Scintillator fundamantals and applications

2021. 1.

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SPDAK 2021

Contents

Particle energy loss in matter

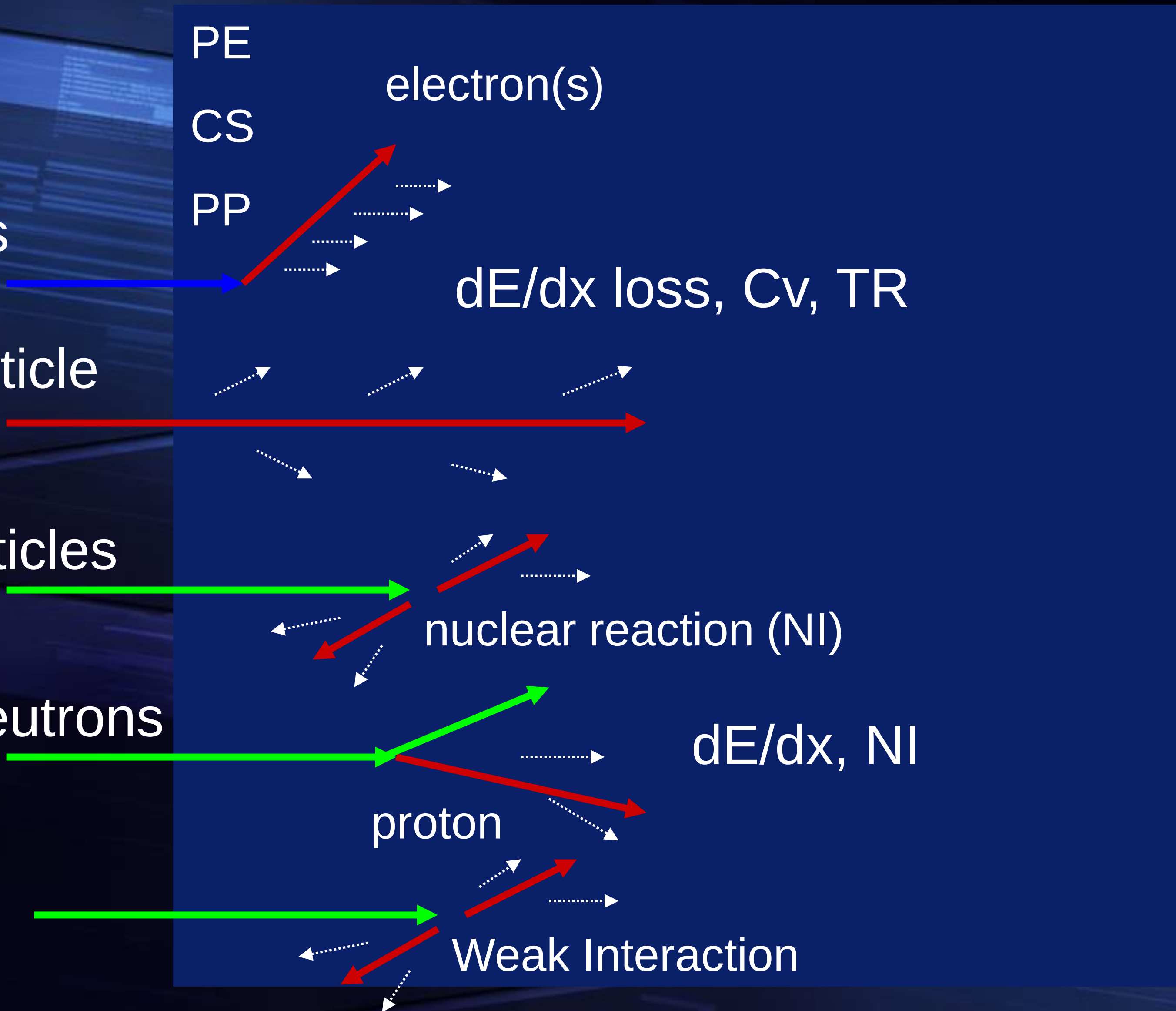
X rays
gamma rays

charged particle

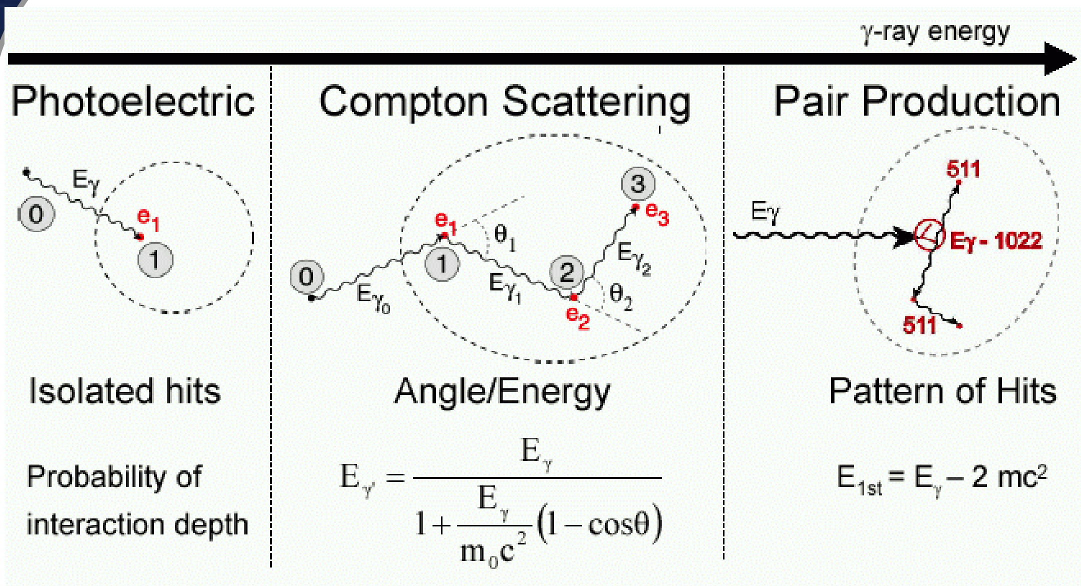
Nuclear particles

energetic neutrons

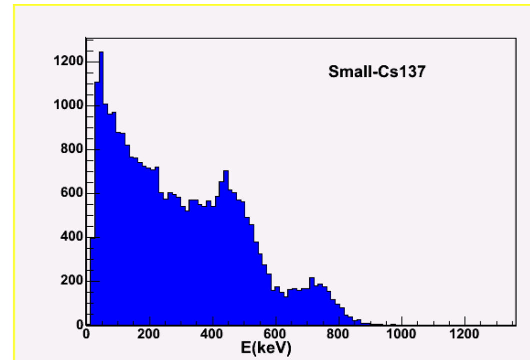
neutrino



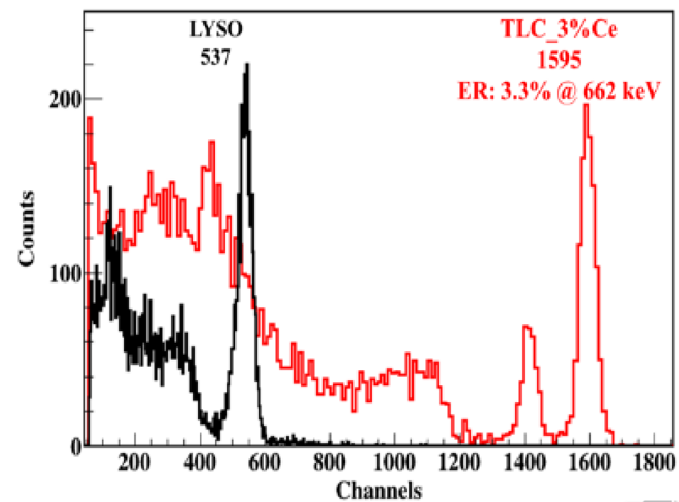
Detection Efficiency of X-ray and γ



CaMoO4



LYSO & Tl2LaCl5:Ce



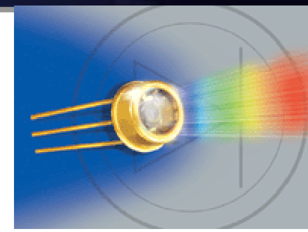
Photoelectric effect : $\rho Z_{eff}^{3\text{-}4}$

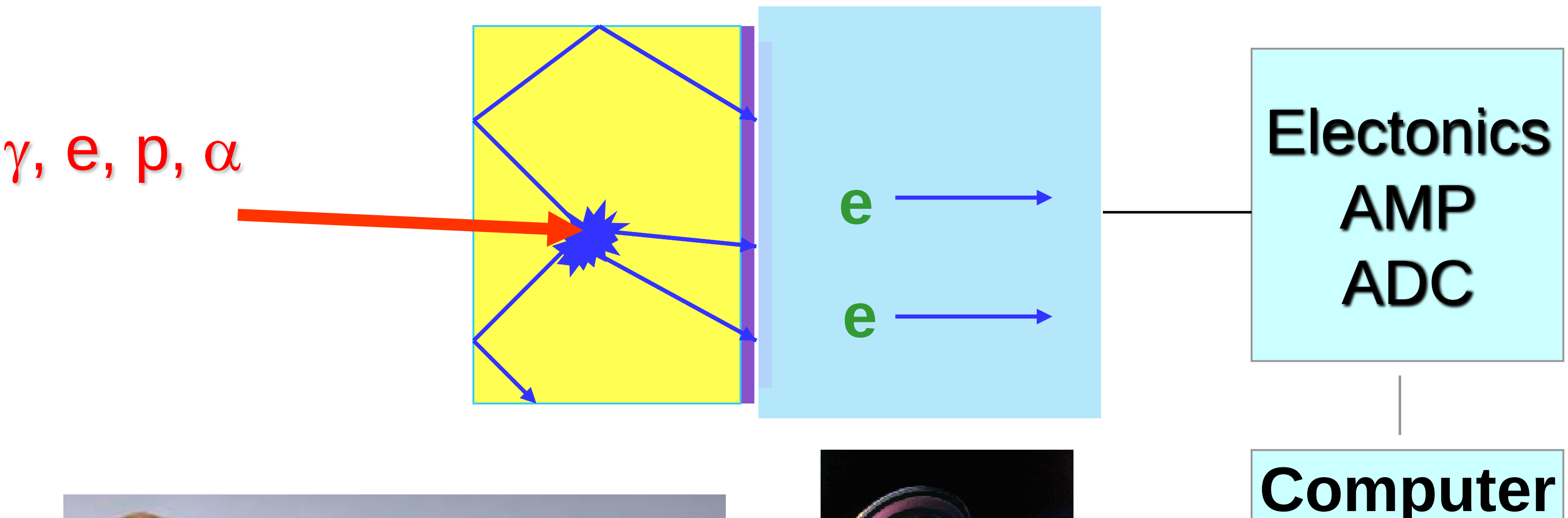
Compton scattering : ρ

Pair production : ρZ

High ρ & Z_{eff}!

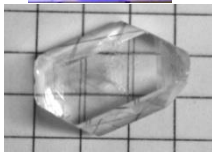
Principle of Radiation detection with Scintillator



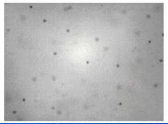


Luminescence materials

- Inorganic crystal

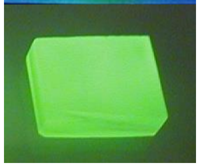


- Organic crystal

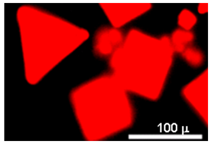


- Inorganic/organic semiconductors

- Organic polymers, organic Liquid



- Glass, Ceramics



- Nanoparticle, powders, QD

By LLAL group

Scintillator

- Inorganic scintillators

  a) Result of crystalline structure

  b) Large band gap, insulators

  c) High light output

  d) Rather expensive, moderate size (~kg - Ton)

- Organic scintillators

  a) Molecular property of hidrocarbons

  b) Moderate light output but fast (~ns)

  c) Cheap, large size (~Ton- kTon)

  d) Liquid scintillator (LSC)

  Plastic scintillator (PSC)

  Crystal (ex:anthracene, stilbene)

- Nobel liquid (gas) scintillator

Scintillator Requirement for Applications

General requirements for scintillator applications

- ❑ High γ detection efficiency : high Z, high density
- ❑ Good energy resolution : high light output (LY)
- ❑ High count rate : fast decay time
- ❑ Cost : low cost material, low melting temp.
- ❑ Handling : non-hygroscopic
- ❑ Background : internal background

None of scintillator has best performance of every aspect
=> Scintillator should be optimized for each application

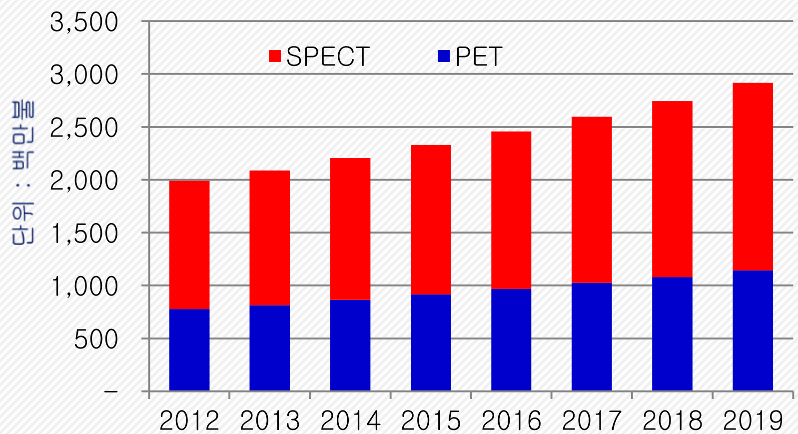
PbWO4 : very low LY but high density and fast τ –>CMS, CALET
CaMoO4, Li2MoO4 : low LY at RT, slow τ, no internal bg. -> AMoRE, CUPID
LYSO:Ce : High LY, fast τ, high Z, internal background, expensive
CsI:Tl, NaI:Tl : high LY, moderate τ, low background, cheap -> Belle, Fermi, KIMS, COSINE

Scintillator Application

- High energy physics
  BELLE, BES, CDF, L3, Phenix, CMS, LC, Focus … Many more!
- Astro-particle physics
  Neutrino (LSND, Super-K, Kamland..), Underground(Darkmatter, neutrino, double beta), Ground array (HE neutrino, UHE cosmic ray, HE gamma)
- Nuclear Physics, Nuclear engineering.
  Neutron, Radioactive decay, heavy ion, radioactive beam. ; Power reactor monitoring
- Astrophysics, Astronomy
  Balloon (ATIC, CREAM..), Satellite (Fermi, INTEGRAL..), Space station (AMS, CALET, ISS-CREAM..)
- Bio-science: Track radioisotopes in biology sample, Quantifying DNA and RNA
- Medical science: X-ray, PET, CT, SPECT, Track radioisotopes
- Environmental science: Monitoring of radioactivity, nuclear waste,
- More :Safety inspection, Military …..-> Homeland security

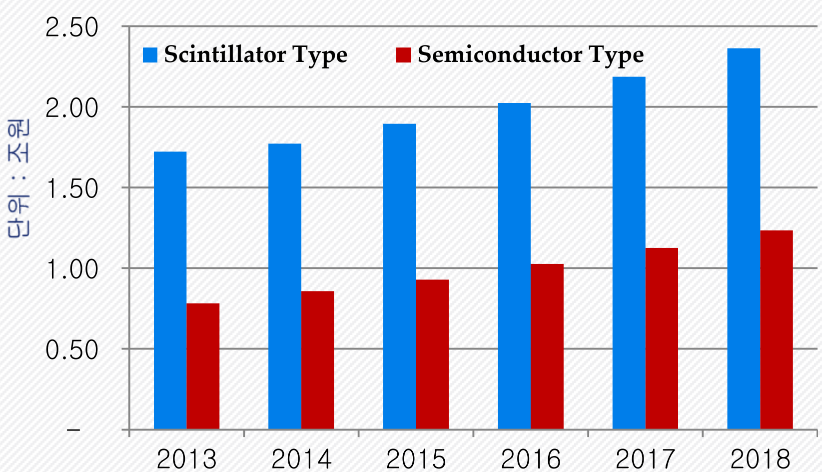
Scintillator supply

Medical Imaging market

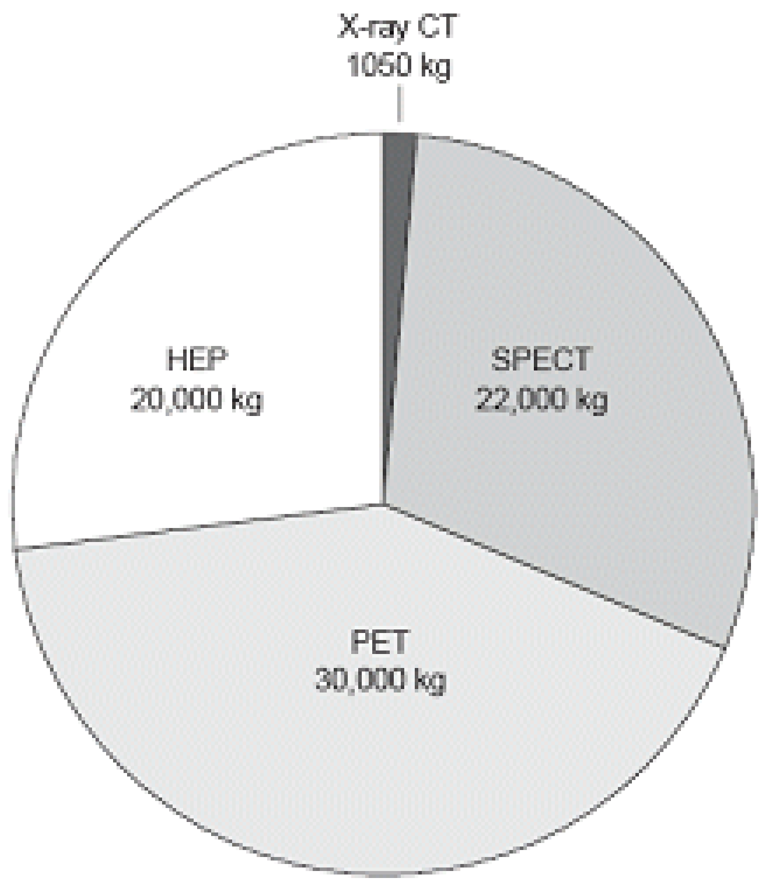


출처 : 의료기기품목시장리포트 Vol 14. 핵의학영상진단장치 (2013.6.30)

Radiation detector market



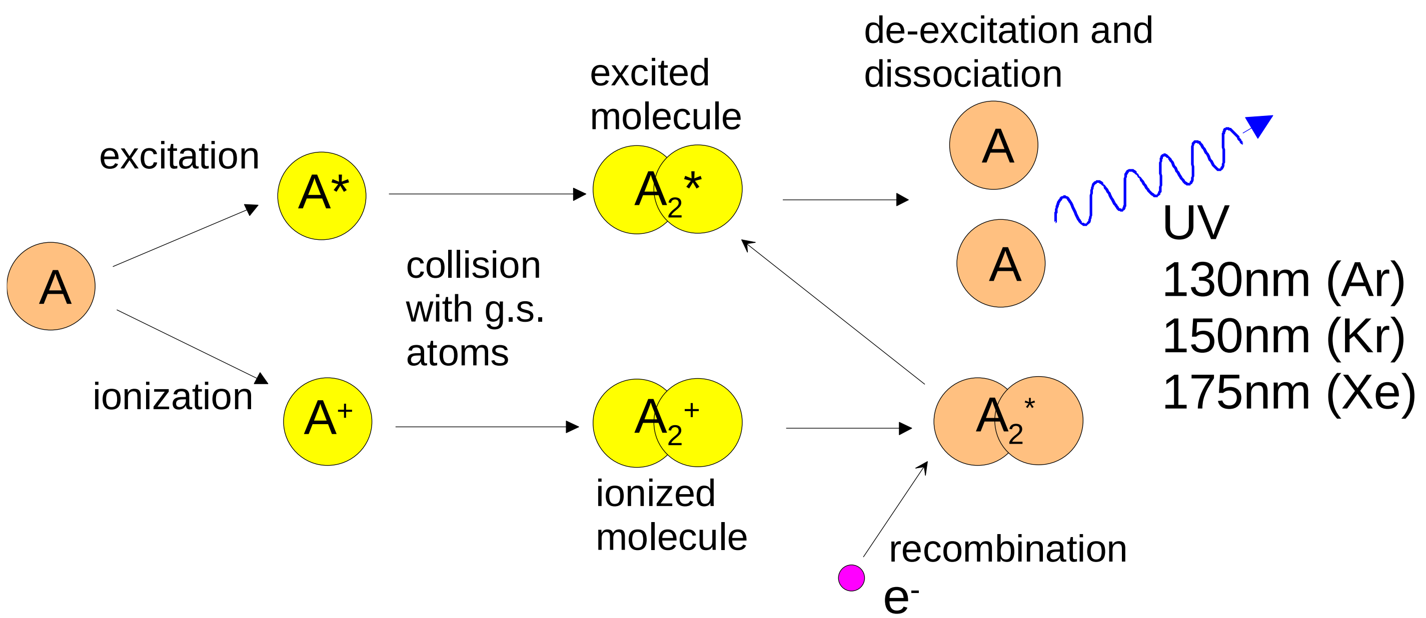
출처 : Radiation Detection Markets 2011 NanoMarkets



Crystal Scintillator market
Total 900 Millon $ (2003)

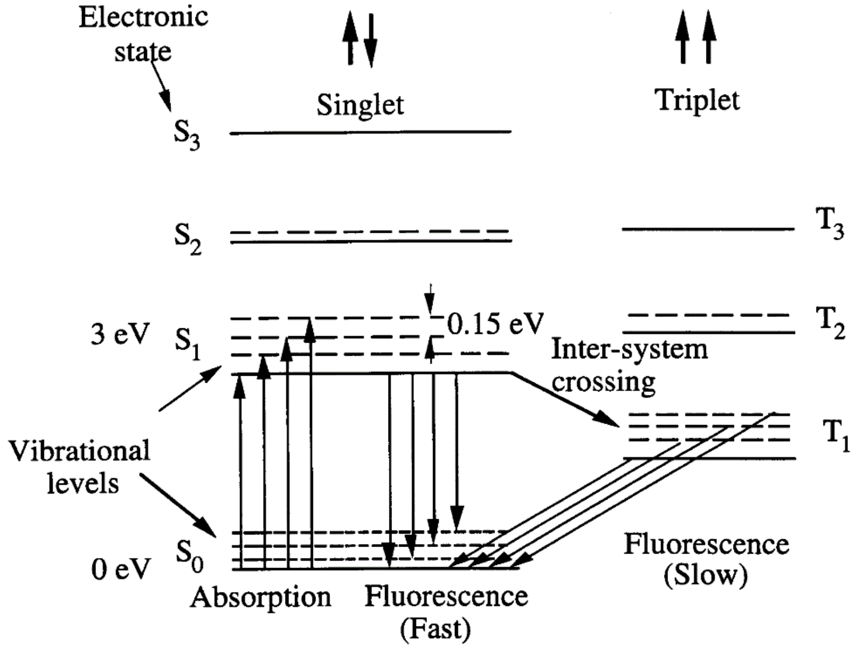
출처 : 서울대병원 핵의학과 이재성 교수

Liquefied noble gases

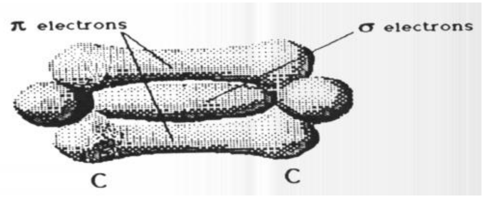


Organic scintillator Fundamentals

Organic scintillator working principle

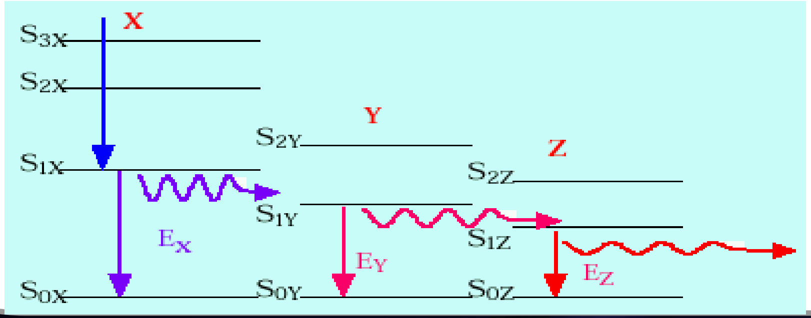


Scintillation is based on the 2 π electrons of the C-C bonds.



Monocrystals: naphtalene, anthracene, p-terphenyl….

