma Tre)

- Oscillations in the beta decay spectrum of ¹⁸⁷Re have been observed experimentally.
- Supposed to be linked to the local environment via an extended Xray absorption fine structure (EXAFS) process. [S.Koonin Nature 354 (1991), 468, F. Gatti et al Nature 397 (1999), 137]
- Important for the determination of the neutrino mass



Beta spectrum measured on a ¹⁸⁷Re single crystal at 60mK with a bolometer detector

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EXAFS Data analysis

Comparison between structural data extracted from BEFS and EXAFS spectra and the crystallographic data

	BEFS		EXAFS	cryst. data
R ₁ (Å)	2.77 ±0.10	2.75 ±0.10	2.74 ±0.02	2.7395
R ₂ (Å)			2.77 ±0.02	2.7610
σ² (10 ⁻³ Ų)	5.9	6.2	11 ±1	-
N ₁ +N ₂	12	12	12	6+6



Conventional EXAFS spectrum collected at GILDA at the Re K edge (71676 eV).

Single photon counting calorimeters

- STJ calorimeters are ideal devices to measure: energy and arrival time of single optical photons with high quantum efficiency
- Application in astrophysics: Detection of faint and red shifted objects Optical emission from ms pulsars Oscillations in white dwarfs and neutron stars
- Application in Quantum Optics, Quantum Teleportation and Quantum Computing(S.Nam forTES calorimeters ,NIST, QIL Boston, Torino Collaboration)
- Pioneering work of ESTEC with tantalum STJ:
 - T.Peacock et al. Astron.Astrophys. Suppl.Ser.123 (1998) 497
- First prove of principle in 1999 : STJ camera directed towards Crab Nebular using William Herschel Telescope at La Palma.
- Other absorber materials under investigation to improve optical photon detection: Al, Mo, Hf
- Increasing responsivity with increasing Al thickness (I.Jerjen for PSI)
- Very fast signal response (30 ps) A.Verevkin for the Moscow, Rochester collaboration



Objective: Improved Energy Resolution

• The tunnel limited energy resolution of an STJ is given by:

$$\Delta E = 2.355 \sqrt{1.75 \Delta_g E(F+G)}$$

- Where: $-\Delta_{g}$ is the energy gap of the absorbing material.
 - E is the photon energy.
 - F = 0.22 is the Fano factor.
 - G = 1 for multiple tunnelling junctions is the tunnel limit.

Material	$\Delta_{\rm g}$	T _C	ΔE at	ΔE at	ΔE at
	(µeV)	(K)	100 eV	500 eV	3 keV
			(eV)	(eV)	(eV)
Nb	1550	9.4	1.35	3.03	7.42
Та	700	5.4	0.91	2.03	4.98
Al	180	1.2	0.46	1.03	2.52
Мо	140	0.915	0.41	0.91	2.23
Hf	19.4	0.128	0.15	0.34	0.83





Guy Brammertz LTD-10 26/06/2003





Responsivity as a function of the AI trap thickness

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Quasars





- Quasars are generally pointlike
- Cosmological beacons
- Need to know how far away they are (measure their redshift)

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Micro-calorimeters for x-ray astronomy



- Provide considerable improvements over conventional systems (Bragg spectrometers and solid state detectors)
- Cover entire x-ray spectrum of interest at once and with high resolution
- However intrinsically slow with limited counting rate
- Deployment in space imposes new technical challenges
- Wide field of physics investigations:

diffuse interstellar x-ray background supernova remnants, elements for new star formations neutron stars galactic black holes gamma ray bursts , neutron star merger versus hypernovae x-ray solar corona (solar spectroscopic imager ATSSI) ASTRO-E2 (2005), XEUS, NEXT (2010), Constellation-X (2013)

- Large arrays of micro-calorimeters required
- Pioneering experiments by Wisconsin, Maryland, NASA Goddard group S.H.Moseley, J.C.Mather, D.McCammon, J.Appl. Phys. 56, 1257 (1984)





XRS onboard Astro-E2

- First microcalorimeter array in orbit $\Delta E=6 \text{ eV}$ at 6 keV, 6x6 format
- cryogen (SNe/LHe) lifetime: 2.5-3.5 years

Astro-E2 flight sensor ADR, He tank, signal processor developed by NASA/GSEC









NeXT (New X-ray Telescope Mission)

• Next X-ray astronomy project in Japan









35 K 80-90 K

10 K (on-orbi)



ESA mission is under study for the end of the decade within the Space Station Utilization Programme



XEUS will be around 250 times more sensitive than XMM-NEWTON.

