High Density Glass & Its Application at Future Collider

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The Institute of High Energy Physics, CAS

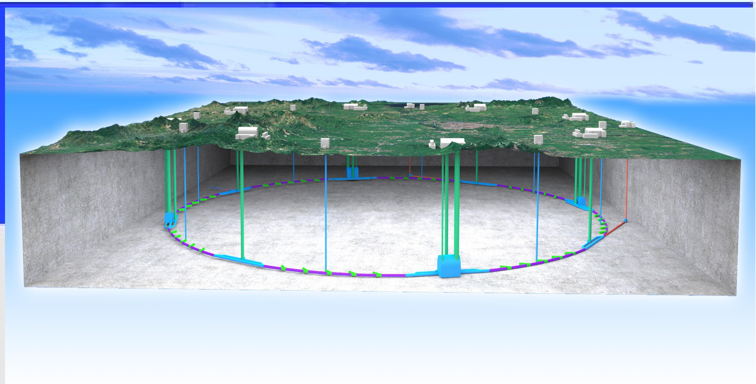
2023. Feb. 12th

Mini-workshops in Theory & Experiment and Detector HKUST Jockey Club Institute for Advanced Study, HKUST

Outline

- 1. The Motivation and Design;
- 2. The Test Facilities for GS;
- 3. The Progress of GS;
- 4. Summary and Next plan;

1.1 The GS-HCAL of CEPC

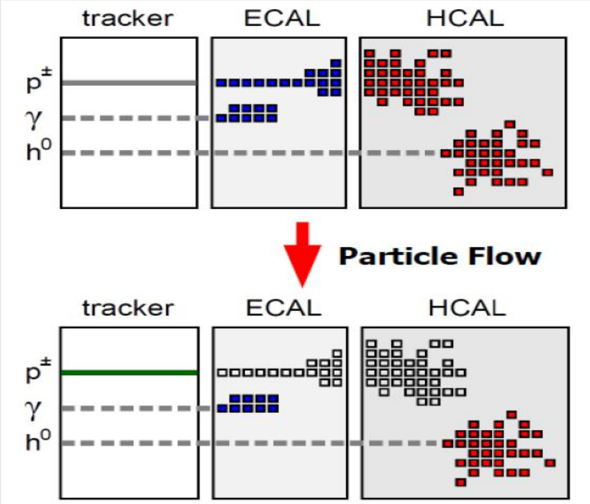


Future electron-position colliders (e.g. CEPC)

- Main physical goals: precision measurements of the Higgs and Z/W bosons
- Challenge: unprecedented jet energy resolution $\sim 30\%/\sqrt{E(GeV)}$

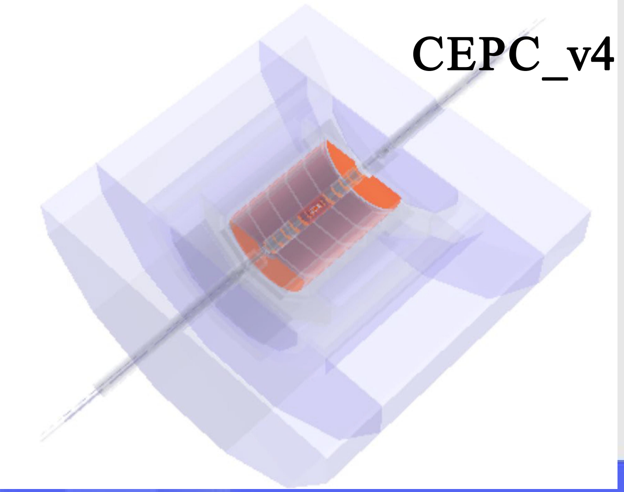
CEPC detector: highly granular calorimeter + tracker

- Boson Mass Resolution (BMR) ~4% has been realized in this baseline design
- Further performance goal: BMR 4%→3%
- Dominant factors in BMR: charged hadron fragments & HCAL resolution



New Option: Glass Scintillator HCAL (GS-HCAL)