Liquid and plastic scintillators



Organic scintillator Solvents

-

  1,2,4-Trimethylbenzene (Pseudocumene)
  p-,m-,o-Xylene, Toluene, Benzene, MN…

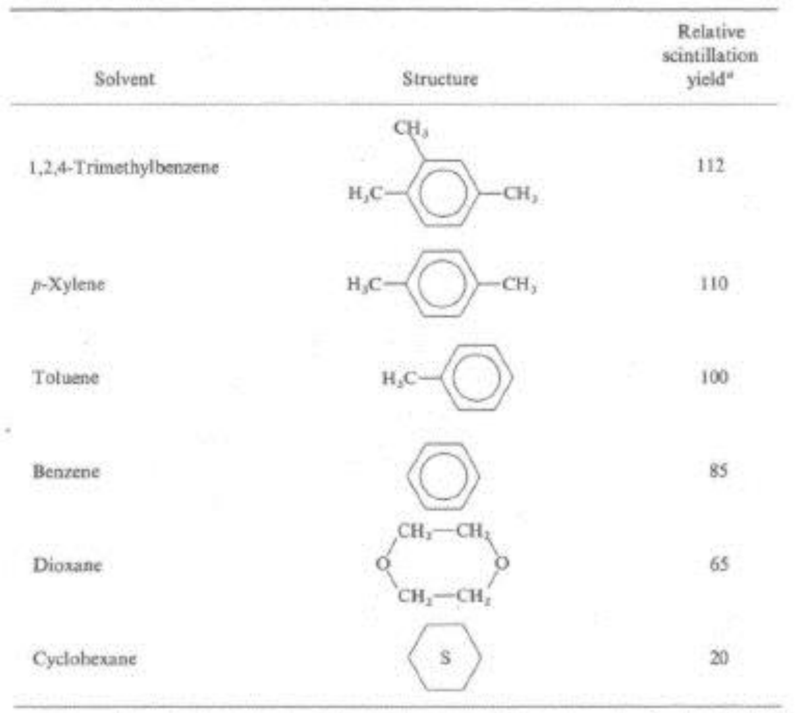
  Polystyrene (Polyvinylbenzene, PS)
  Polyvinyltolunen (PVT)

-

  PPO, p-Terphenyl, PBD, Butyl-PBD, Nap

-

  POPOP, M_2-POPOP, bis-MSB….



Solvent	Structure	Relative scintillation yield[a]
1,2,4-Trimethylbenzene		112
p-Xylene		110
Toluene		100
Benzene		85
Dioxane		65
Cyclohexane		20

- Standard Scintillator : PC + PPO(1.5-4g/l) +POPOP(10-50mg) : 65% of anthrecene, safe, Pulse shape discrimination of n/gamma

SAINT-GOBAIN & ELJEN tech

Physical Constants of SGCD Plastic Scintillators

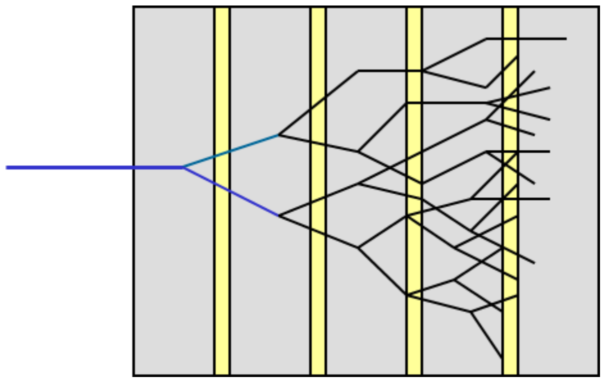
Scintillator	Light Output % Anthracene[1]	Wavelength of Maximum Emission, nm	Decay Constant, Main Component, ns	Bulk Light Attenuation Length, cm	Refractive Index	H/C Ratio	Loading Element % by weight	Density	Softening Point °C
BC-400	65	423	2.4	250	1.58	1.103		1.032	70
BC-404	68	408	1.8	160	1.58	1.107		1.032	70
BC-408	64	425	2.1	380	1.58	1.104		1.032	70
BC-412	60	434	3.3	400	1.58	1.104		1.032	70
BC-414	68	392	1.8	100	1.58	1.110		1.032	70
BC-416	38	434	4.0	400	1.58	1.110		1.032	70
BC-418	67	391	1.4	100	1.58	1.100		1.032	70
BC-420	64	391	1.5	110	1.58	1.100		1.032	70
BC-422	55	370	1.6	8	1.58	1.102		1.032	70
BC-422Q	11	370	0.7	<8	1.58	1.102	Benzephenone,1%*	1.032	70
BC-428	36	480	12.5	150	1.58	1.103		1.032	70
BC-430	45	580	16.8	NA	1.58	1.108		1.032	70
BC-436	52	425	2.2	NA	1.61	0.960 D:C	Deuterium,13.8%	1.130	100

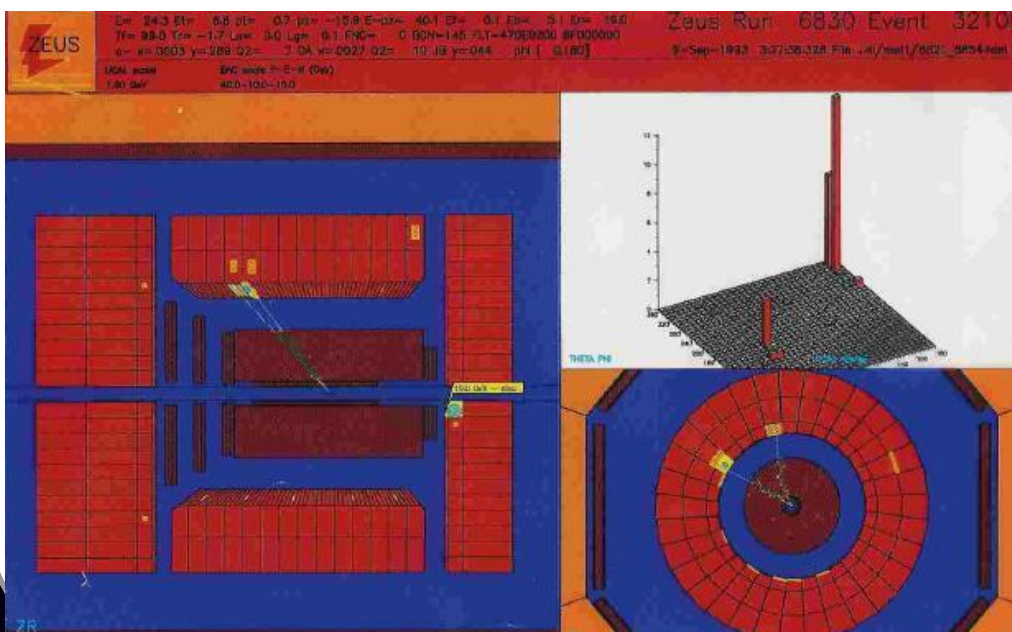
Physical Constants of SGCD Liquid Scintillators

Scintillator	Light Output % Anthracene*	Wavelength of Maximum Emission, nm	Decay Constant, ns	HC Ratio	Loading Element	Density	Flash Point °C
BC-501A	78	425	3.2[1]	1.212		.874	26
BC-505	80	425	2.5	1.331		.877	48
BC-509	20	425	3.1	.0035	F	1.61	10
BC-517L	39	425	2	2.01		.86	102
BC-517H	52	425	2	1.89		.86	81
BC-517P	28	425	2.2	2.05		.85	115
BC-517S	66	425	2	1.70		.87	53
BC-519	60	425	4	1.73		.87	63
BC-521	60	425	4	1.31	Gd (to 1%)	.89	44
BC-523	65	425	3.7	1.74	Nat. ^{10}B (5%)	.93	-8
BC-523A	65	425	3.7	1.67	Enr. ^{10}B (5%)	.93	-8
BC-525	55	425	3.8	1.56	Gd (to 1%)	.88	81
BC-531	59	425	3.5	1.63		.87	93
BC-533	51	425	3	1.96		.80	65
BC-537	61	425	2.8	0.99 (D:C)	^{2}H	.954	-11
BC-551	40	425	2.2	1.31	Pb (5% w/w)	.902	44
BC-553	34	425	3.8	1.47	Sn (10% w/w)	.951	42

* Anthracene light output = 40-50% of NaI(Tl)

ZEUS detector with Plastic +U sandwich calorimeter at HERA(ep)



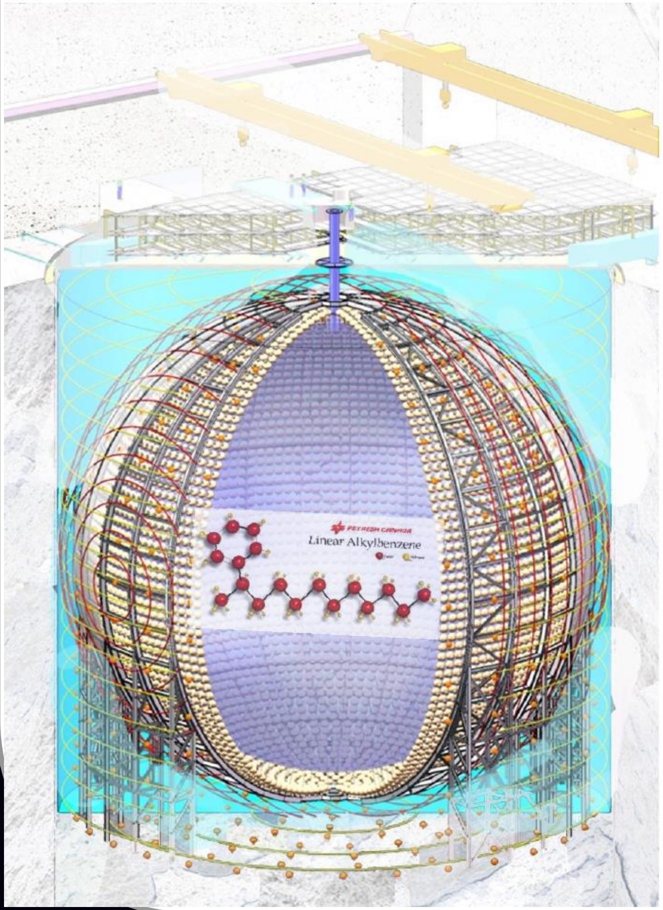


Large LSC for neutrino physics

Jiangmen Underground Neutrino Observatory

Central detector (CD)

*KAMLAND
kTon LSC
*RENO
LSC



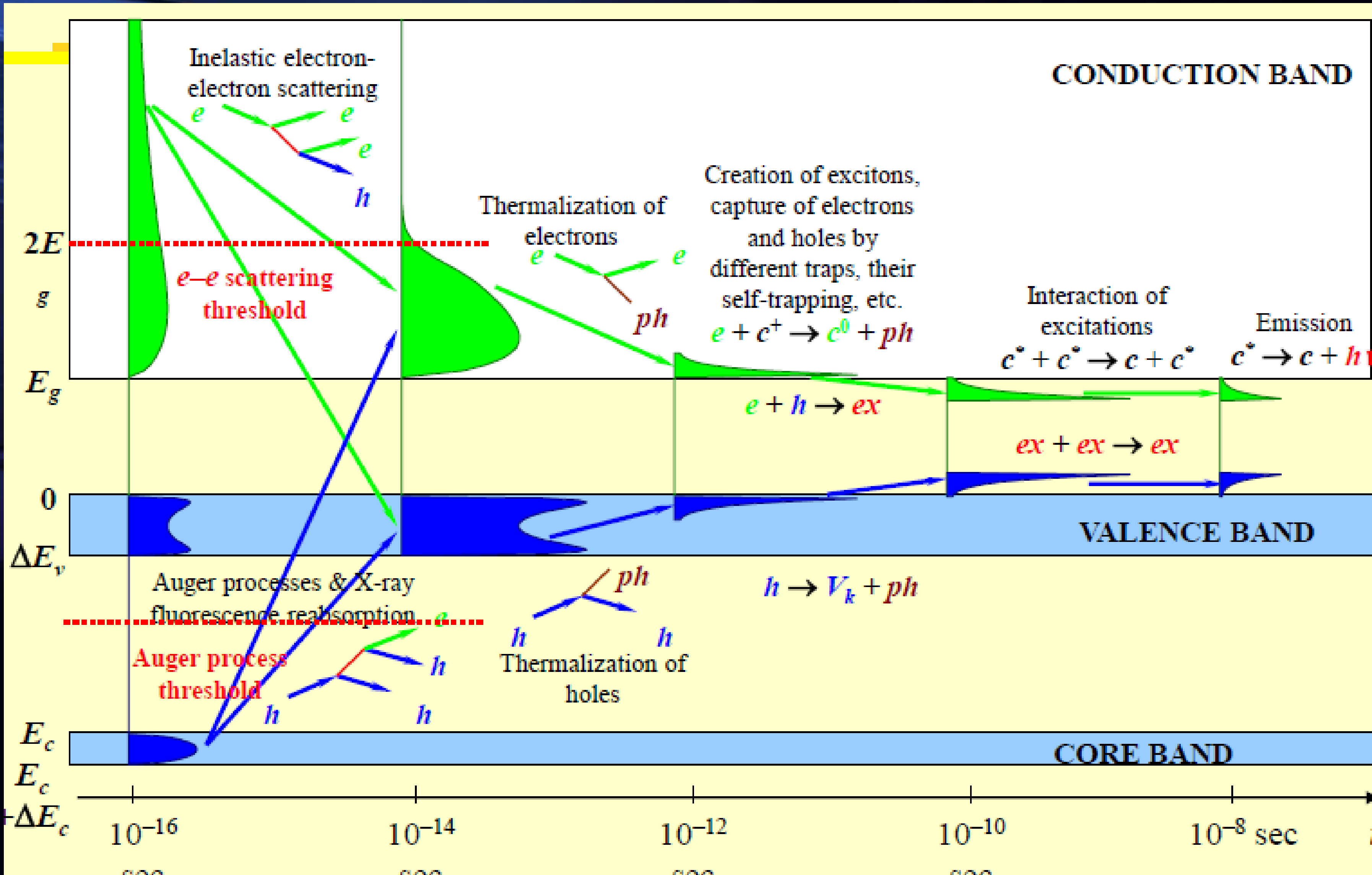
- **LS in acrylic vessel (35.4 m diam.)**
  - Requirements for JUNO LS
    - Lower background for physics: $^{238}U<10^{-15}g/g$, $^{232}Th<10^{-15}g/g$, $^{40}K<10^{-17}g/g$
    - High light yield: ~10 k ph./MeV
      concentration of flour need to be optimized
    - Long attenuation length: >20m@430nm
  - Preliminary LS recipe (based on DYB experiment)
    20 kt **LS** : 3g/l **PPO** +15 mg/l **bis-MSB** in **LAB**
    - PPO: 2,5-Diphenyloxazole
    - Bis-MSB: 1,4-di-(2-methylstyryl)benzene, p-bis(o-methylstyryl)benzene
    - LAB: linear alkyl benzene

Central detector (CD)

- Optical separation: *Acrylic sphere*
- Stainless Steel Latticed Shell
- 20 kton *Liquid Scintillator*
- *PMTs*: 17k 20'' PMTs + 25k 3'' PMTs
- Ultra-pure water buffer (2 m)

Inorganic scintillator Fundamentals

General scheme of relaxation



by A. Vasilev

Scintillator Development Direction

Invited Article

The quest for high resolution γ-ray scintillators

Pieter Dorenbos

Optical Materials: X 1 (2019) 100021

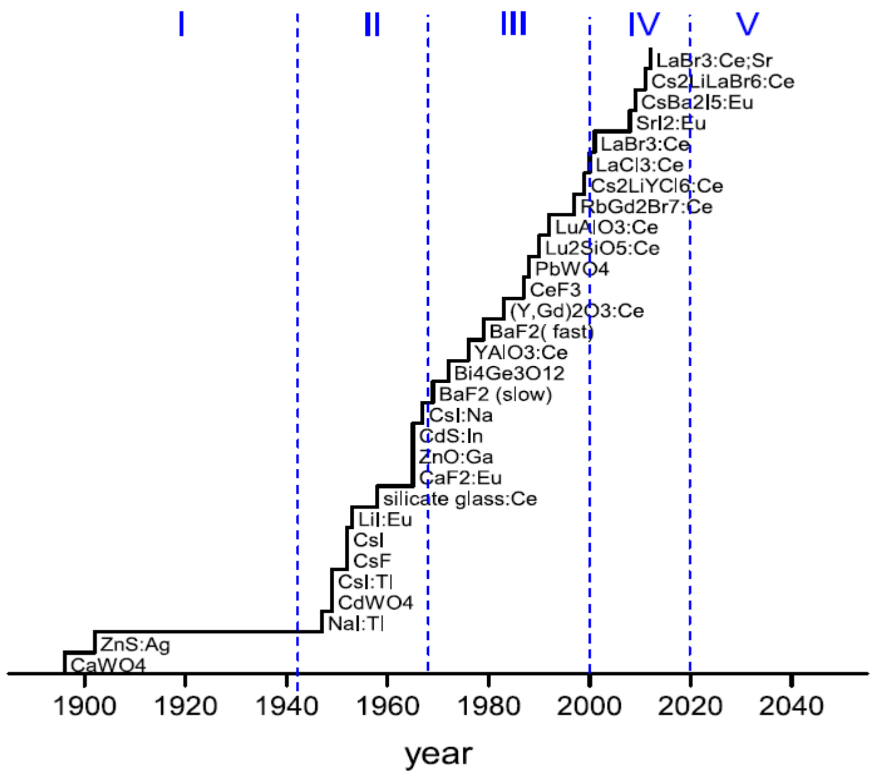


Fig. 2. History of scintillator discovery that distinguishes phases I to IV and phase V for future discoveries.

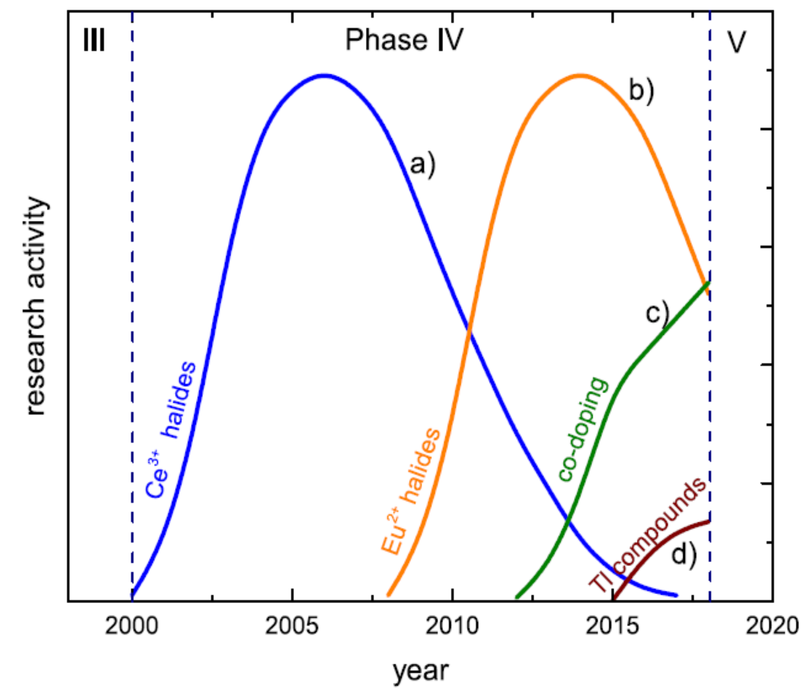


Fig. 4. Main lines of research during phase IV of scintillator discovery. a) The research on Ce^{3+} activated halide compounds inspired by the discovery of $LaBr_3$:Ce^{3+}, b) the research on Eu^{2+} doped halide compounds initiated by the re-discovery of SrI_2;Eu^{2+}, c) the increased research on co-doped scintillators stimulated by discovery of Sr^{2+} co-doped $LaBr_3$:Ce^{3+}, d) the research on Ce^{3+} activated Tl-based compounds initiated by $Tl_2LiGdCl_6$.

SAINT-GOBAIN crystal scintillator

SAINT-GOBAIN

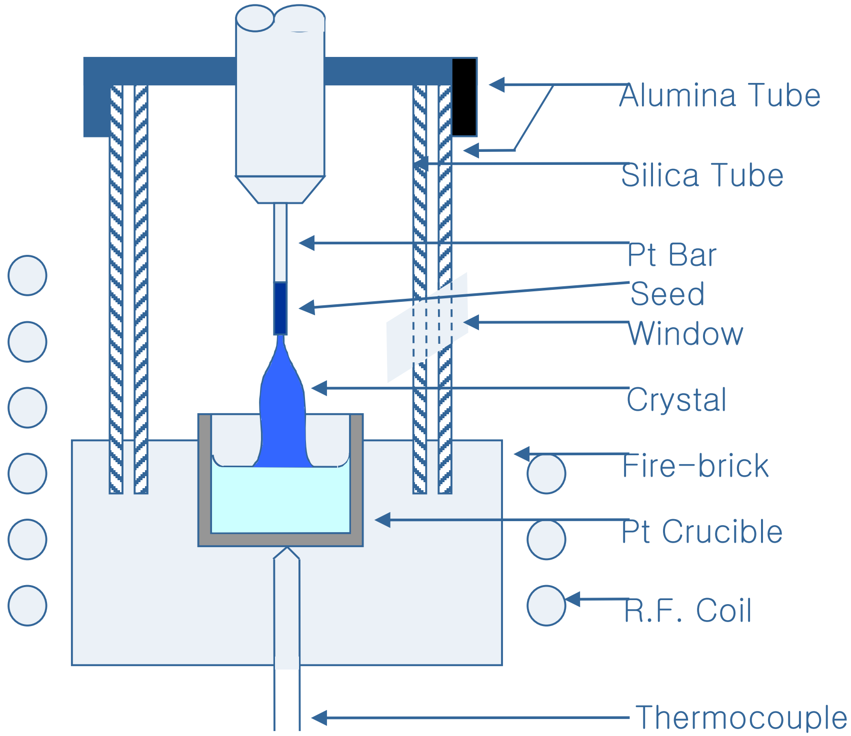
Saint-Gobain Crystals
Physical Properties of Common Inorganic Scintillators

Scintillator	Light yield (photons/keV)	Light ouput(%) of NaI(Tl) bialkali pmt	Temperature coefficient of light output(%/C) 25°C to 50°C	1/e Decay time(ns)	Wavelength of max emission lm(nm)	Refractive index at lm	Thickness to stop 50% of 662 keV photons (cm)	Thermal expansion $(/C) \times 10^{-6}$	Density g/cm^3	Hygroscopic	Comments
$LaBr_3$(Ce+Sr)	73	190	0	25	385	~2.0	1.8	8	5.08	yes	Ultimate energy resolution (2.2% @ 662keV)
$LaBr_3$(Ce) BrilLanCe™ 380	63	165	0	16	380	~1.9	1.8	8	5.08	yes	General purpose, excellent energy resolution
CLLB $Cs_2LiLaBr_6$(Ce)	43	115		180 1080	420	~1.85	2.2	--	4.2	yes	Dual Gamma-Neutron detection, excellent
NaI(Tl)	38	100	-0.3	250	415	1.85	2.5	47.4	3.67	yes	General purpose, good energy resolution
NaI(Tl+Li)	35	100	-0.3	230, 1.1µs 240, 1.4µs	419	1.85	2.5	47.4	3.67	yes	Neutron-Gamma Scintillator
$LaCl_3$(Ce) BrilLanCe™ 350	49	70-90	0.7*	28	350	~1.9	2.3	11	3.85	yes	General purpose, good energy resolution
CsI(Na)	41	85	-0.05	630	420	1.84	2	54	4.51	yes	High Z, rugged
LYSO $Lu_{1.8}Y_{.2}SiO_5$(Ce)	33	87	-0.28	36	420	1.81	1.1	--	7.1	no	Bright, high Z, fast, dense, background from ^{176}Lu activity
CdWO4	12-15	30-50	-0.1	14000	475	~2.3	1	10.2	7.9	no	Low afterglow, for use with photodioides
CaF2(Eu)	19	50	-0.33	940	435	1.47	2.9	19.5	3.18	no	Low Z, α & β detection
CsI(Tl)	54	45	0.01	1000	550	1.79	2	54	4.51	slightly	High Z, rugged, good match to photodiodes
BGO	8 - 10	20	-1.2	300	480	2.15	1	7	7.13	no	High Z, compact detector, low afterglow
YAG(Ce)	8	15	--	70	550	1.82	2	~8	4.55	no	β-ray, X-ray counting, electron microscopy
CsI(Pure)	2	4-6	-0.3	16	315	1.95	2	54	4.51	slightly	High Z, fast emission
BaF2	1.8	3	0	0.6-0.8	220(195)	1.54	1.9	18.4	4.88	slightly	Fast component (subnanosecond)
	10	16	-1.1	630	310	1.50	1.9	18.4	4.88	slightly	Slow component
ZnS(Ag)	~50	130	-0.6	110	450	2.36	--	--	4.09	no	Coated on BC-400 or acrylic for α detection

The data presented are believed to be correct but are not guaranteed to be so.
Please see individual data sheets for full details at https://www.crystals.saint-gobain.com/products/crystal-scintillation-materials