6 m² of collecting area at 1 keV, 30 m² after refurbishment from ISS

Spectral resolution of between 1 and 10 eV over therenergy range 0.05 to a 3 for keV with TES and StJ







Interstellar & Intergalactic Medium

GRB Observatory & Spectroscopy Survey High Resolution Cryogenic Spectrometer for X-ray Sky Survey on the International Space Station

•X-ray bolometer (R=300-1000) in the 0.1-10 keV to be flown on ISS

•It will an all-sky survey with an unprecedented spectroscopic resolution with a beam of 10°

•See poster by ColasantistzL.P. et al



Cryogenic Detectors for Infrared Astronomy: the Single Aperture Far-InfraRed (SAFIR) Observatory (2015-2020) Dominic Benford Harvey Moseley

EXPERIMENTAL COSMIC MICROWAVE BACKGROUND RESEARCH

Silvia Masi and Paolo de Bernardis Dipartimento di Fisica Universita' La Sapienza Roma – Italy

Genova – LTD-10 Prez 10/July/2003

Cryogenic Bolometers

- Ge thermistor bolometers have been used in many CMB experiments:
 - COBE-FIRAS, ARGO, MAX, BOOMERanG, MAXIMA, ARCHEOPS
- Ge thermistor bolometers are extremely sensitive, but slow: the typical time constant C/G is of the order of 10 ms @ 300mK
- Transition Edge Superconductor (TES) thermistors can do much better using electro-thermal feedback (100 μs) – Recent development (hear Adrian Lee, next talk)







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Measurements of CMB Polarization Anisotropy and Searches for Galaxy Clusters with Bolometer Arrays

Adrian Lee

Department of Physics, LBNL Physics Division University of California, Berkeley

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TES Bolometer Array



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Microcalorimeter arrays and position sensitive detectors

- Microcalorimeter arrays (C.Stahle) :
- 36 pixel array for ASTRO-E2 well studied
- 1000 arrays needed for next missions XEUS, CONSTELLATION-X NEXT, PLANCK(CMB)
- Technological challenge, but can be done
- Need to involve industry
- Position sensitive detectors:
 - E.Figueroa-Feliciano, B.Cabrera, C.Hammock
- First position sensitive detector: ZIP from CDMS
- Other clever ideas have been demonstrated at this conference
- Need 5 micron pixels to resolve the magnetic reconnection process on the sun surface leading to 30 MK



If you cannot the position fixel You need to use many pixel



TES noise

- Need of a better understanding of the fundamental noise sources in a superconductor.
 - Several effects can lead to excess noise: Fluctuations in number of Cooper pairs Fluctuations in magnetic flux penetration
- Conductivity of normal electrons is affected by these fluctuations
- Excess noise can be reduced by:

magnetic field-->forces first order phase transitions "ZEBRA" geometry (bars vertical to current)

Noise performance of TES devices with different normal metal geometries J.G.Staguhn

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X-ray microcalorimeters for material science



- Industrial applications in x-ray micro analysis
- Application in synchrotron radiation facilities (F.d Acapito)
- Considerable improvement over semiconductor devices
- Excellent energy resolution allows to measure:
 - contaminant particles and defects for semiconductor industry chemical shifts in x-ray spectra due to changes in electron binding
- Small detector surface to be compensated by focusing device using poly-capillary optics
- Pioneering work by NIST using TES D.A.Wollman et al J.Microscopy 188 (1997) 196
- Slow devices limited in counting rate capability
- Development of multipixel devices

Thin layer systems SrBi₂Ta₂O₉ (SBT) / Pt / TiO₂ / SiO₂ / Si -Substrat



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Microcalorimeter with TES sensor exposed to GILDA beam

Genova, Grenoble GILDA, Frascati group F.dAcapito et al.