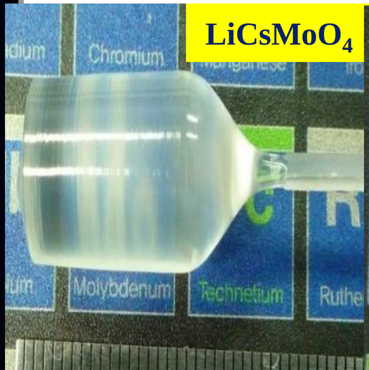
Revised October 2018

Crystal growing system with Czochalski method



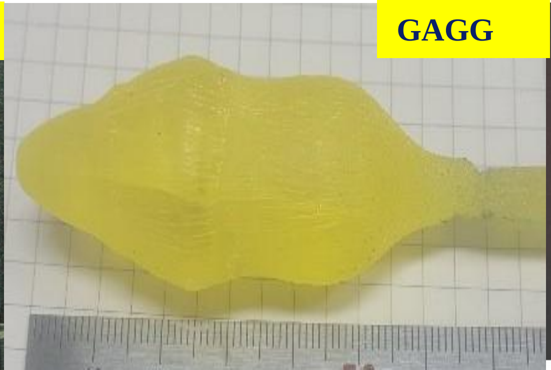
At KNU

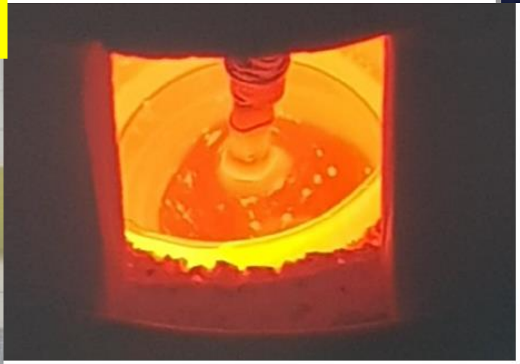
LiCsMoO$_4$



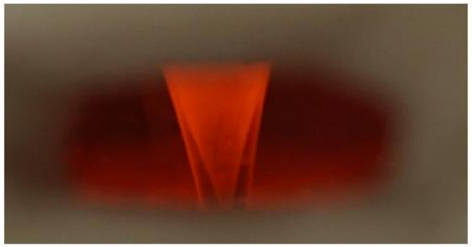
Cs$_2$MoO$_4$

GAGG

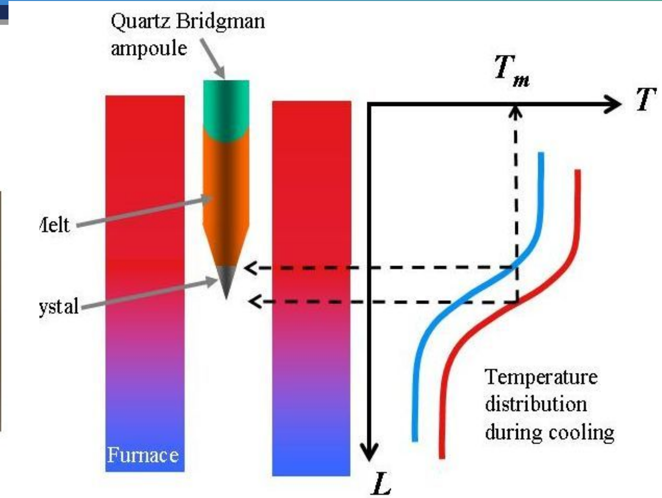




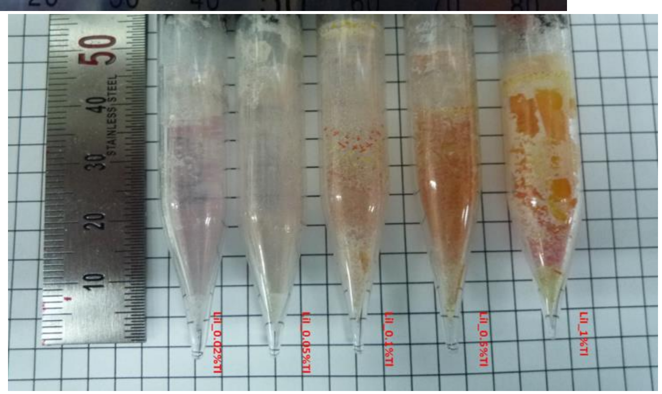
Bridgman Crystal Growing Methods



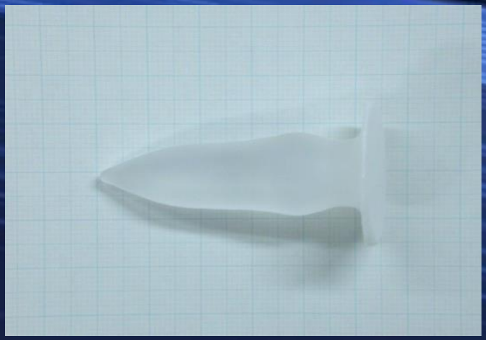
Crystal is growing in Bridgman furnace



At KNU



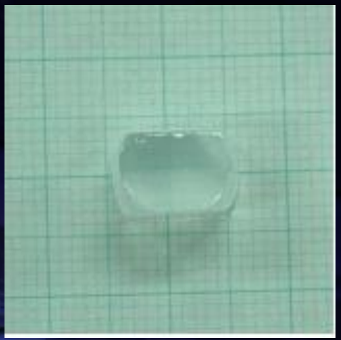
Crystals growing research at KNU over 20 years



$SrCl_2(Eu)$

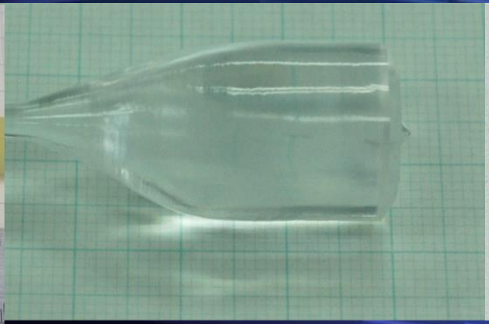
$CeCl_3$

$LaCl_3(Ce)$

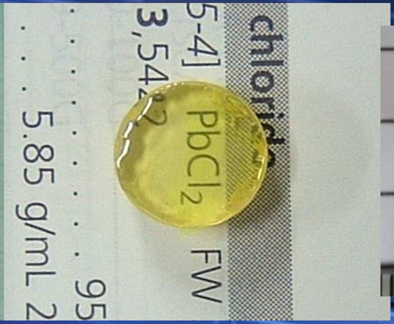


$CeBr_3$

GAGG:Ce



$Ba_{0.2}Sr_{0.8}Cl_2$



$PbCl_2:Eu^{2+}$

BGSO

- NaI:Tl, CsI(Tl, Co3, Na), BGO, BSO, BGSO, SrWO4, CaMoO4, SrMoO4 et al.
- New material : BaSrCl2, CsCe2Cl7, Cs(Rb)2Li(Na)CeCl6, Cs2LiGd(Lu)Cl(Br)6:Ce, Li6Lu(Gd,Y)(Bo3)3, NaGd(Wo4)3, LiBaF3, ZnMnTe, Tl-based scintillators et al.

Discovered Tl-based novel scintillators

- The pioneer research work on the discovery and development of Tl-based scintillators was started in 2009 by our research group and published $Tl_2LiGdCl_6$:Ce as 1st paper in 2015.

Elpasolites

- $Tl_2LiGdCl_6$:Ce [1]
- $Tl_2LiGdBr_6$:Ce [2]
- Tl_2LiYCl_6:Ce [3-6]
- $Tl_2LiLuCl_6$:Ce [7]
- $Tl_2LiScCl_6$ [8]

[1] H.J. Kim et al., J. Lumin., 164 (2015) 86–89.
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ORIGINAL PAPER

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Discovery, Crystal Growth, and Scintillation Properties of Novel Tl-Based Scintillators

HongJoo Kim, Gul Rooh, Arshad Khan, Phan Quoc Vuong, and Sunghwan Kim*

Ternary Halides

- Tl_2LaCl_5:Ce [9-12]
- Tl_2LaBr_5:Ce [13]
- Tl_2GdCl_5:Ce [14, 15]
- $TlGd_2Cl_7$:Ce [16]
- $TlSr_2Br_5$ [17]
- $TlSr_2I_5$:Eu [18, 19]
- $TlCaCl_3$ [20]
- Tl_2HfCl_6 [21-24]
- Tl_2ZrCl_6 [25,26]
- $TlAlF_4$ [27, 28]
- $TlMgCl_3$ [29]
- $TlCdCl_3$ [30]
- $TlCaI_3$ [31]

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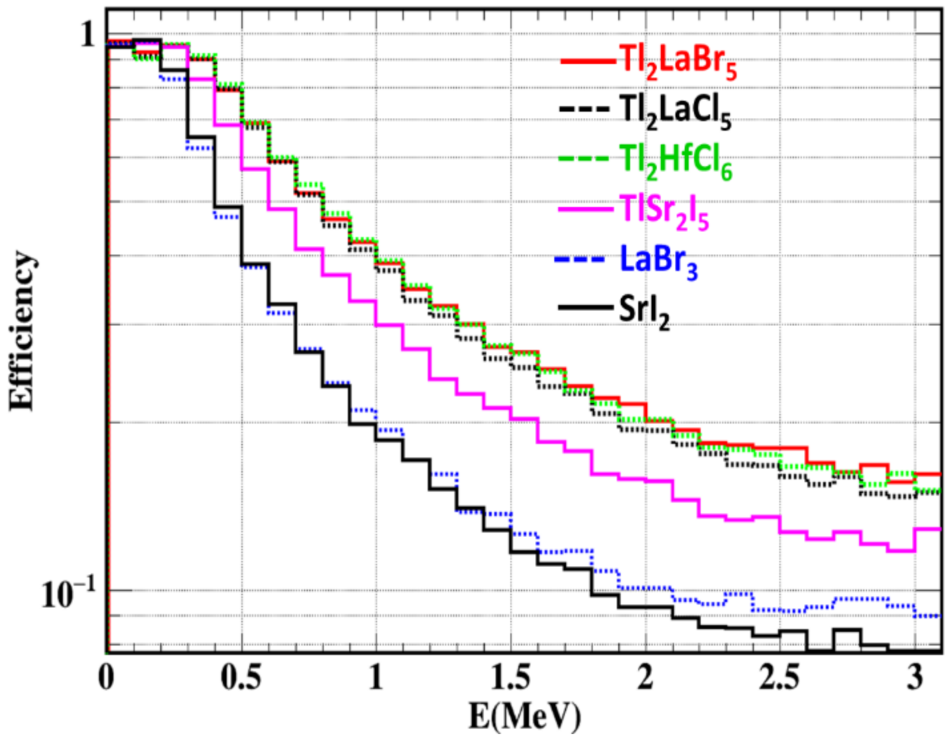
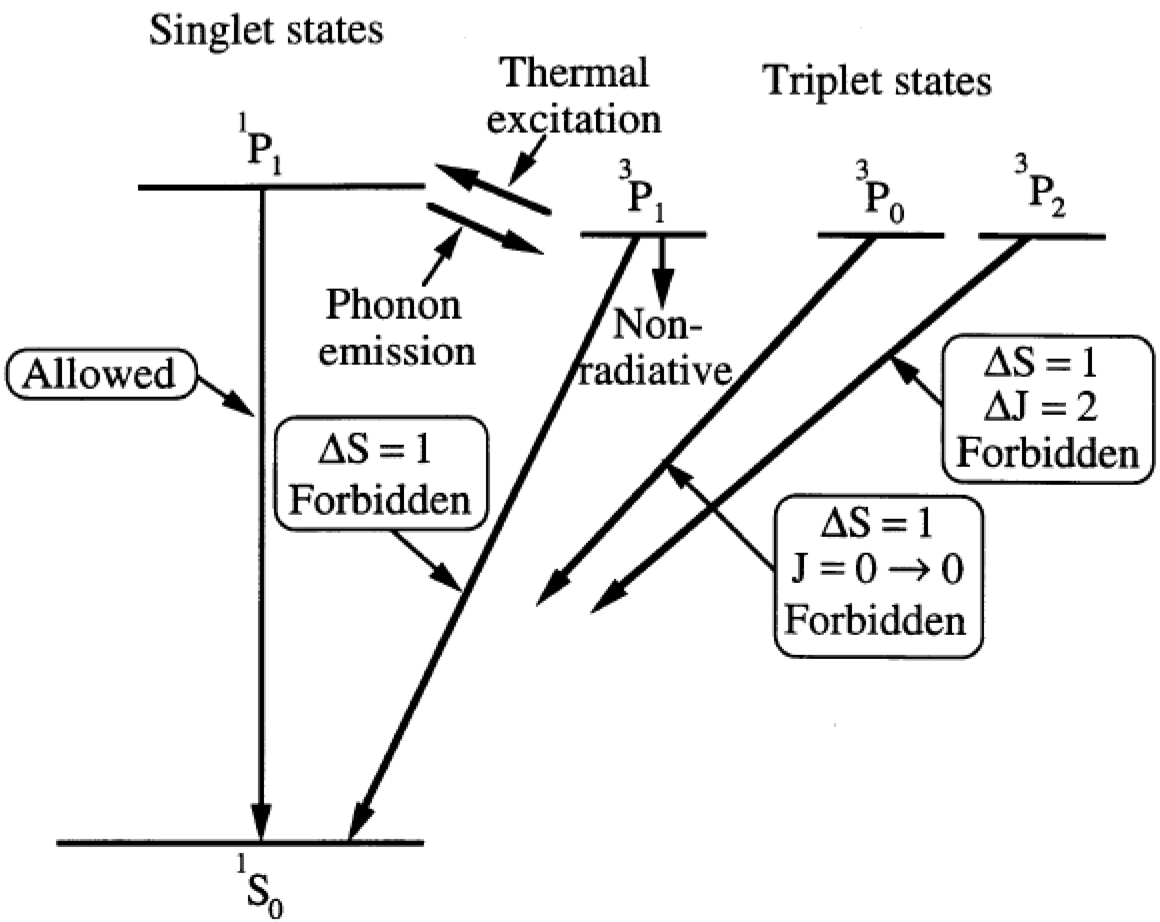
Detection efficiency comparison



- *The γ-rays full absorption peak detection efficiencies were calculated for 3 cm thick crystals using GEANT4 a Monte Carlo simulation package.*
- *These Tl-based scintillators has higher detection efficiencies than commercial halide scintillators.*
- *Tl_2LaBr_5 and Tl_2LaCl_5 are more promising for ToF-PET application due to better detection efficiency, higher light yield and fast decay time (25 ns, 31 ns).*
- *Tl_2HfCl_6 and $TlSr_2I_5$ can be use potentially for γ-rays spectroscopy.*

Intrinsic luminescence

- Bi, Pb, Tl, WO4, MoO4
- BGO, PbWO4, CdWO4, CaWO4



Dopant Luminescence :NaI:Tl (CsI:Tl, LiI:Tl)

Well-known NaI:Tl

Hofstadter 1948

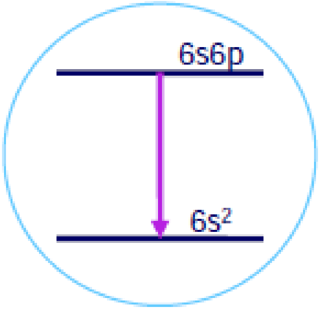
$^{2S+1}L_J$

Tl^{+} ions ground state 6s2 couple to $^{1}S_0$

excited state 6s6p

$^{1}P_1$ singlet

$^{3}P_2$, $^{3}P_1$, $^{3}P_0$ triplet



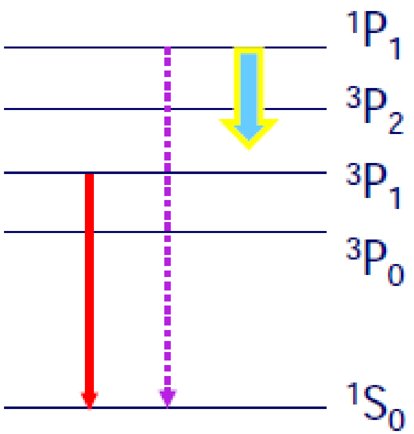
Dopant LC

Selection rules Allowed transitions

$\Delta J = 0, \pm 1$ (not $J = 0 \rightarrow J' = 0$), $\Delta S = 0$

Singlet → singlet allowed, fast

Triplet → singlet forbidden, slow

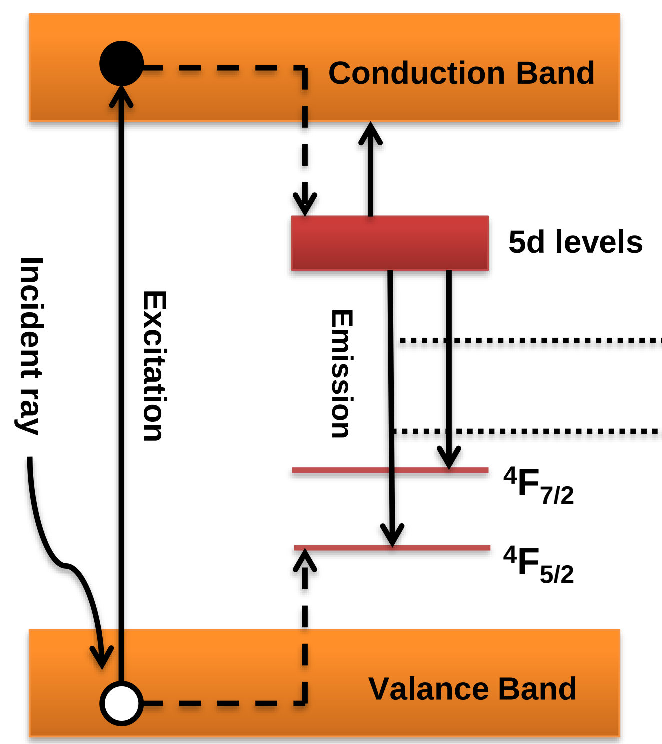


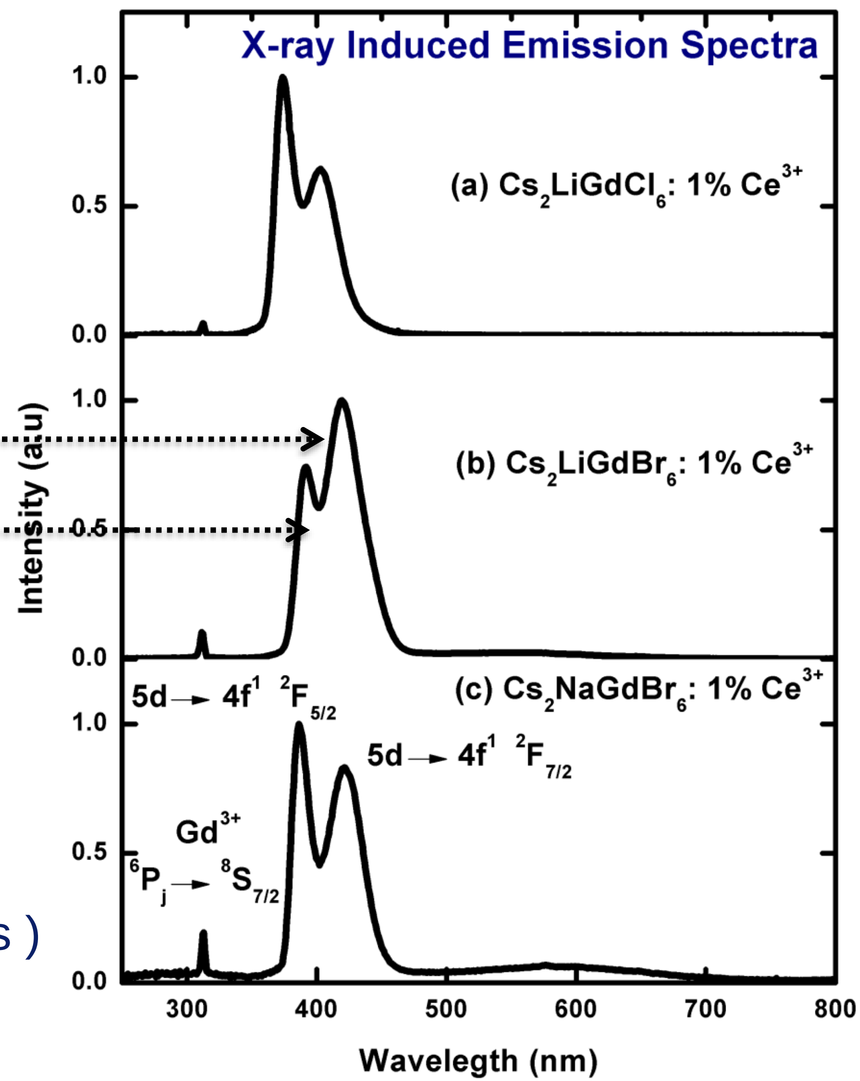
By C.W.E. Van Eijk

NaI:Tl 230 ns **slow**

Ce3+ f-d transition

Ce^{3+} Emission

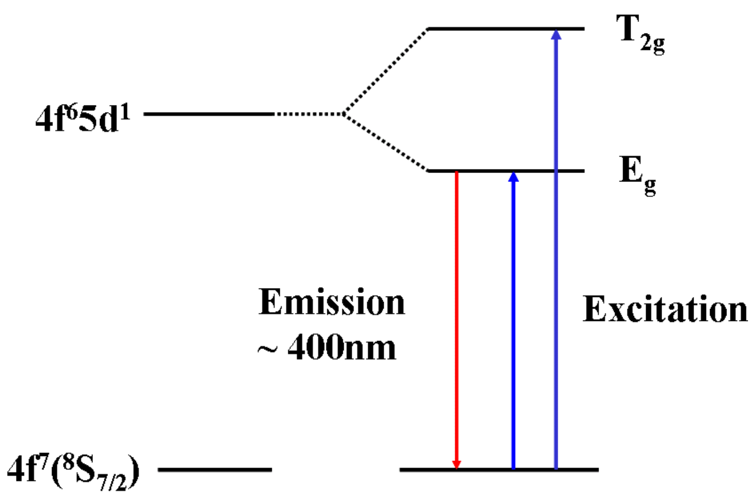


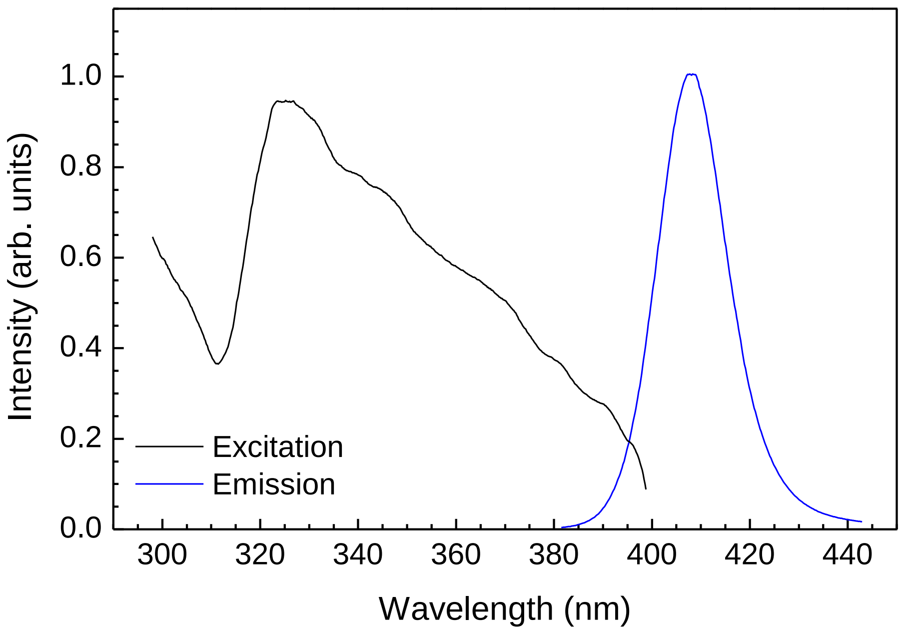


High LY & fast decay time (~10–100 ns)

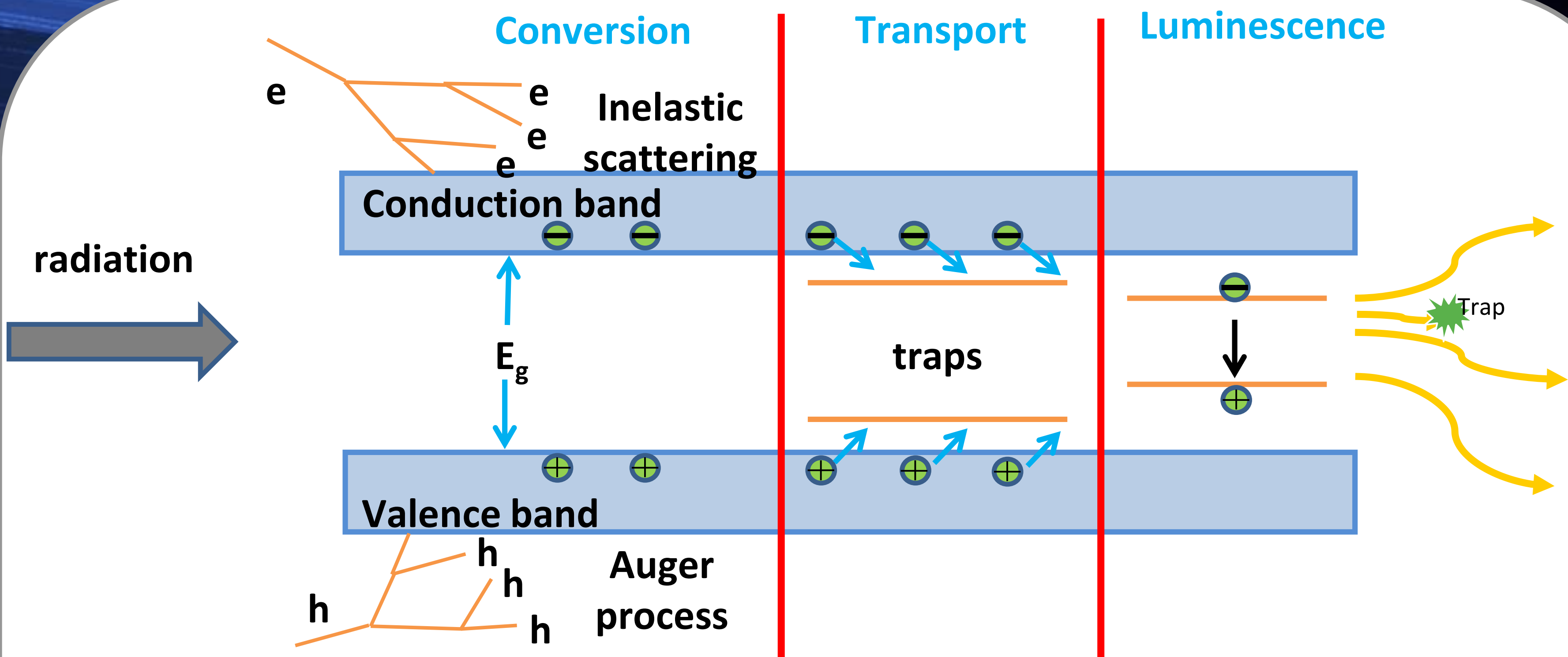
Eu2+ f-d transtion

- SrCl2:Eu, SrI2:Eu, CaF2:Eu, LiI:Eu
- High light output but rather slow (~μs)





Scintillation light yield fundamentals



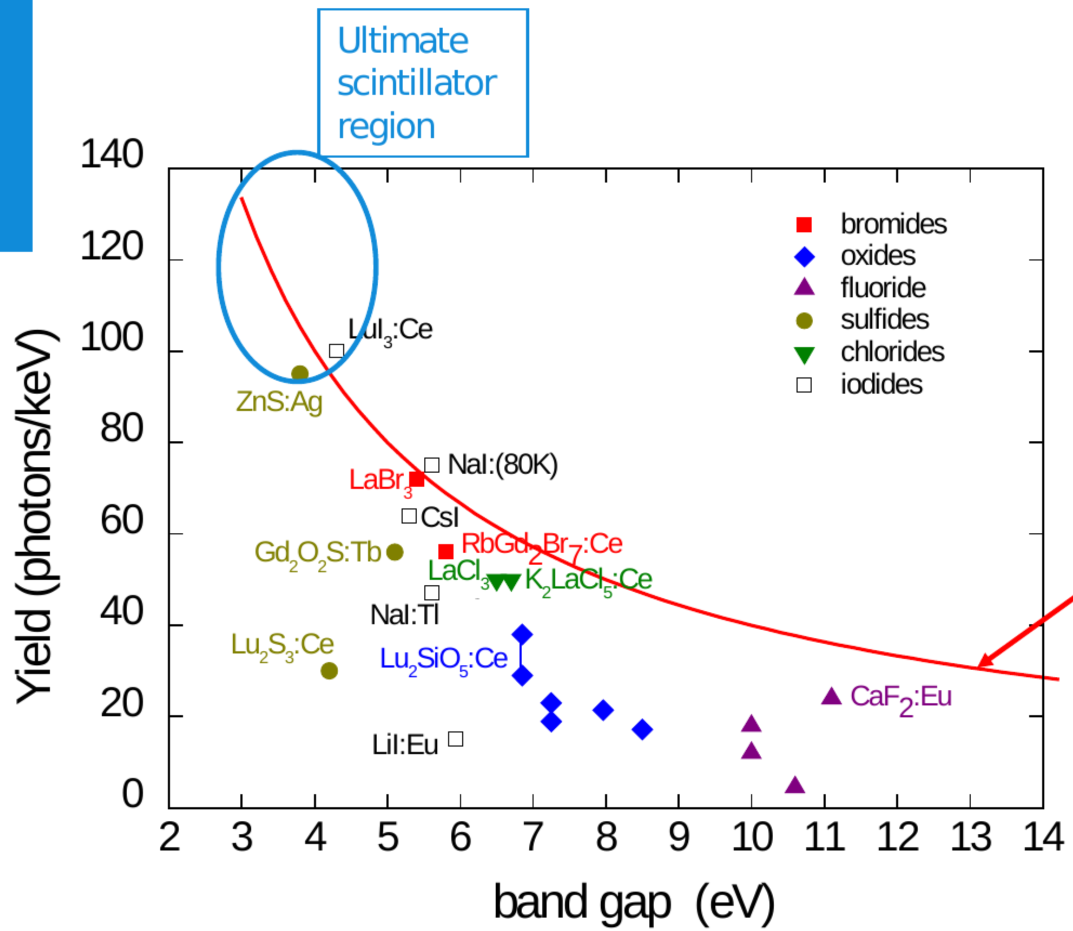
Incident E	e-h eff.	Transfer eff.	Quantum eff.	Transmission eff.
E	$1/\beta$	S	Q	T

$$N_{ph} = S \times Q \times T \times N_{eh} = S \times Q \times T \times E/\beta E_g (N_{eh} = E/\beta E_g)$$

The best case S, Q, T=1 and β=2.5 : $N_{ph} = E/(2.5 \times E_g)$

Scintillation Light yield

The ideal scintillator has S=Q=1



$$Y = \frac{10^6}{2.5E_{gap}}$$

By P. Dorenbos

Energy Resolution

Typical NaI(Tl) system (from H. Spieler)

511 keV gamma ray

⇓

25000 photons in scintillator

⇓

15000 photons at photocathode

⇓

3000 photoelectrons at first dynode

⇓

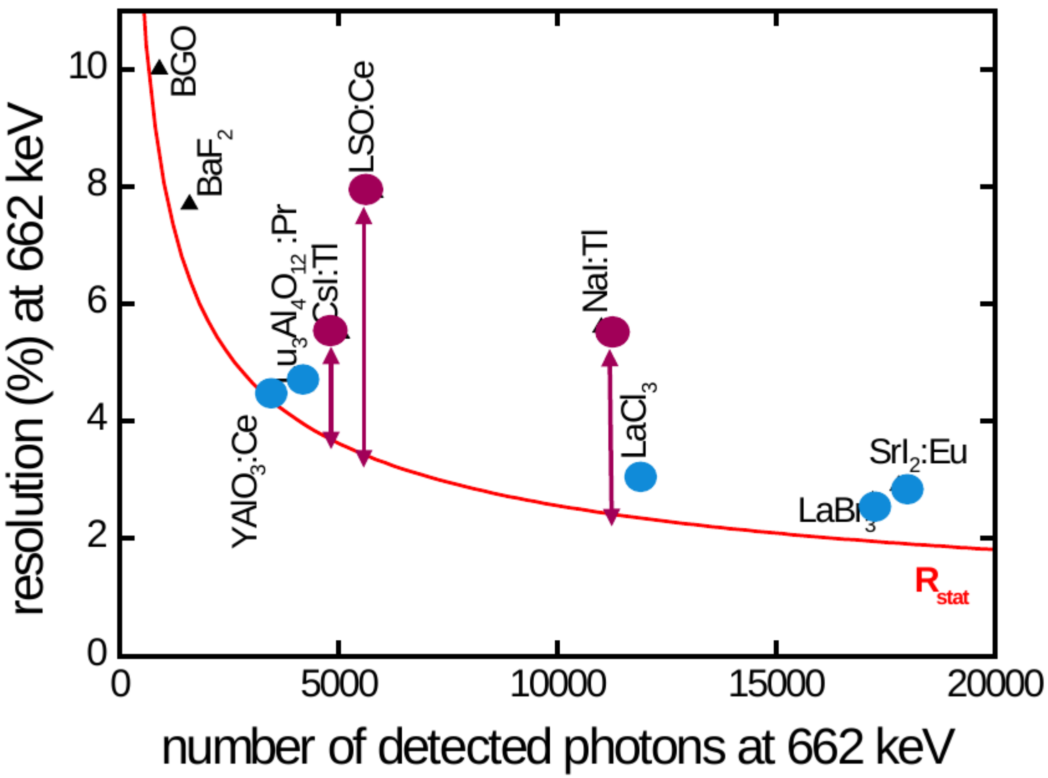
3×10^9 electrons at anode

2 mA peak current

Resolution of energy measurement determined by statistical variance of produced signal quanta.

$$\frac{\Delta E}{E} = \frac{1}{\sqrt{3000}} = 2\%\ r.m.s = 5\%\ FWHM$$

Energy resolution @ 662 keV

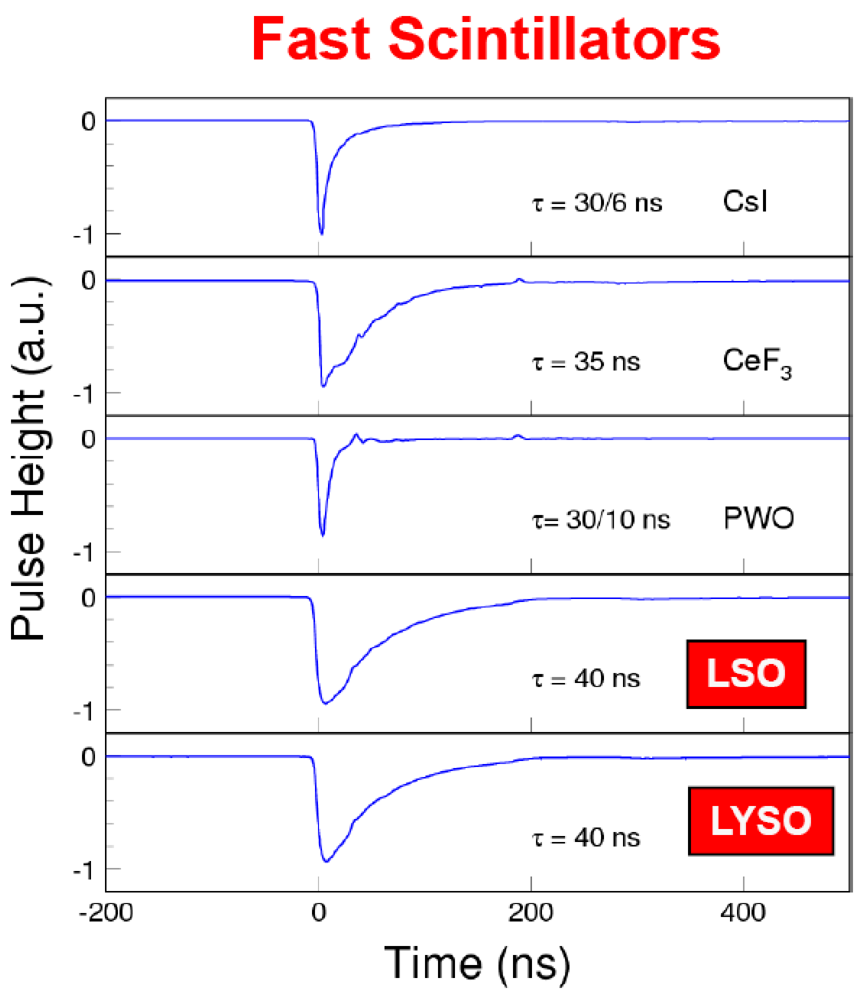


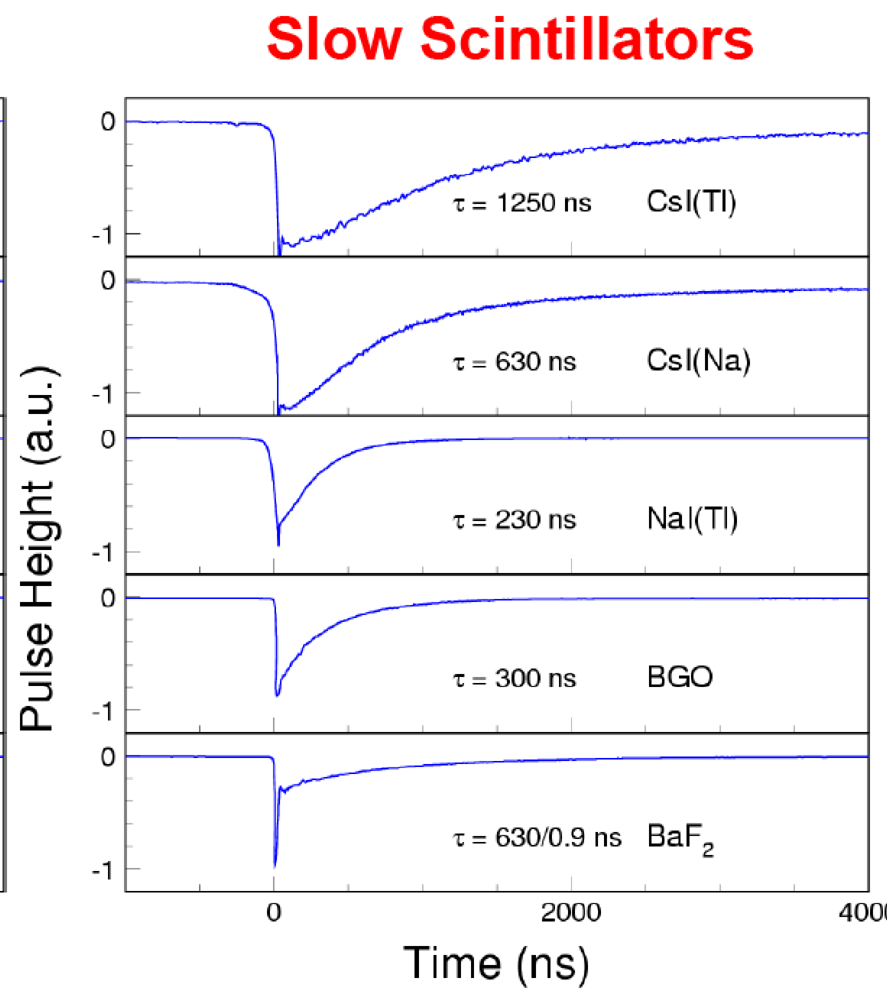
By P. Dorenbos

$$R_{stat} = 2.35\sqrt{\frac{1+0.15}{N_{dph}}}$$

- $YAlO_3$:Ce, $Lu_3Al_5O_{12}$:Pr, $LaCl_3$:Ce, $LaBr_3$:Ce, SrI_2:Eu are reasonably close to fundamental limit.
- For LSO, NaI:Tl, CsI:Tl, $R_{nonprop}$ dominant

Decay time of inorganic scintillator





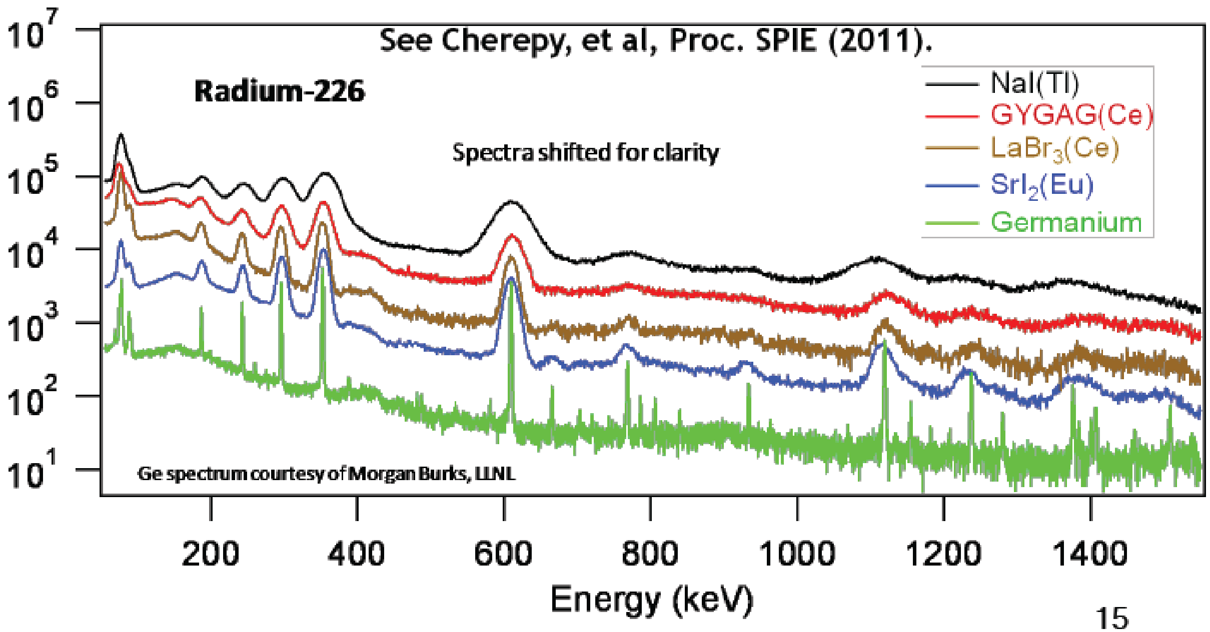
By R.Zhu

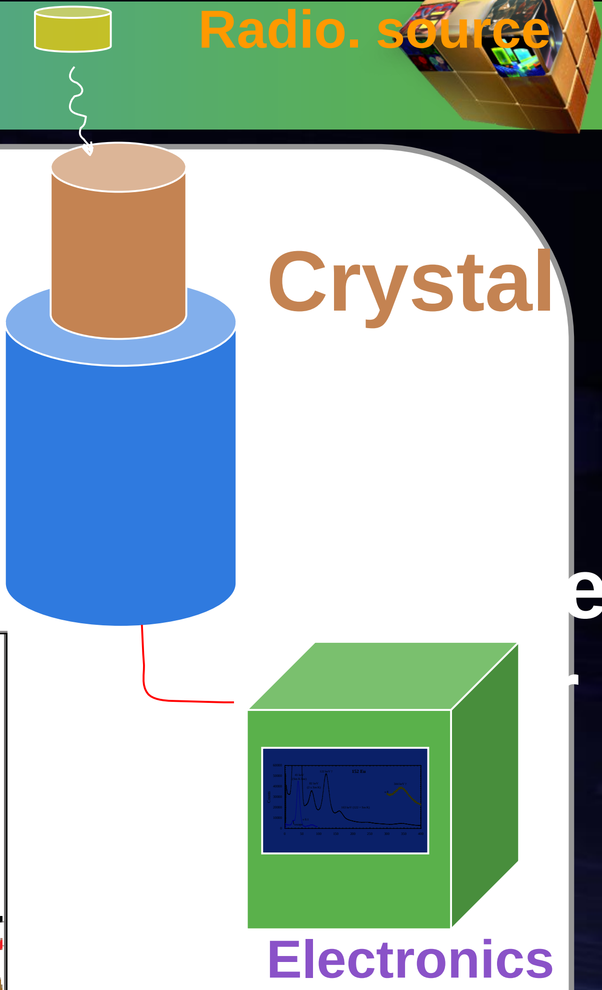
Low energy applications
Dose monitoring, Medical imaging

X-ray and gamma spectroscopy

Radiation Monitoring

1) Near Nuclear reactor
2) Accelerator beamline
3) Cancer treatment with gamma, x-Ray
4) Envirnmental radiation monitoring





Potable Dose Monitoring Development

Ethernet interface

Notebook

1.5x1.5x1.5 cm^3

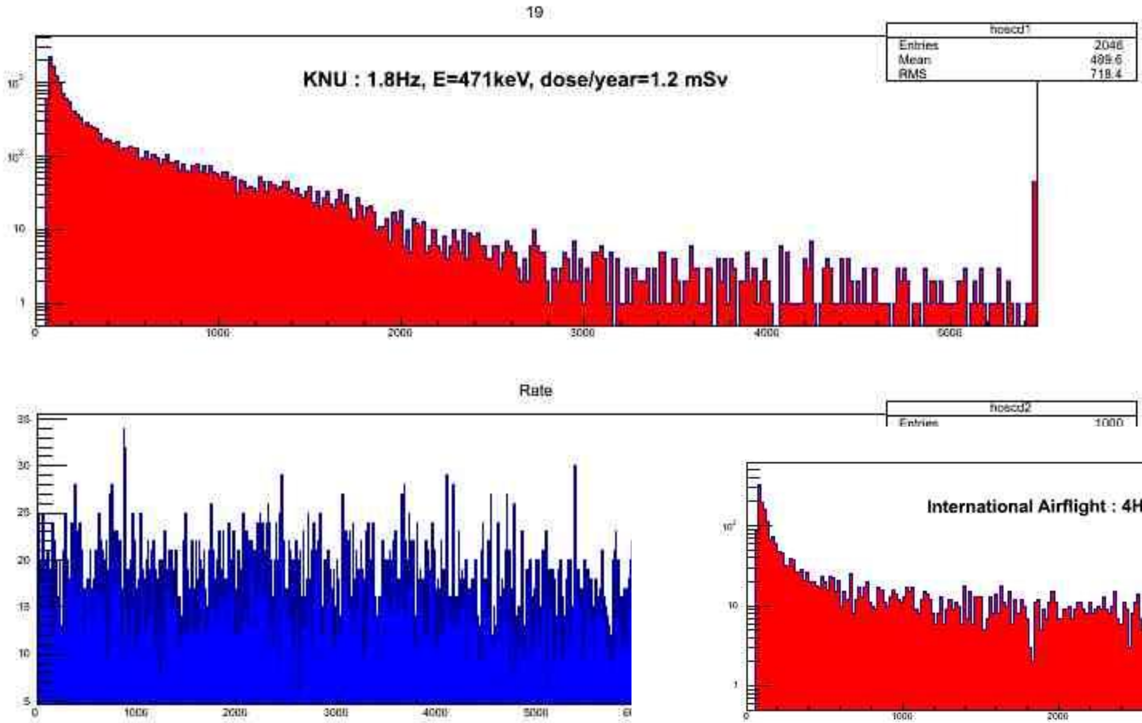
Plastic scintillator

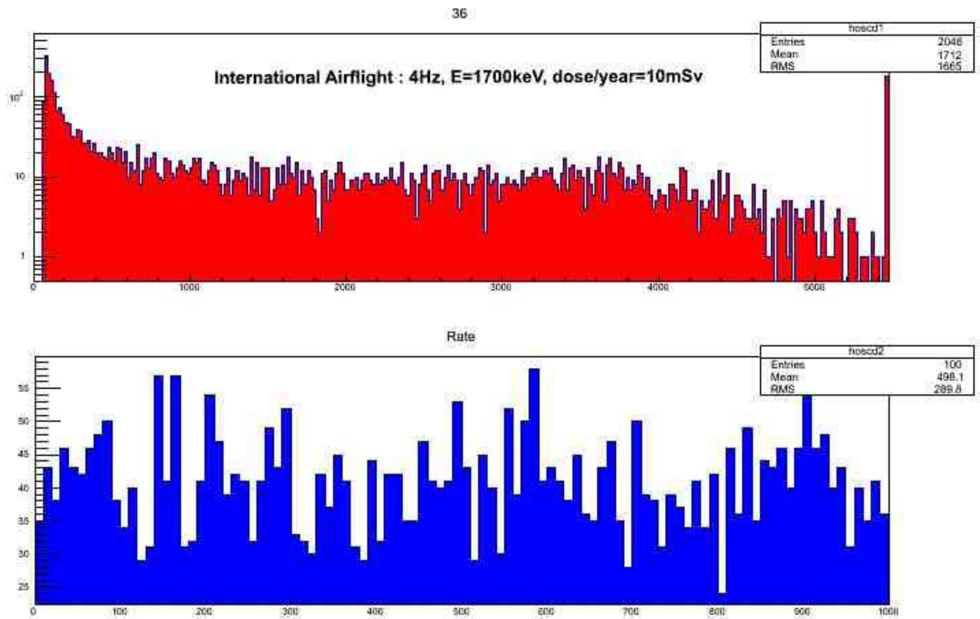
Photomultiplier Tube

Signal digitizer (400 Mhz FADC)