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LTD in Atomic and Molecular Physics

Accelerator mass spectroscopy:

S.Kraft for the GSI, Mainz, Vienna Collaboration

- VERA=Vienna environmental Research Accelerator
- Cryogenic calorimeters measure kinetic energy
- **Obtained energy resolution of** $\Delta E / E = 4.6 \cdot 10^{-3}$
- First results:

measurement of the natural isotop ratio

²³⁶U/²³⁸U=1.2 10⁻¹¹

Measurement of Lamb shift at GSI Ion beam:

E.Silver vor Smithonian Astroph.Observatory, Berkeley, GSI Collab.

Use NTD micro-calorimeters to measure the 2s Lamb shift in Au and U
Sensitive test of QED

Biological applications



S.Friedrick, D. Twerenbold, S. Rutzinger, J.Maillard

- TOF Mass spectrometers for DNA sequencing, protein identific. Neuchatel group D.Twerenbold, ,NIM A 370 (1996) 253
- Advantages:

mass independent detection sensitivity sensitive to very large molecules signal proportional to molecule energy -->clean mass spectrum

• Disadvantages:

slow signals 100ns

limited sensitivity due to small size detectors (Nb/T STJ)

• Users want:

fast detector response 1ns

large detector areas

high operating temperatures 5 K Klaus Pretzl

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Magnetic calorimeters



A. Fleischmann for the Brown, Heidelberg Collaboration

• Pioneering work of

E.Umlauf and M.Bühler, Euro.Phys.Lett. 5, 297 (1988)

- **Problems with long relaxation times**
- Break through due to metallic paramagnet
- Can be used as thermometer and as absorber
- Temperature sensitivity follows Curie Law over a wide temperature range: 10mK<T<1K
- Short relaxation times:
 - rise time : <10⁻⁶s
 - Decay time: 10⁻³s
- Energy resolution: 3.4eV at 5.9 keV
- Application in X-ray spectroscopy
- For detectors requiring large heat capacities



Low Temperature Tracking Devices

- RD 39 collaboration at CERN (T. Niinikoski): Optimization of silicon trackers and readout electronics for luminosity upgrade of LHC (L=10³⁵cm⁻²s⁻¹)
- Expected fluence 10¹⁶ particles/cm²
- Detectors being operated at around 130 K
- Effects of radiation damage strongly reduced due to LAZARUS effect : V.Palmieri et al. NIM A 413 (1998) 475
- At low temperatures:
 - increased carrier mobility higher signal speed lower noise of CMOS front end electronics

Annular STJ with injected current as a new configuration of radiation detector. M.P.Lissitski,^{a,b*} M. Ejrnaes,^b C. Nappi,^{a,b} R. Cristiano,^{a,b} M. Huber,^c K. Rottler,^c J. Jochum,^c F.v. Feilitzsch^c

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 $Al_{bottom}(370nm)/Al_2O_3/Al_{top}(200nm)$





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Pulse height spectrum of the annular Al-STJ irradiated by the ⁵⁵Fe Xray source obtained in absence of external magnetic field. The Josephson critical current and Fiske resonances have been suppressed by trapping a number (~12) of magnetic flux quanta through the barrier. The obtained energy resolution of about 100 eV for K_{α} line of the top electrKdausaRtsezattributed to the junction quality. 54

Conclusion



- The 10 th anniversary of LTD was highly successful due to:
- The interesting physics results reported
- The progress in detector developments
- The future plans in the field
- The charming participants (250)
- The fantastic organization of the conference

Many many thanks to Flavio and the Genova group !!!!!!



"NO, THIS ISN'T LOW TEMPERATURE PHYSICS. HE'S JUST TOO CHEAP TO TURN ON THE HEAT."

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