Module size
15x7x2 cm^3

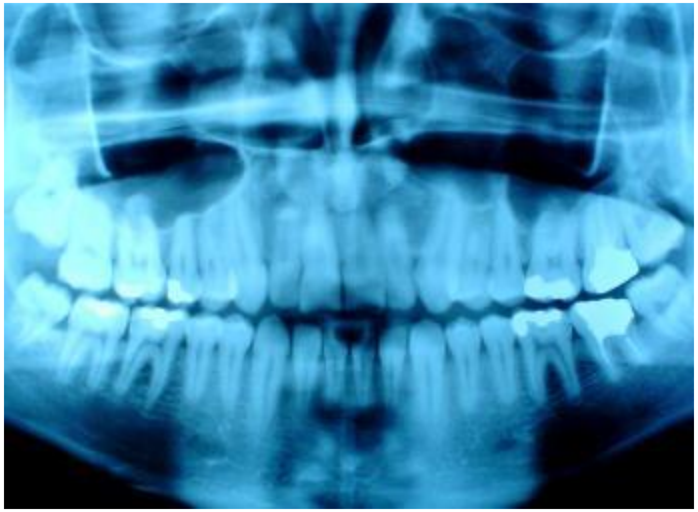
Dose monitoring with flight





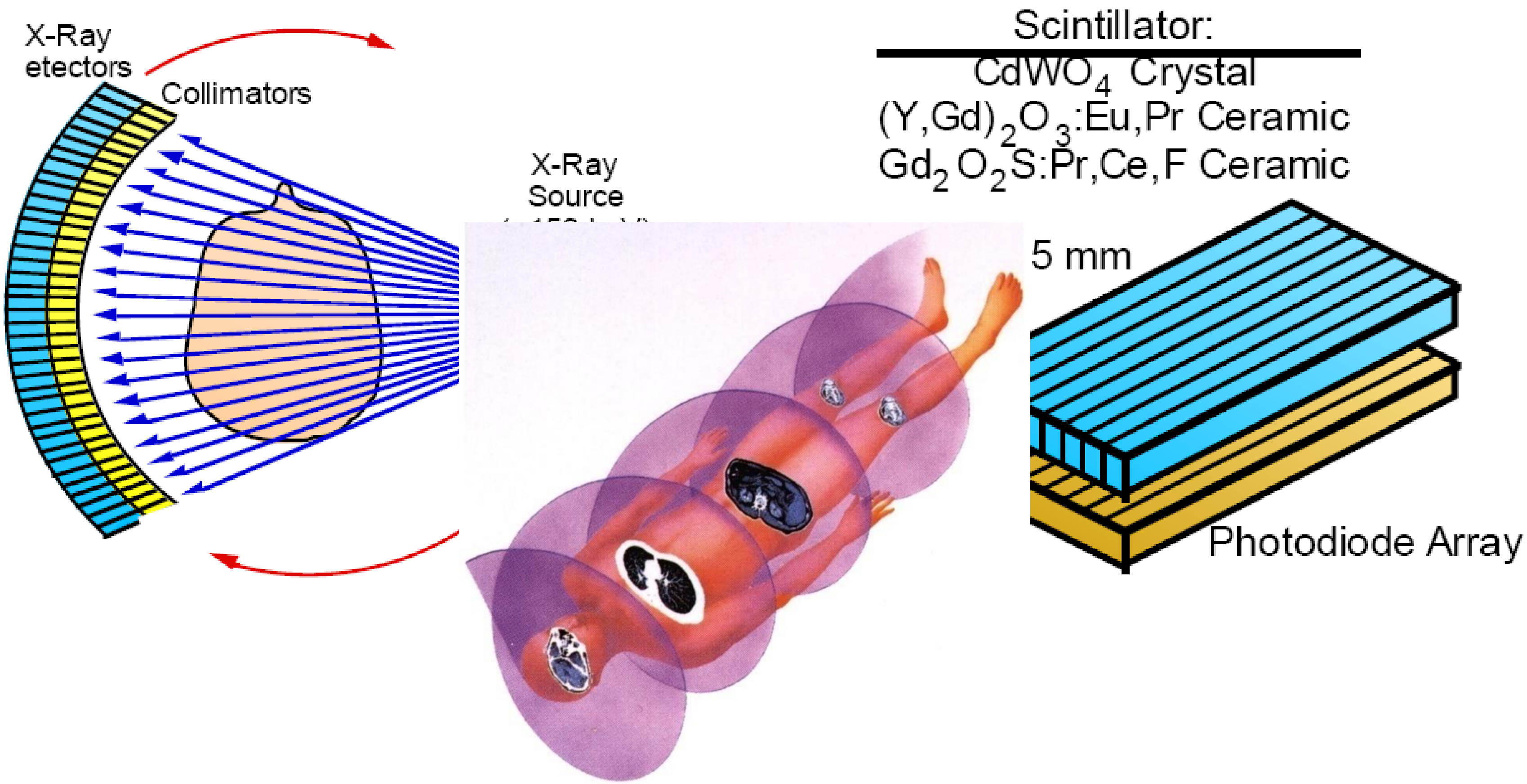
1.2 mSv/y at KNU
0.6 mSv/y at Jakarta
10 mSv /y at international Flight

Dental Computed Tomography (CT)



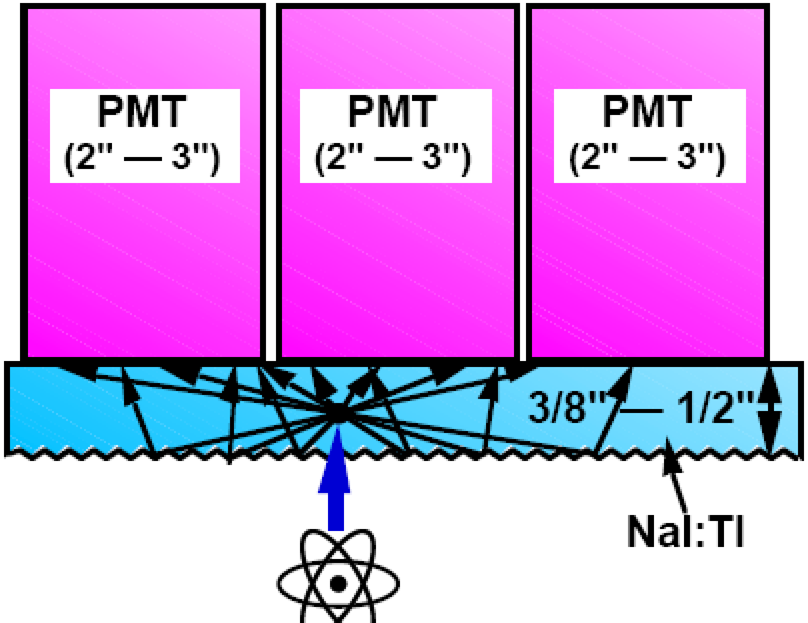
CsI:Tl pixelated scintillator
+ CMOS sensors
=> Chest X-ray (DR)

CT (computed tomography)

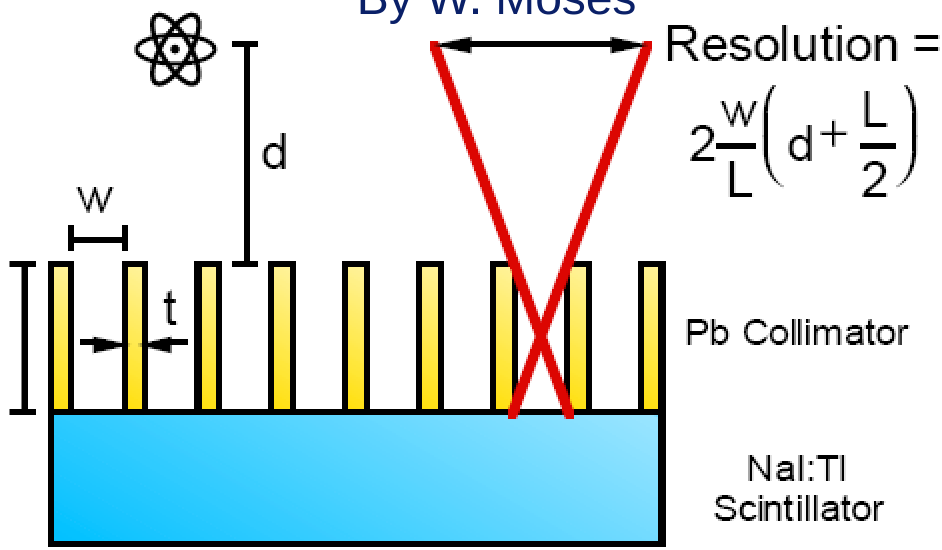


By W. Moses

Gamma Camera

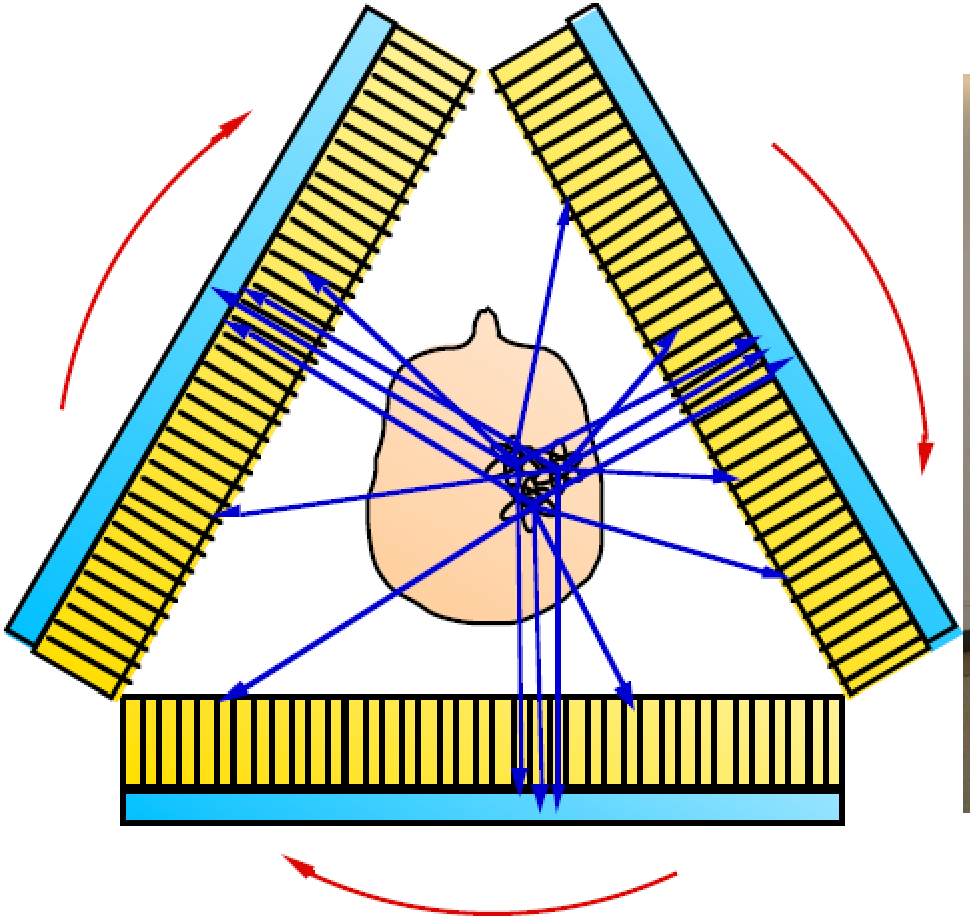


By W. Moses



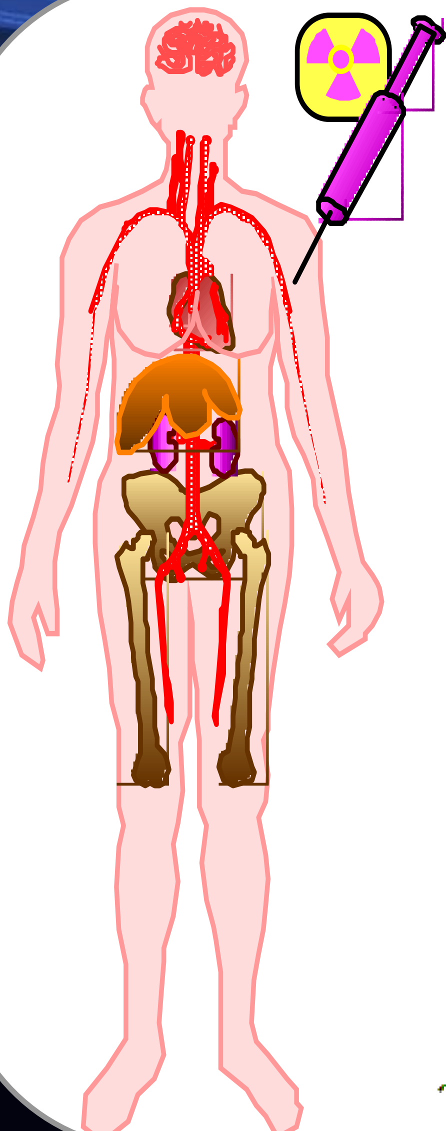
Siemens

SPECT(single photon emission computed tomography)

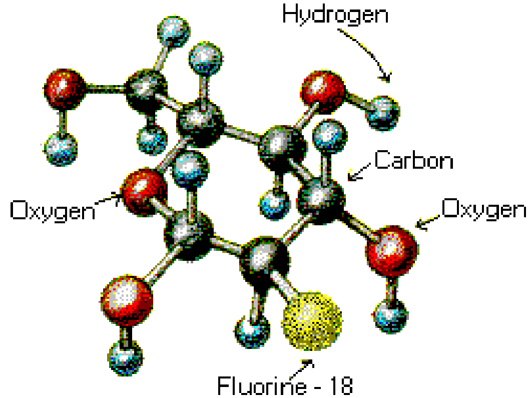


By W. Moses

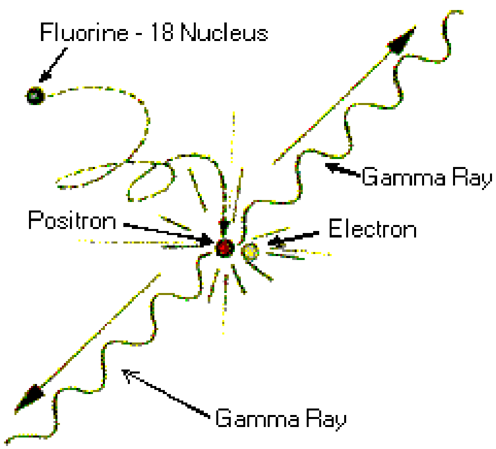
Inject Patient with Radioactive Drug

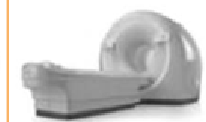


2-fluoro-2-deoxy-D-glucose "FDG"



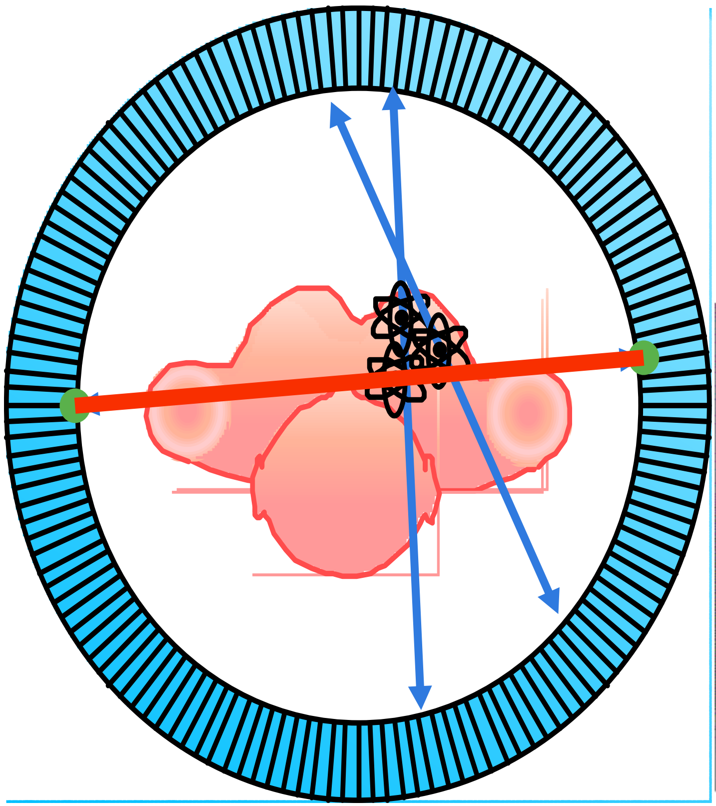
Positron Emission Tomography



기업명	GE Healthcare	Philips Healthcare	Siemens Medical Solutions
모델명	Discovery PET/CT 710 	Ingenuity TF 	Biograph mCT 
DETECTOR Assembly			
– Number of detector rings	24	44	39, optional 52
– Number of crystals	13,824	28,336	24,336, optional 32,448
– Crystal material	LYSO	LYSO	LSO
– Axial FOV, mm	157	180	162, optional 216
CT Specifications			
– Number of slices acquired simultaneously	64, 128	64,128	40, 64, 128
X-ray generator			
– kW output	72	105	80, 100
– mA range	5–800	20–500(64 CT) 20–665(128 CT)	20–800
PET Image Acquisition			
– 2D	NO	NO	NO
– 3D	YES	YES, 3-D RAMLA with LOR	YES, UltraHD 3-D
– Time of flight	YES	YES	555 ps
Gantry			
– H x W x D, cm	193 x 230 x 226	213 x 225 x 223.7	203 x 234 x 136
– Weight, kg	6,215	4,201	3,977
– Patient port diameter, cm	70	70(PET), 70(CT)	78
Image Reconstruction			
– Coincidence window, nsec	4.9(3D)	3.8	4.1
Purchase information			
– Price	$3,722,884	Not specified	$3,500,000–5,000,000
– year first sold	2012	2011	2008

자료 : ECRI Institue, Healthcare Product Comparison System

Positron Emission Tomography (PET)



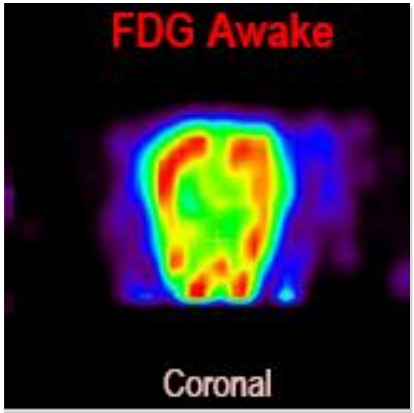
POSiTRACE

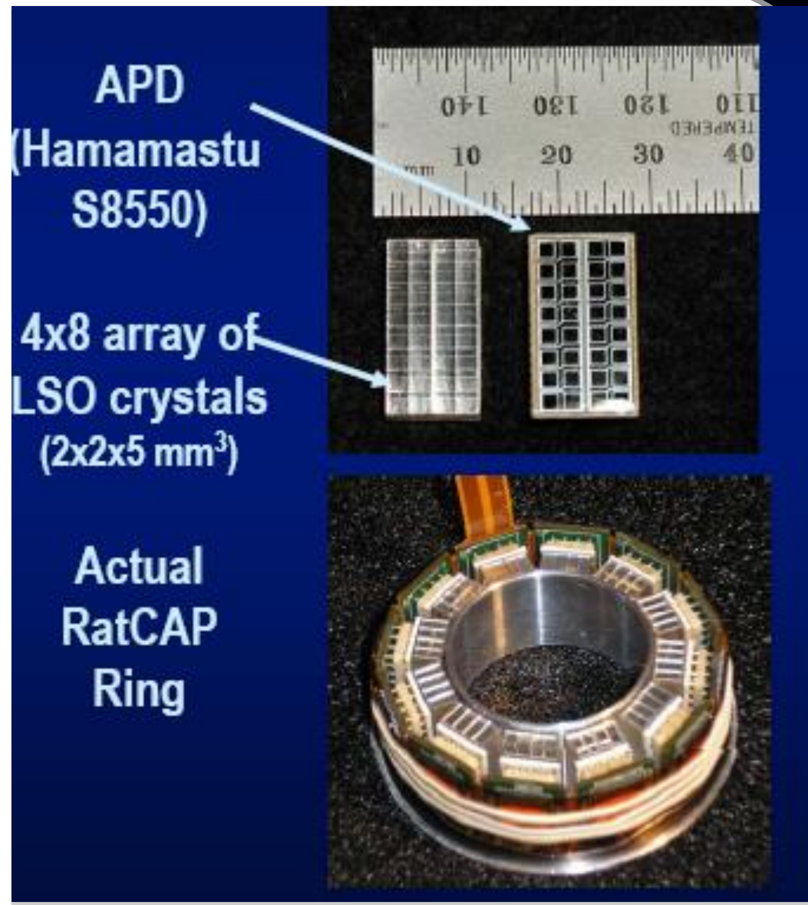
Dual Mode PET/CT
Oncology System

- Detects Pairs of Back-to-Back 511 keV Photons
  - No Collimator Needed ⇒ High Efficiency

By W. Moses

RatCAP: Rat Conscious Animal PET

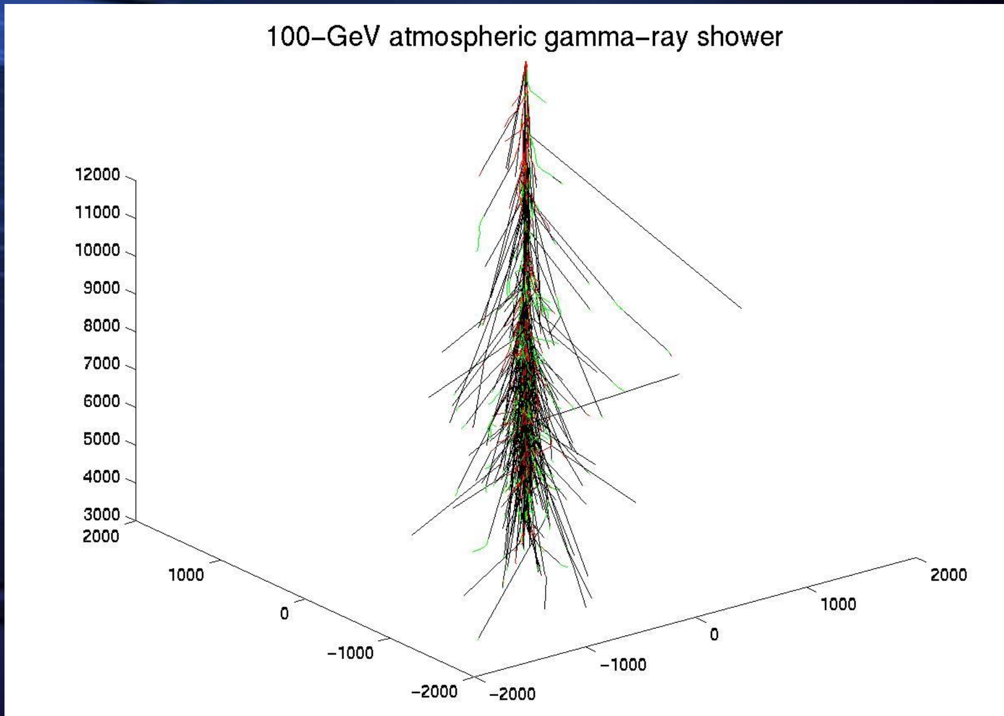




C.Woody, SCINT 07, 6/7/07

High energy applications
High energy, Astro, Astroparticle

Example of Shower at High Energy



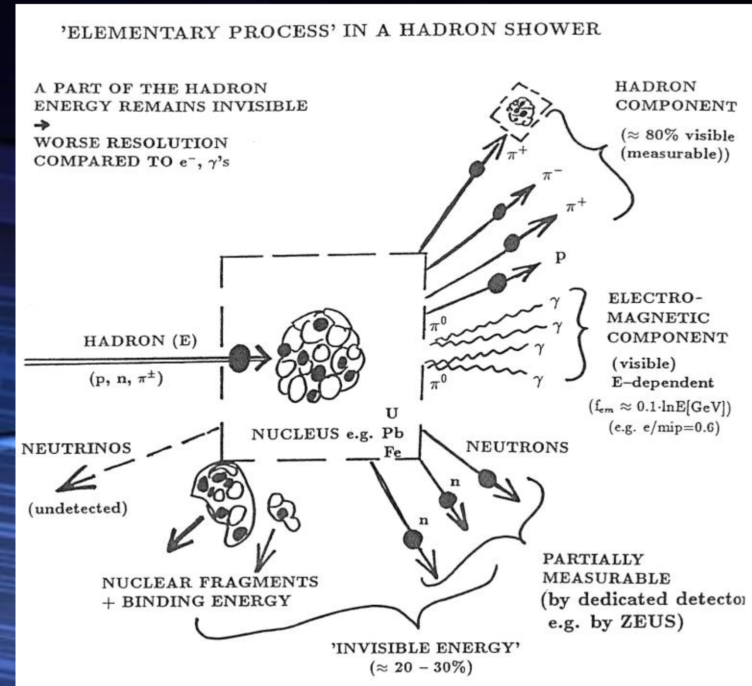
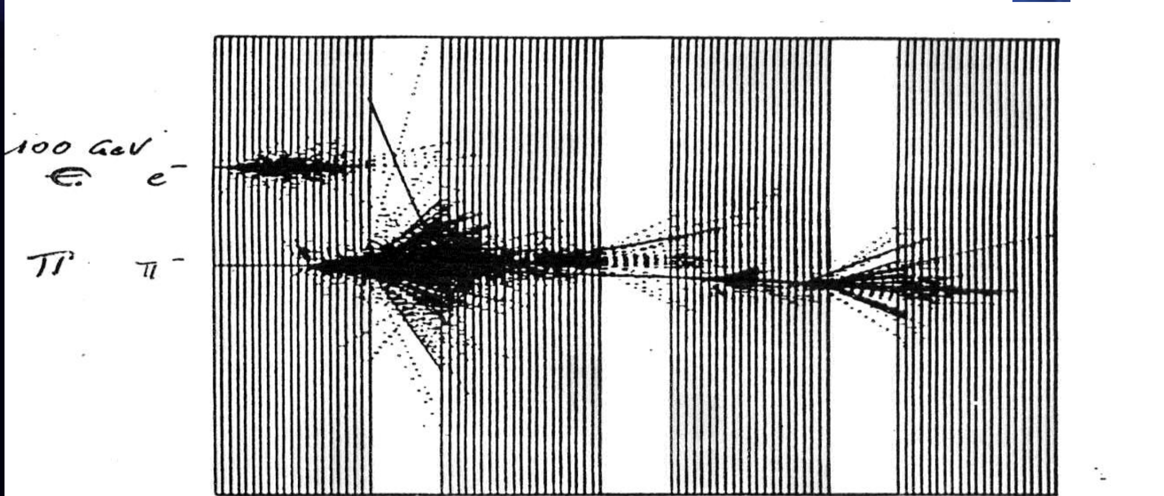
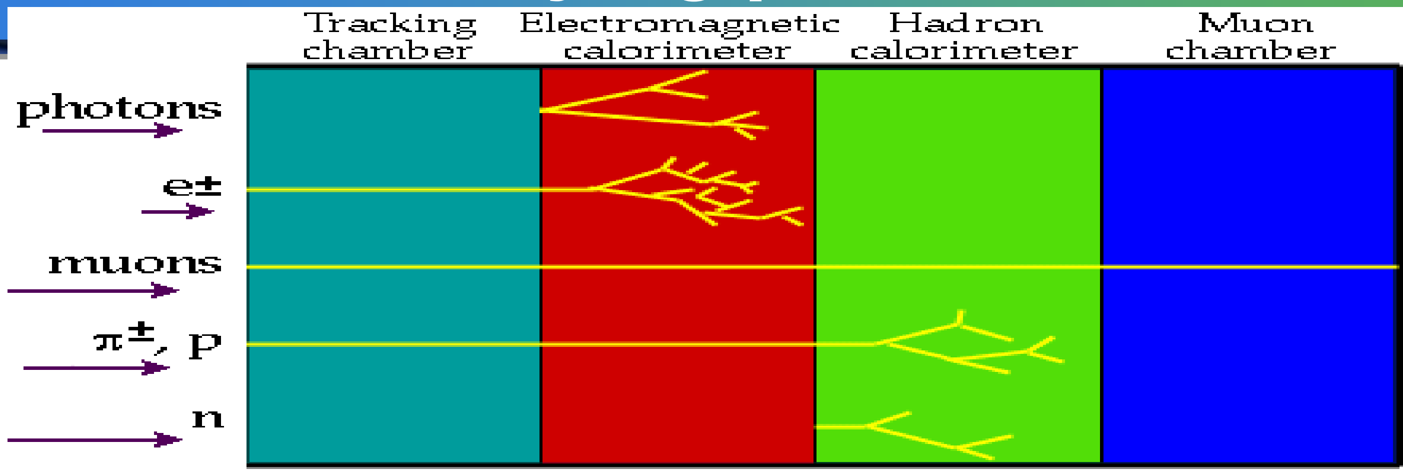


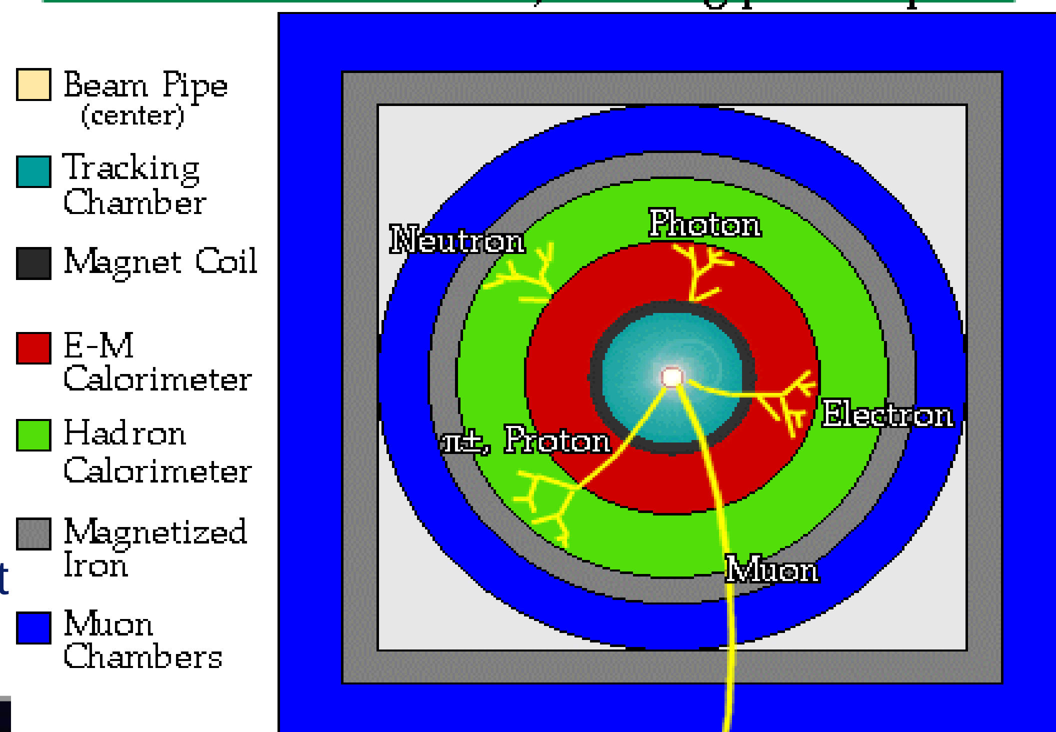
Fig. 3.6 'Elementary physical process' in a hadron shower.



Identifying particles

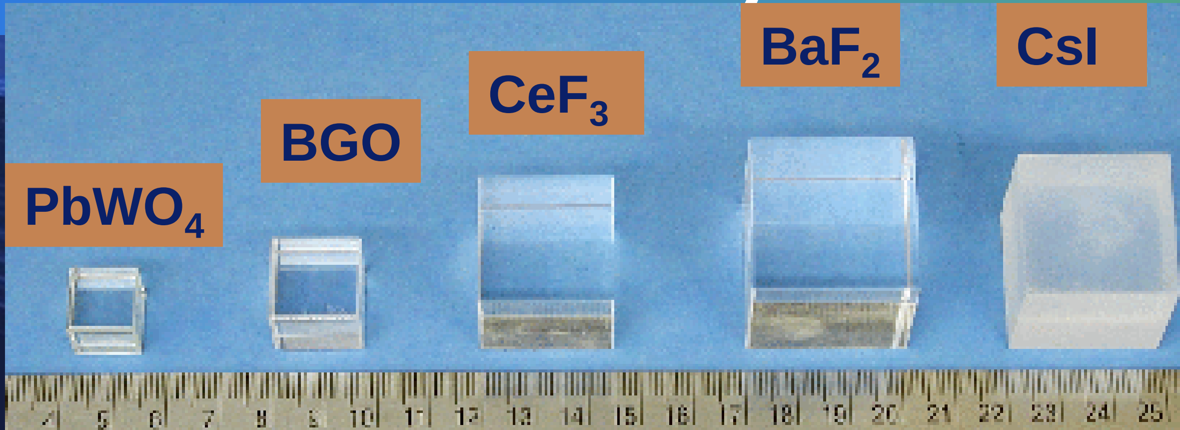


A detector cross-section, showing particle paths

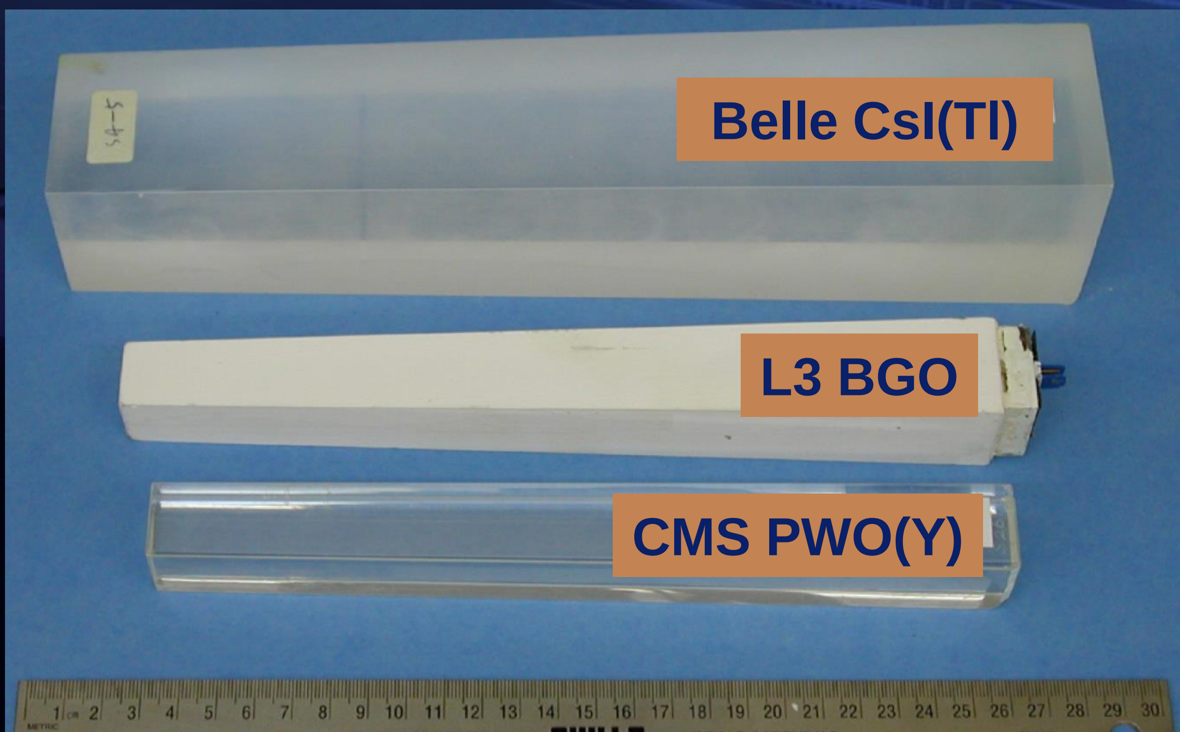


Particle Data Booket

Crystal scintillators



1.5 X_0 Cubic



Full Size Samples

Belle CsI(Tl): 16 X_0

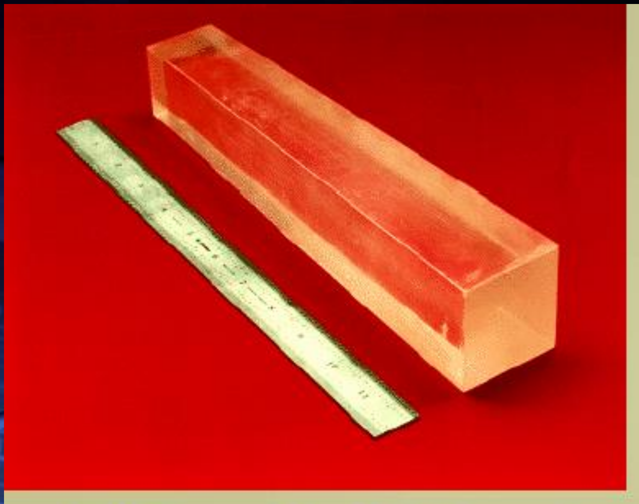
L3 BGO: 22 X_0

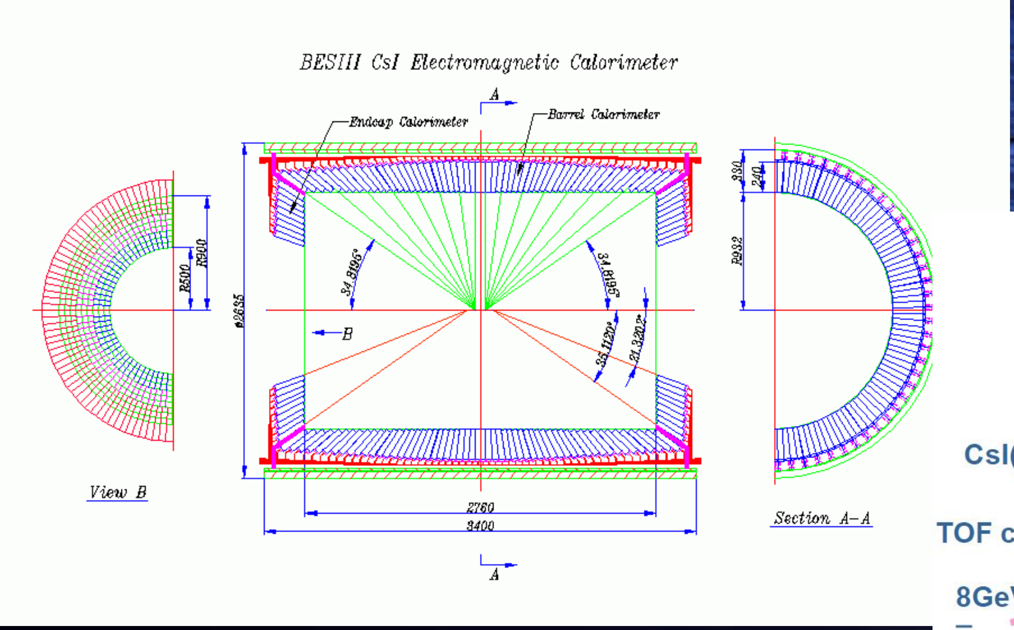
CMS PWO: 25 X_0

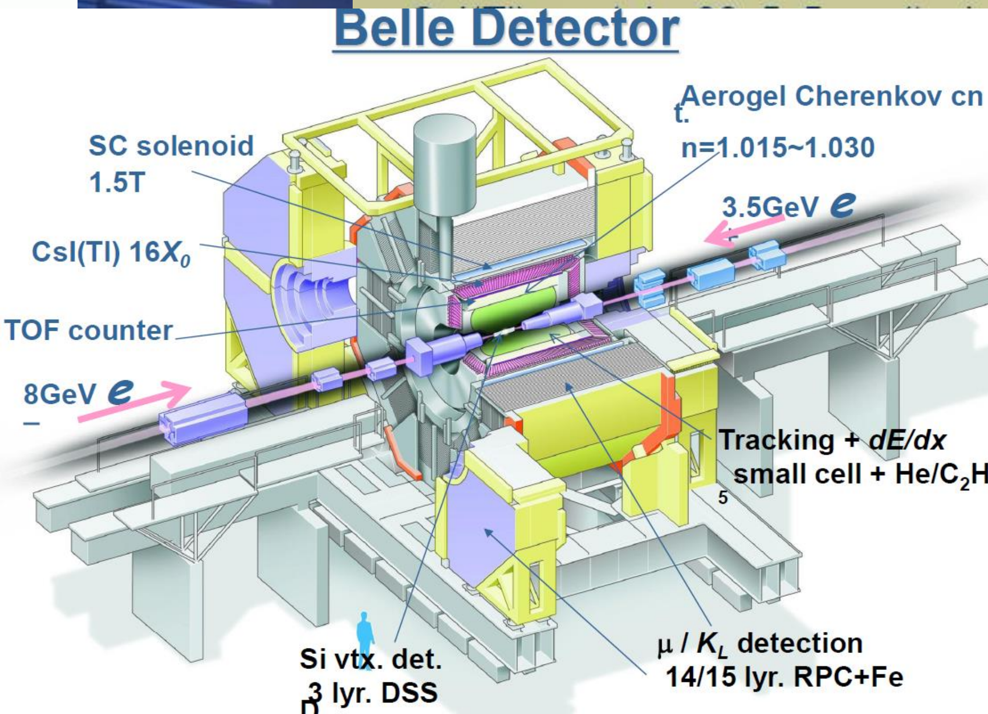
By R.Zhu

CsI(Tl) Calorimeter for High Energy physics

- B factory : Belle, Babar
  ~8000, ~20 ton
- Charm : CLEO, BESIII





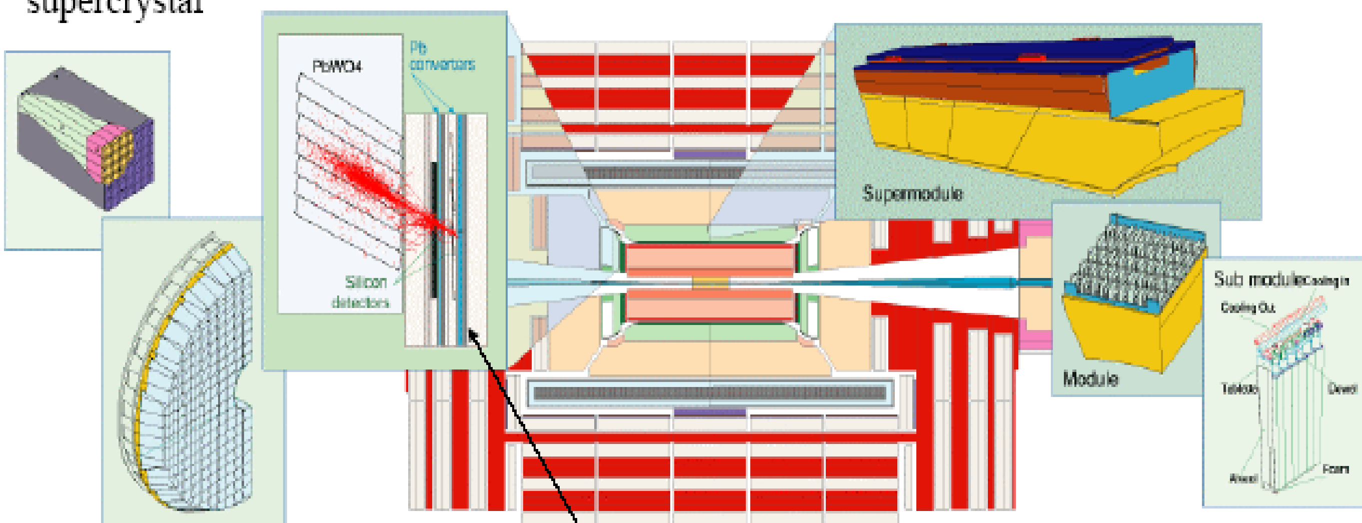


PbWO4 in CMS, LHC

90 Ton of PbWO4

CMS Electromagnetic calorimeter

5x5 "supercrystal"



Endcap, readout with VPT

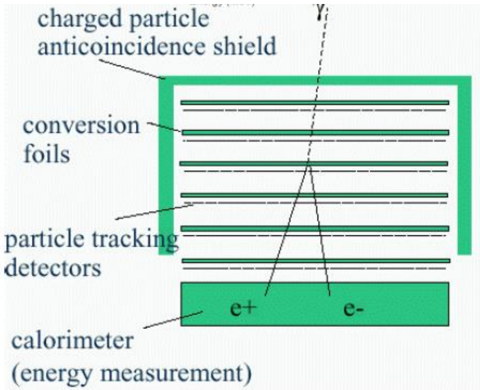
Preshower

Barrel, readout with APD

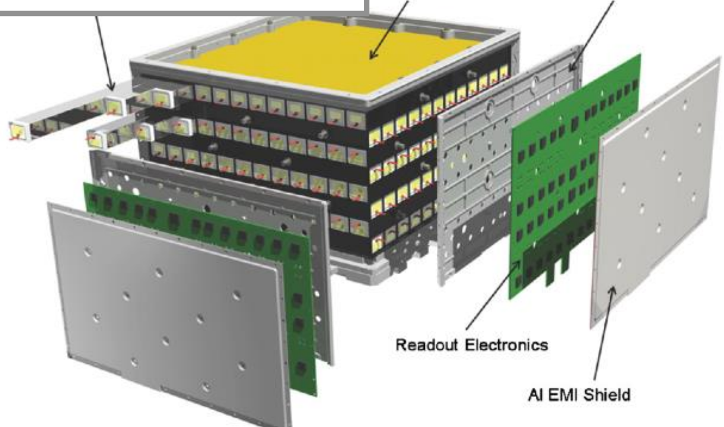
CsI:Tl calorimeter for astrophysics

FERMI (CsI:Tl, 8.6Xo)

Fermi Gamma-ray Space Telescope

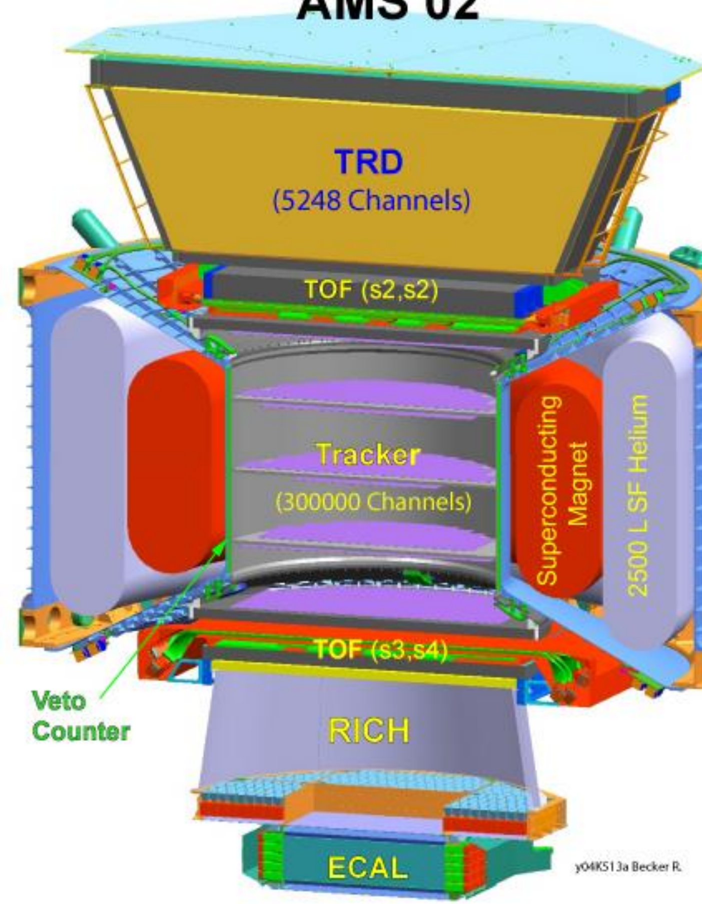


CsI Detectors Photo-Diode sensor



LAT calorimeter module [ref. The Astrophysical Journal, vol 697:1071-1102, 2009]

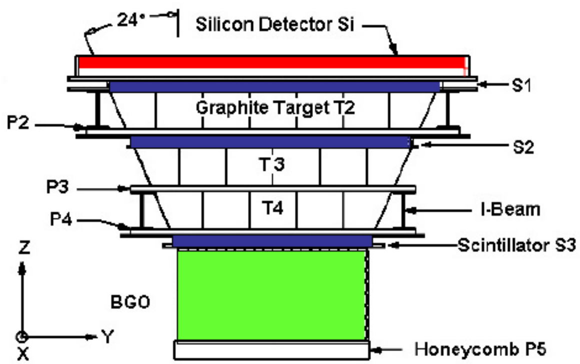
AMS 02



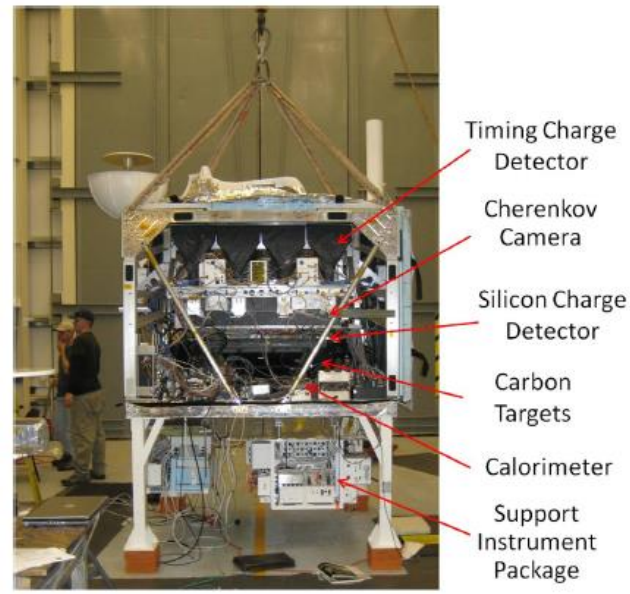
CsI Detectors Photo-Diode senso

High energy cosmic-ray Exp.

ATIC (BGO, 22.4 Xo)



CREAM(W+plastic)



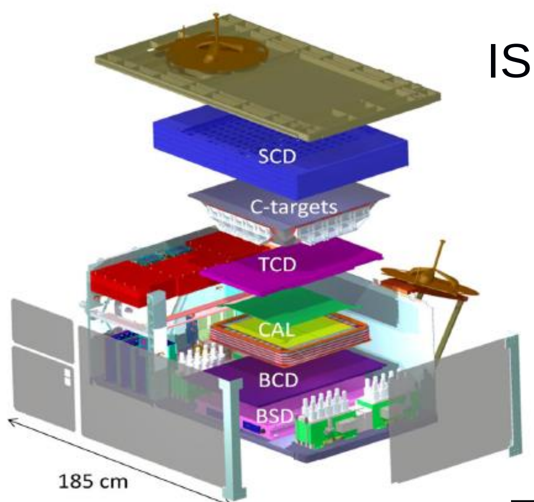
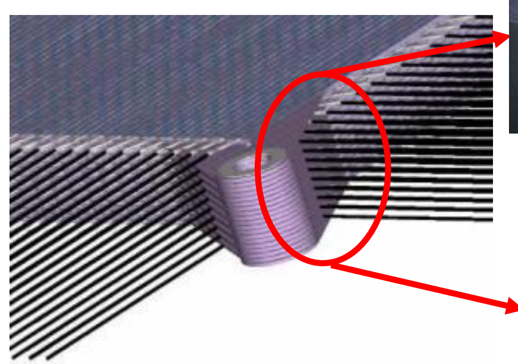
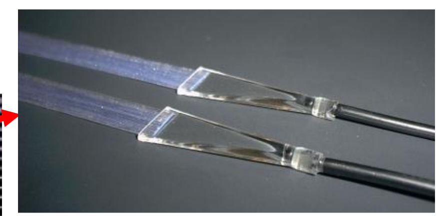


Fig. 2. Exploded view of the ISS-CREAM Instrument.

ISS-CREAM(W+plastic)



Tungsten / Scintillating Fiber Stack



Fiber Light Guides

Tungsten Plates

High energy cosmic-ray Exp.

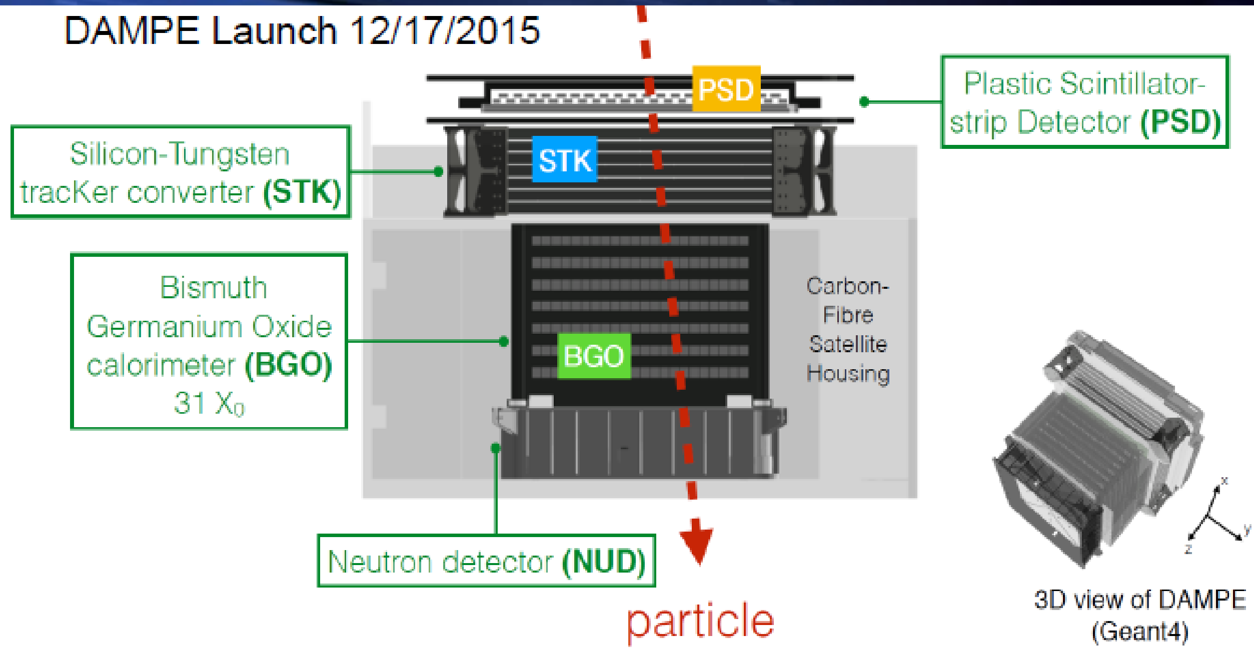
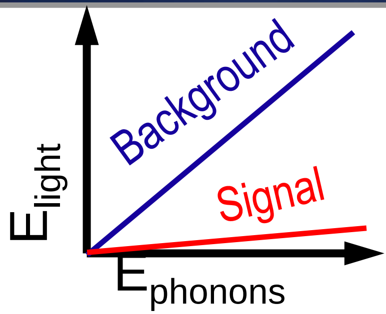


Table 1. Comparison of ISS-CREAM with other relevant space missions.

Project	Aperture (m^2sr)	Mass (kg)	Calorimeter thickness	Energy resolution electrons/nuclei	e/p rejection power	Charge Detector Type/resolution
NUCLEON	0.06	~300	16 X_0	10%/70%	~10^3	Si pad (3 x 1.5 cm^2)/0.3e
ISS-CREAM	0.43	1258	20 X_0, 1 λ_0	5%/40%	5×10^5 @50% eff.	Si pad (1.37 x1.55 cm^2)/0.2e
CALET	0.12	613	27 X_0, 1.35 λ_0	2%/ Not Avail.	10^5 @80% eff.	Plastic Scin. strips/0.35e
DAMPE	0.2-0.3	1400	33 X_0	1.5%/40%	~10^5	Plastic Scin. strips/0.25e
GAMMA-400	1 m^2 area	4100	~25 X_0, 1.1 λ_0	1%/ Not Avail.	5×10^5	Plastic Scin. Strips/ Not Avail.

Direct WIMP detection technique

Cryogenic
Detector
CRESST



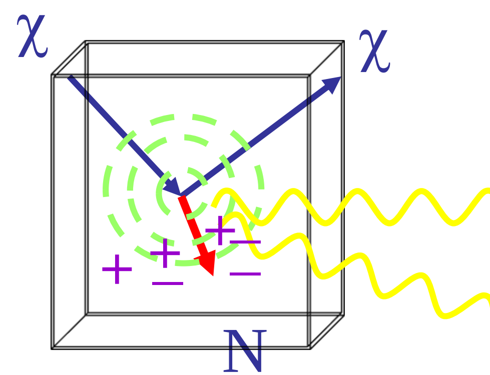
NaI(Tl), CsI(Tl), CaF_2(Eu),LXe
DAMA/LIBRA ,NAIAD,ANAIS
KIMS, COSINE, XMASS
Annual Modulation,
Decay time based PSD

Phonon(heat)

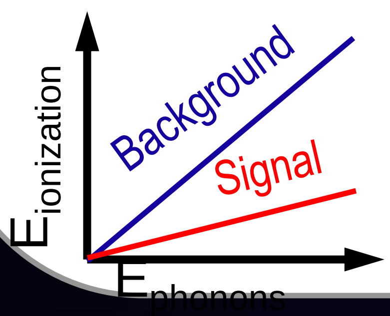
Photon(light)

EUREKA

Cryogenic
Detector Ge, Si
CDMS, EDELWEISS

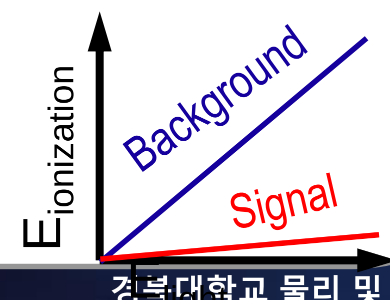


2 phase LXe, LAr,
LNe
ZEPLIN II,
XENON, WARP



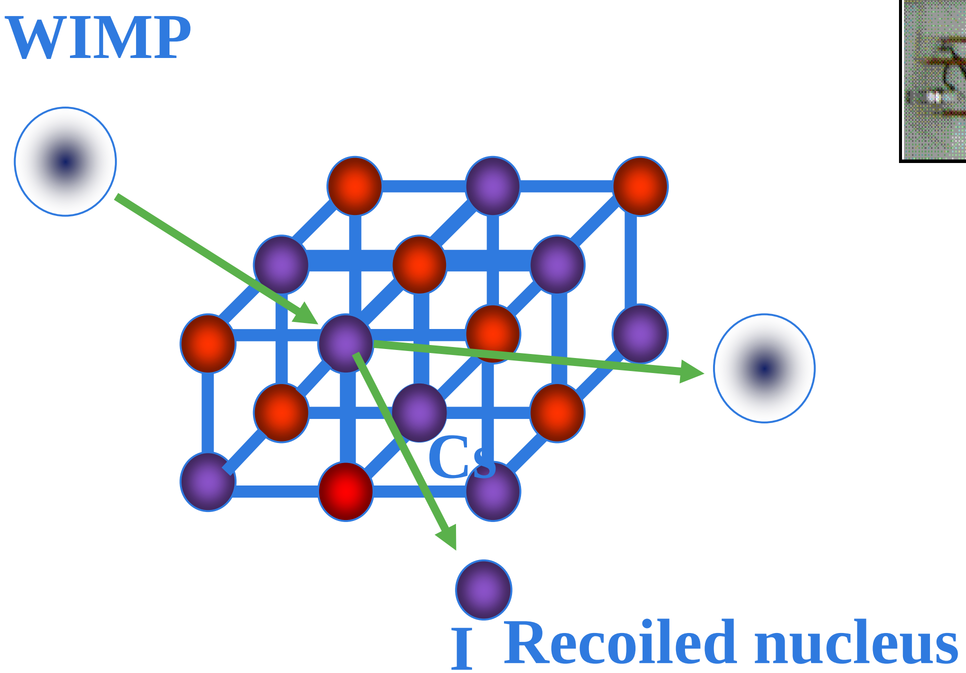
Ionization(current)

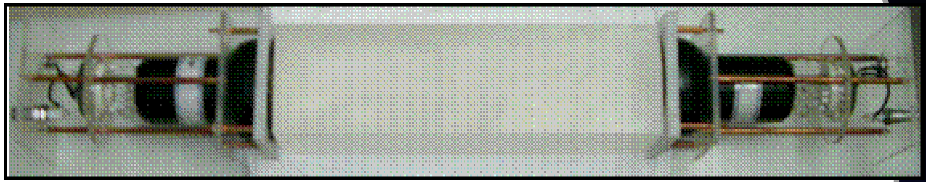
HPGe detector(PPC)
CoGeNT



Dark matter Search (KIMS)

Elastic Scattering of WIMP off a nucleus in the detector

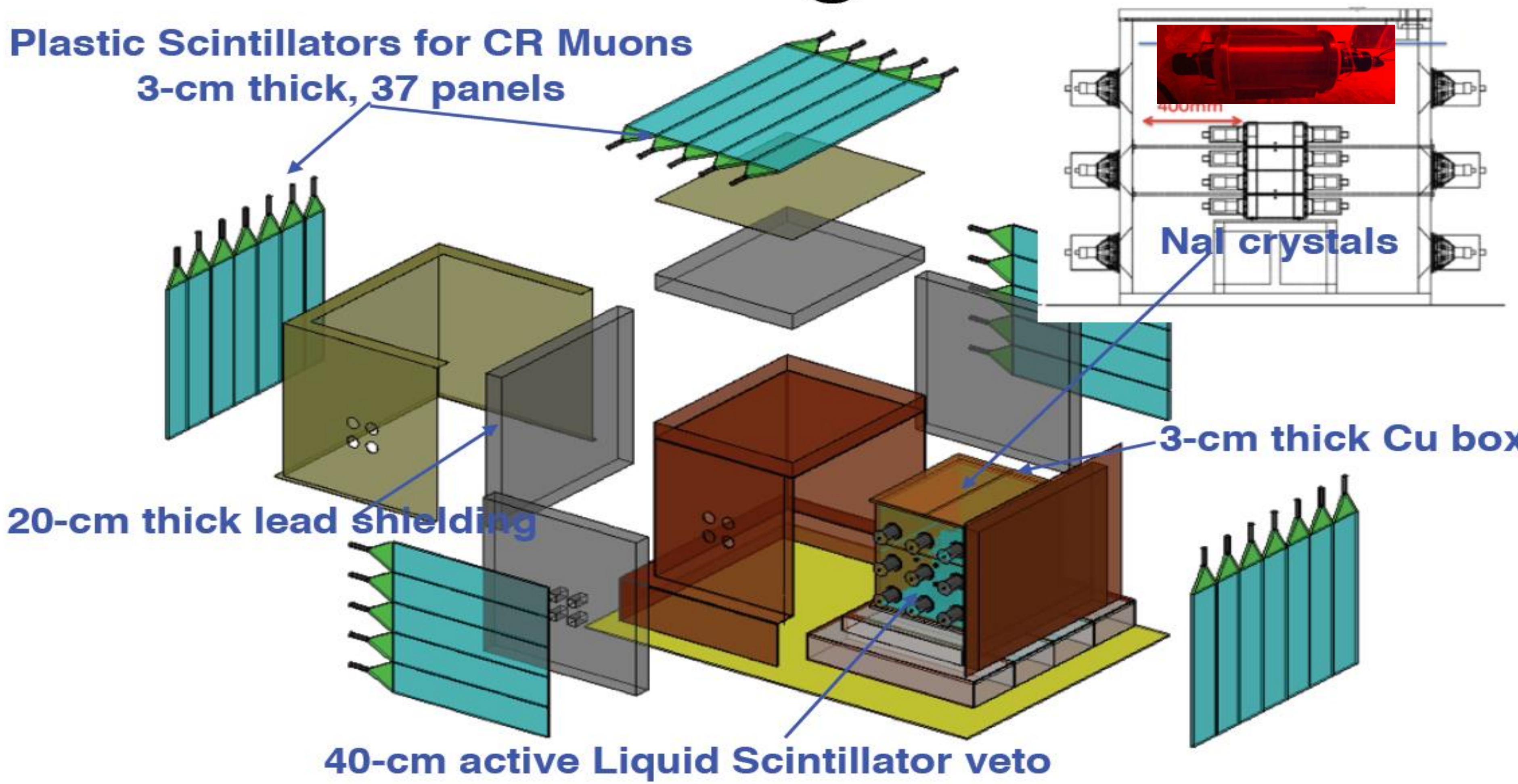




Energy loss by ionization(scintillation) and lattice vibration

COSINE @Y2L, KOREA

New Shielding Structure



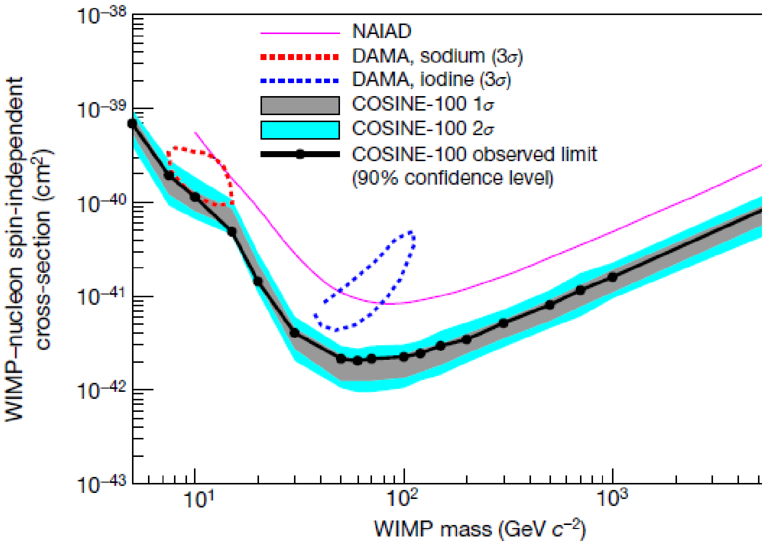
LETTER

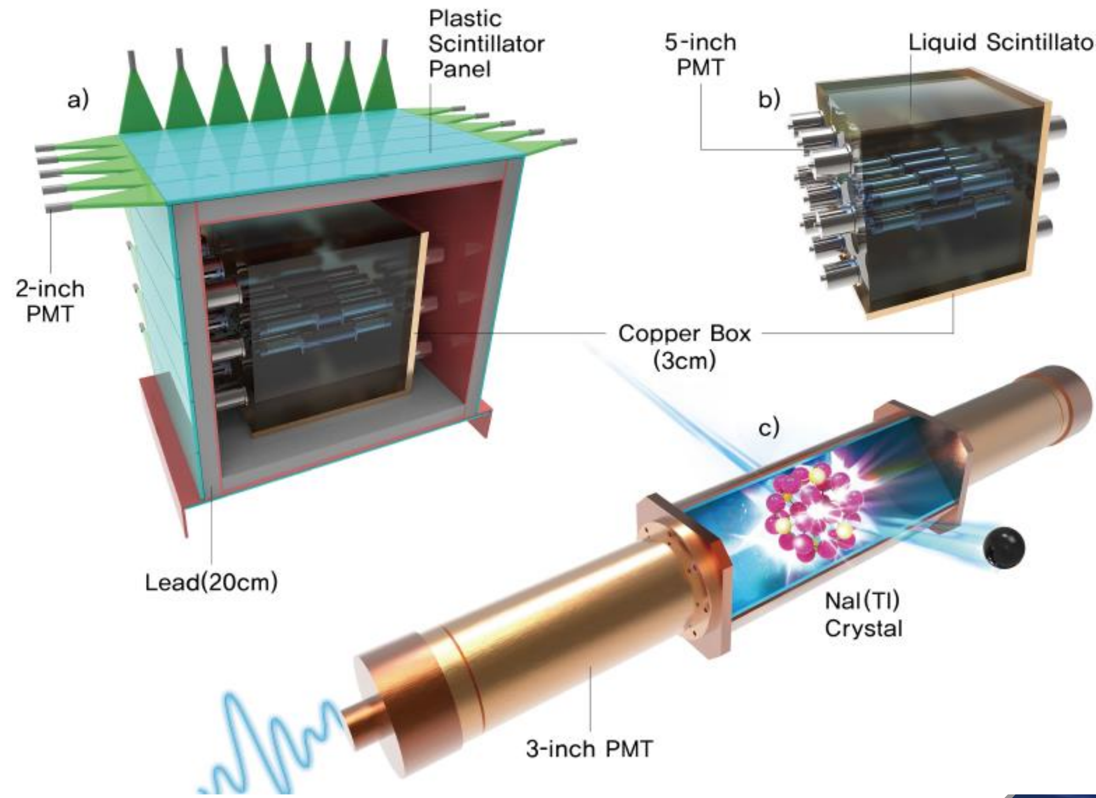
Nature

https://doi.org/10.1038/s41586-018-0739-1

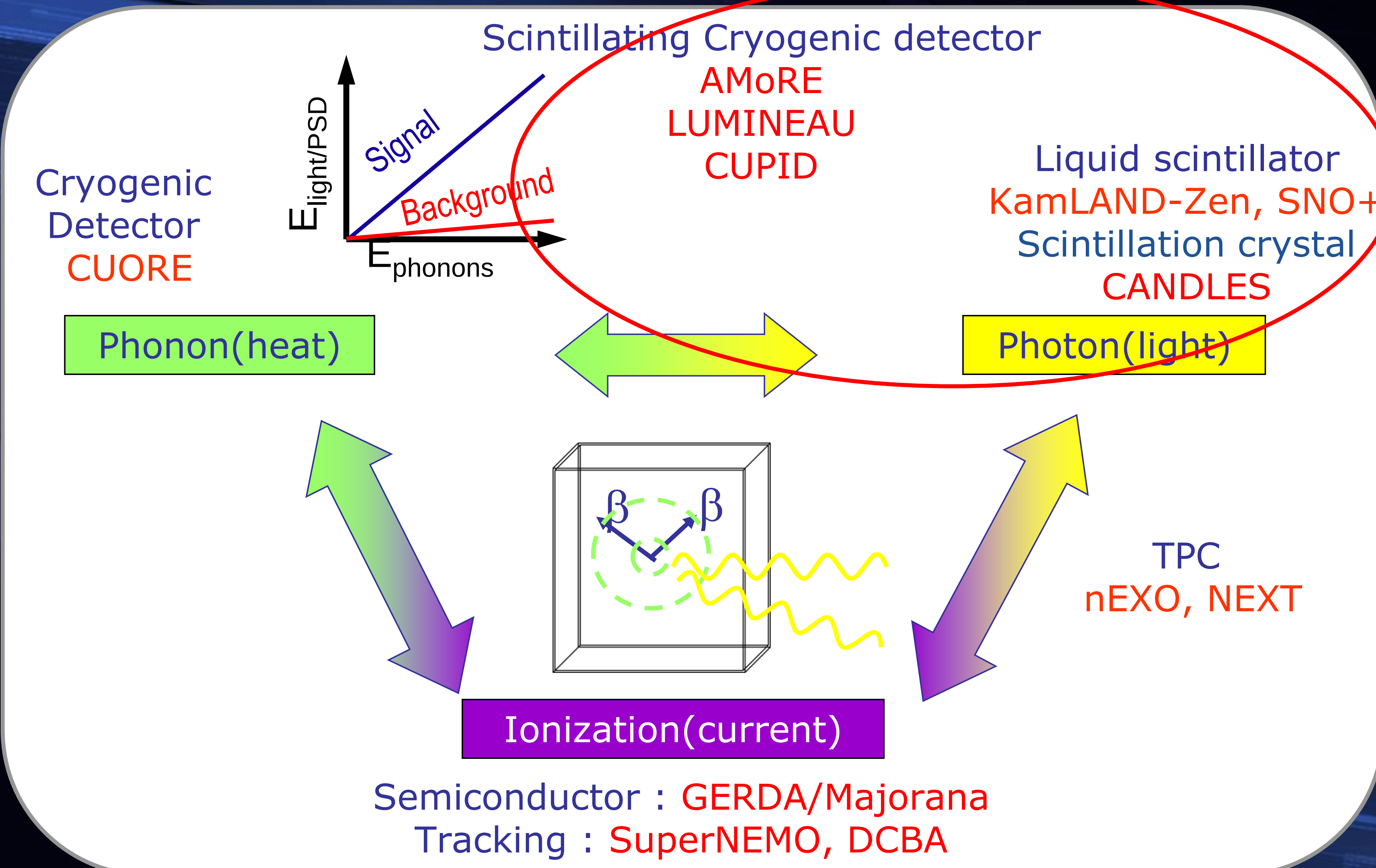
An experiment to search for dark-matter interactions using sodium iodide detectors

The COSINE-100 Collaboration*





Double beta decay detection technique



AMoRE-II: Mo crystals grown and tested

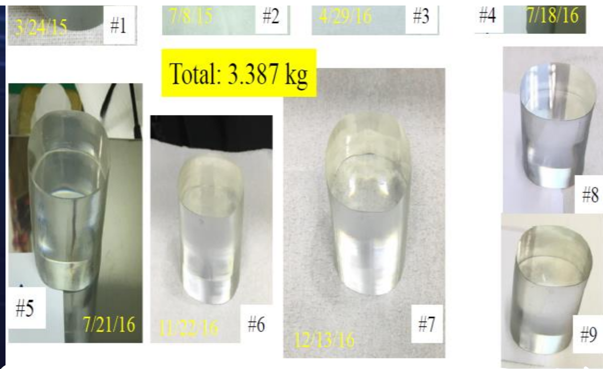
ORIGINAL PAPER

CRYSTAL Research & Technology

www.crt-journal.org

Search for New Molybdenum-Based Crystal Scintillators for the Neutrino-Less Double Beta Decay Search Experiment

HongJoo Kim, Indra Raj Pandey, Arshad Khan, Ju-Kyung Son, Moo Hyun Lee,* and Yeongduk Kim*

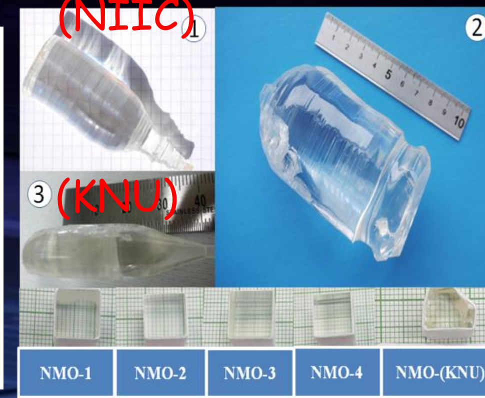


O (CUP)

NMO (KNU)

(NIIC)

(KNU)



PMO (NIIC)

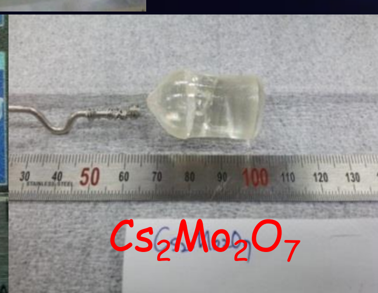
LMO (KNU)

AMCRYS

CMO (NIIC)

CMO (CARAT)

Cs_2MoO_4



$Cs_2Mo_2O_7$

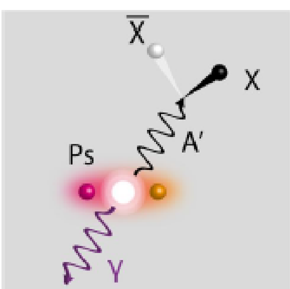
$Cs_2Mo_3O_{10}$

LMO (CUP)

The Final Goal

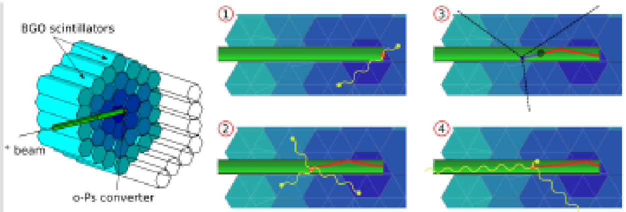
- Positronium: C-violation & QED test & rare decay
- Invisible decay
  - → Experimentally interesting branching ratio of the order of 10^{-8}
  - → Extra-demensions
  - → Milli-Charged particles
  - → Darkmatter of a mirror particle type
  - → Axion
  - → Dark photon

Search of invisible decay



Searching for light dark matter through Positronium decay

Eur. Phys. J. D (2018) 72: 44



First search for invisible decays of orthopositronium confined in a vacuum cavity

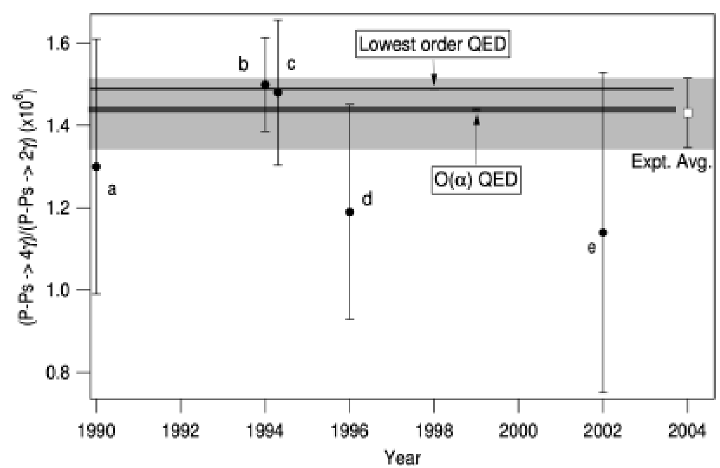
PHYS. REV. D 97, 092008 (2018)

Search for C-violation

- C-violation
  o-Ps -> 4 γ search
  o-Ps -> 2 γ search

- Approximate calculation
  10^8 → ~10^{-7} (10^{-6}) : 10 times improvement

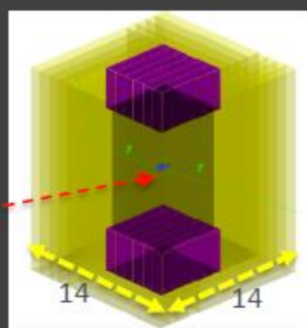
High order QED process Rare decay



Positronium decay experiment

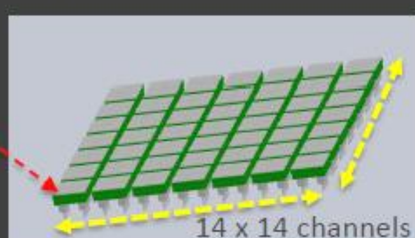
Full Design of Detector

- The trigger part is surrounded by the gamma detection part with an array of 14 x 14 BGO scintillators (7.5 x 7.5 x 150 mm³)

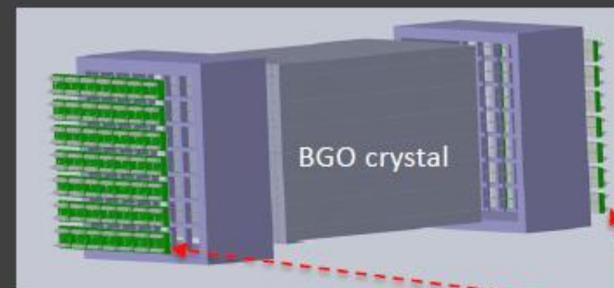


- For dual readout both sides of the BGO scintillators are coupled with 7 x 7 arrangement of 2 x 2 arrays for a total of 14 x 14 SiPMs

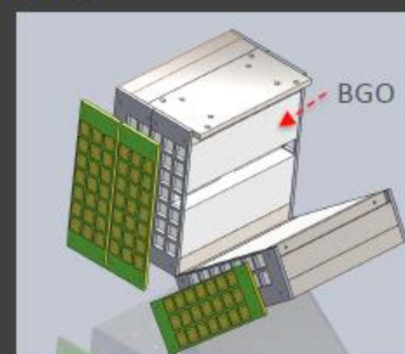
4 channel
(2 x 2 arrays)



1st Design



2nd Design



1 channel

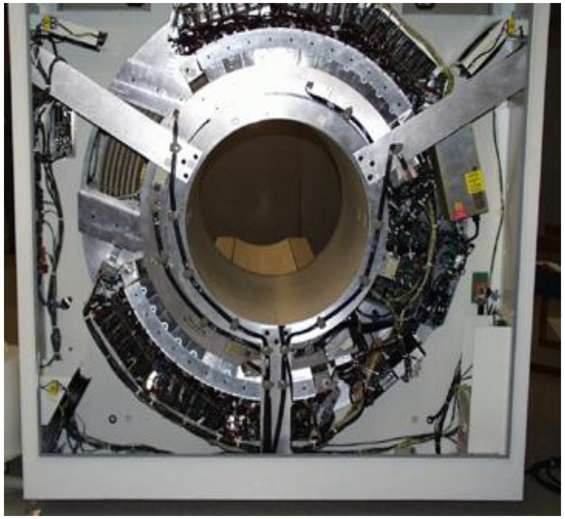
Trigger
Signal line

Trigger
Gas chamber

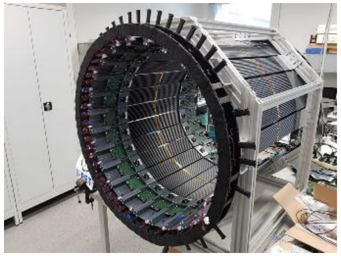
Calorimeter, PET and Ps decay

Calorimeter

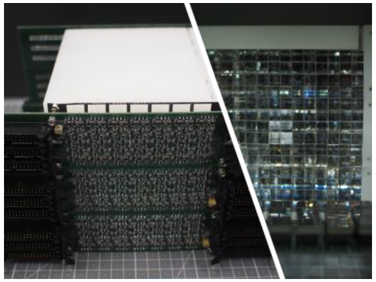
PET Camera



Ps decay



JPET

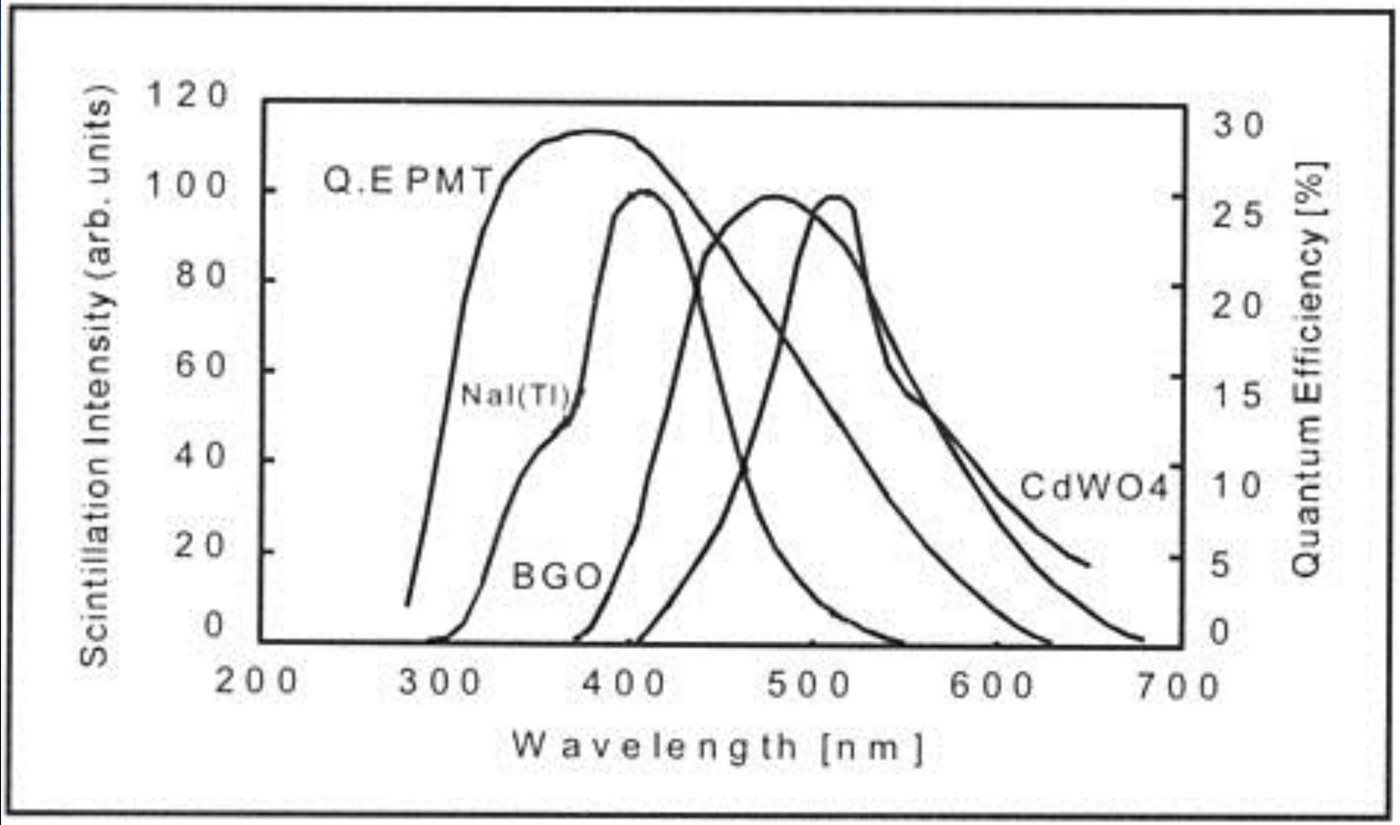


KAPAE

- Cylindrical Gamma Ray Detectors
- High Efficiency, Hermetic
- Segmented, High Density Scintillator Crystals

Thank you for
your attention

Emission Spectra of Scintillators



Emission spectra of NaI(Tl), BGO and $CdWO_4$, scaled on maximum emission intensity.

GAGG:Ce

- Recent development on high light output oxide crystal
  : $Gd_3Al_2Ga_3O_{12}$:Ce (GAGG:Ce by Yoshikawa group) :
  (46,000 ph/MeV (Yoshikawa), ~76,000 ph/MeV(TPS)

=> Column structure by Vapor deposition?

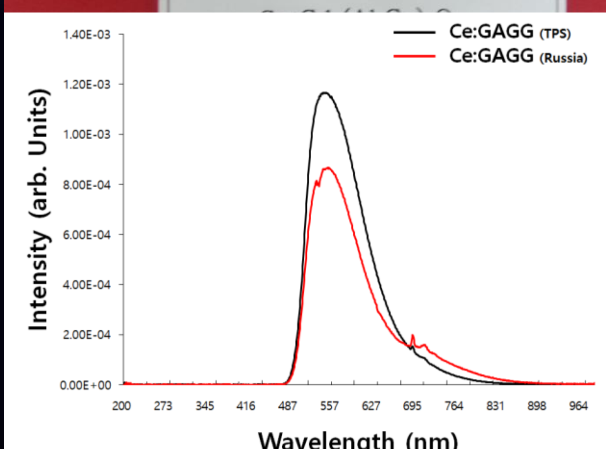
Journal of Ceramic Processing Research. Vol. 16, No. 00, pp. 1~5 (2015)

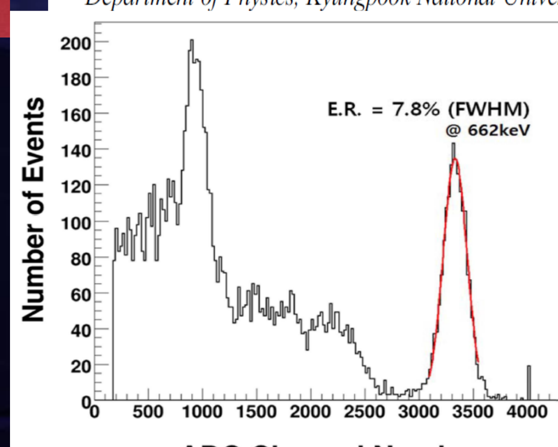
JOURNAL OF
Ceramic Processing Research

Scintillation properties of the $Gd_3Al_2Ga_3O_{12}$: Ce crystal

Hye-Lim Kim[a], Hong-Joo Kim[a,*], Eun-Jung Jang[a], Won-Guen Lee[b], Moon-Kwang Ki[b], Heun-Duk Kim[b], Gu-Sik Jun[b] and Vladimir Kochurikhin[c]

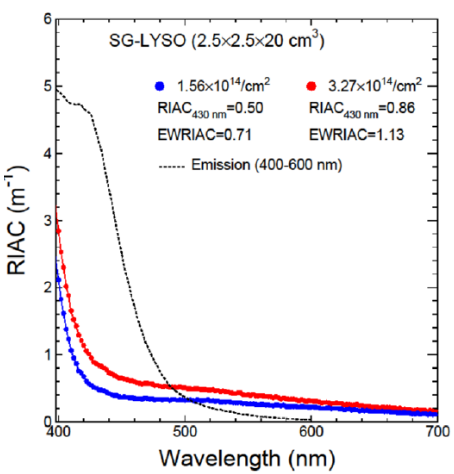
[a]*Department of Physics, Kyungpook National University, Daegu 702-701, Korea*





경북대학교 물리 및 에너지학부

Radiation hardness of Crystal Calorimeter

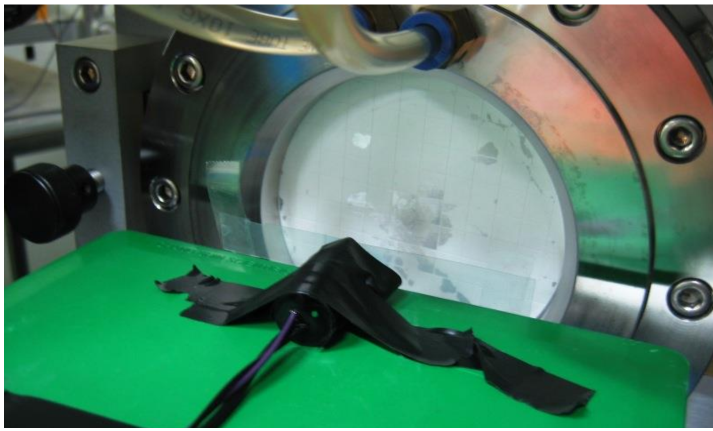


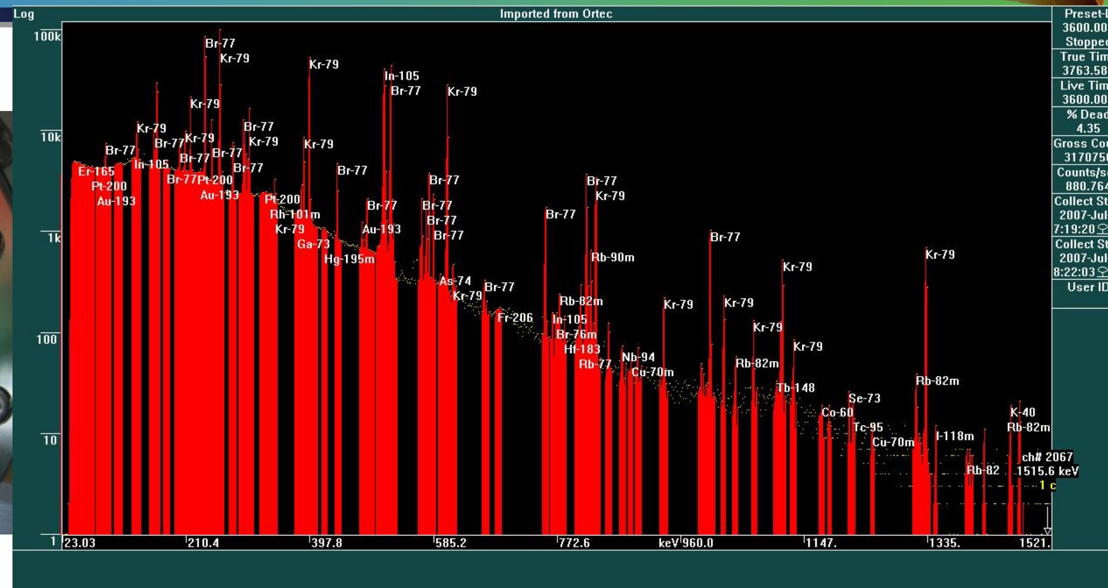
Measured Values at about E14, and extracted to 3E14 p/cm^2

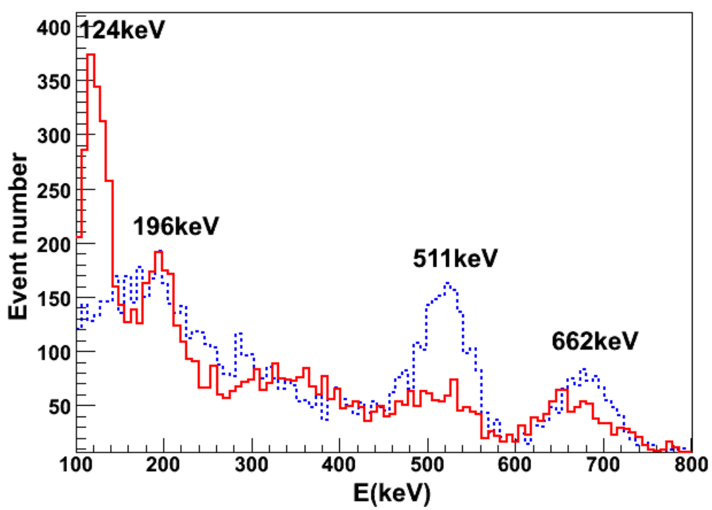
Crystal	Dimensions (mm^3)	ID	Emission Peak (nm)	Fluence (p/cm^2)	RIAC at EP (1/m)	@ 3E+14
BGO	25×25×200	SIC-BGO	480	1.77E+14	14.7	24.9
CeF_3	$22^2×26^2×150$	SIC-CeF	340	1.40E+14	17.4	37.3
LYSO	25×25×200	SG-LYSO	430	3.27E+14	0.86	0.8
LFS	25×25×180	OET-LFS	430	3.55E+14	3.7	3.1
PWO*	$28.5^2×30^2×220$	SIC-PWO	420	1.80E+14	> 36	> 60

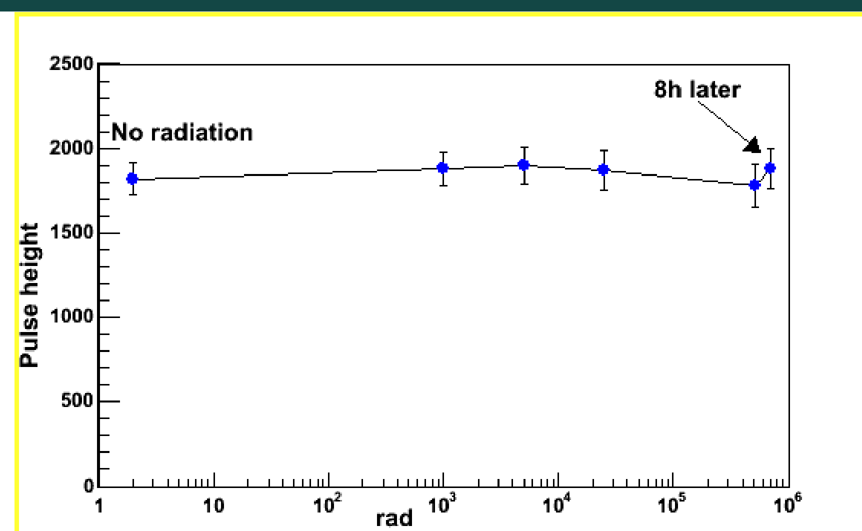
LYSO is the most radiation hard among all tested at LANL

LYSO radiation hardness by by proton beam

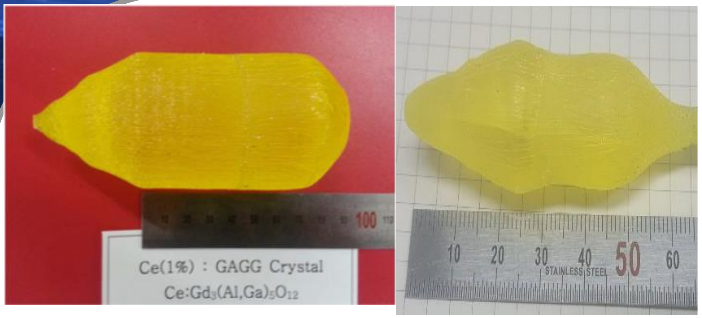




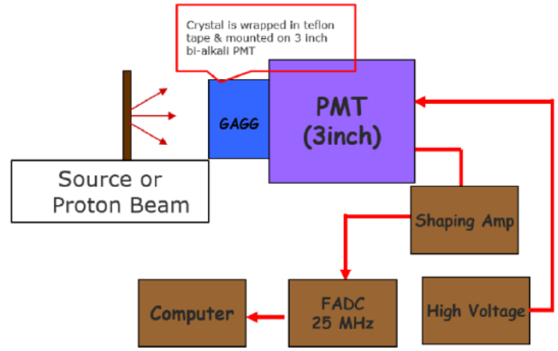


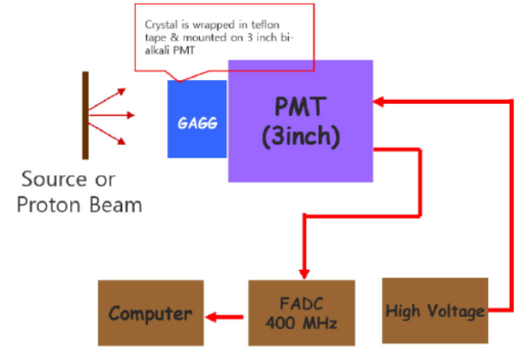


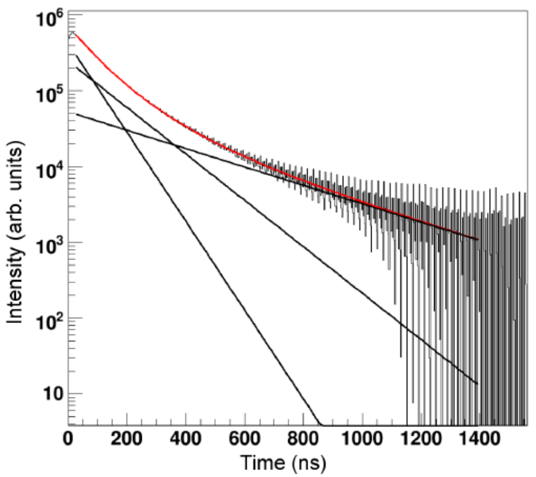
Proton test with Gd3Al2Ga3O12:Ce

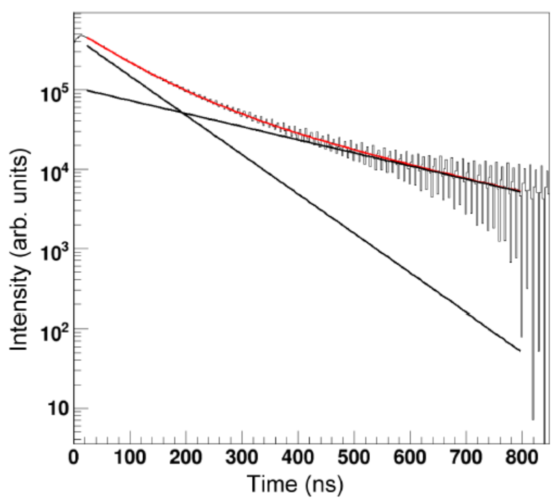


GAGG crystal grown by Co. and KNU

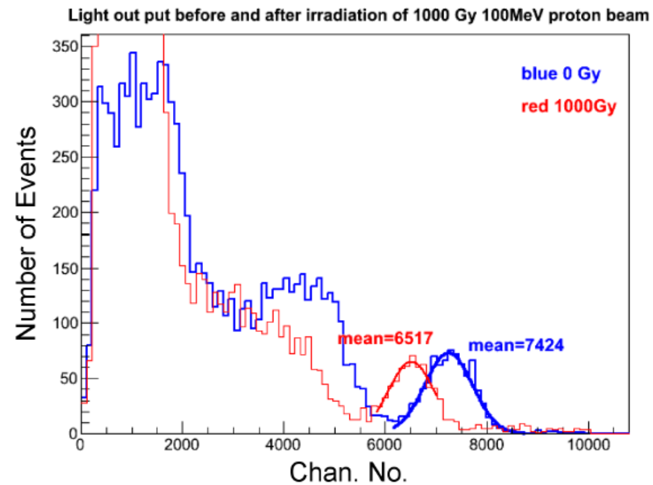








Decay time before and after proton irradiation
No significant change is observed (87, 263 nm)



Light yield change after 1000 Gy proton (12% lower)