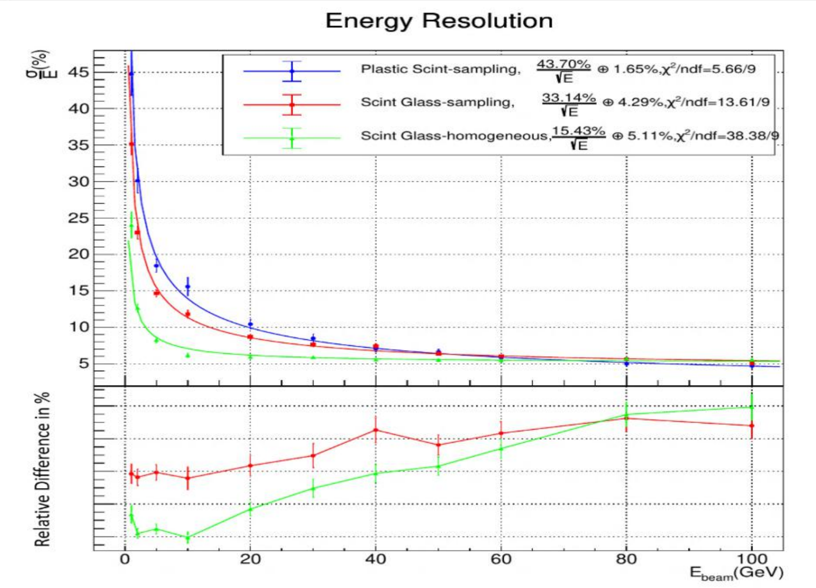
- Higher density provides higher energy sampling fraction
- Doping with neutron-sensitive elements: improve hadronic response (Gd)
- More compact HCAL layout (given 4~5 nuclear interaction lengths in depth)



1.2 The Simulation for GS-HCAL

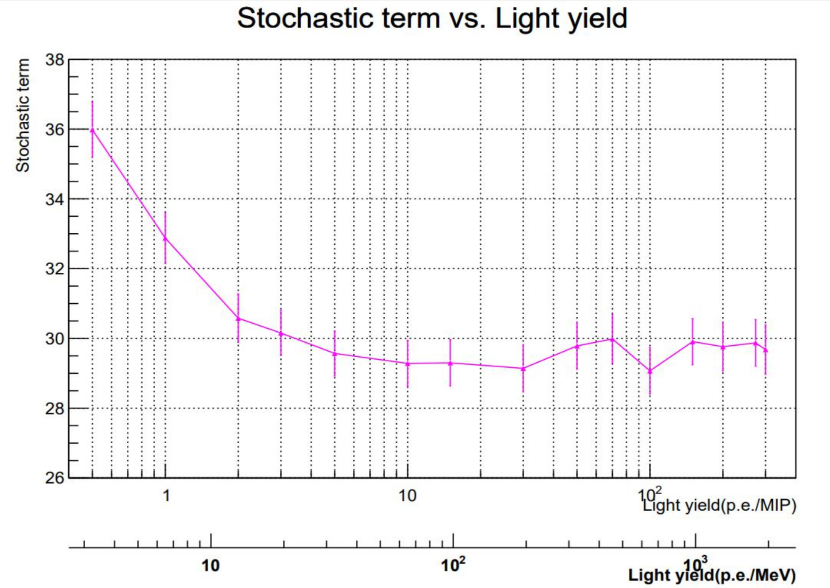
How to achieve the optimized energy resolution (Boson Mass Resolution, BMR)

➢ Impact of Scintillator type



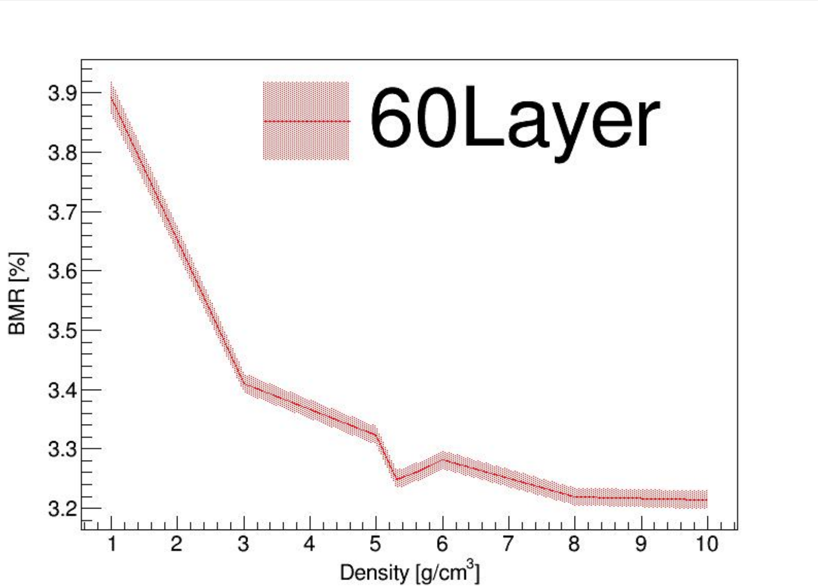
Plastic Scintillator vs Glass Scintillator: GS has better hadronic energy resolution in low energy region (<30GeV)

➢ Impact of Light Yield



A light yield of 100 p.e./MIP or 1000p.e./MeV seems to be good enough for better BMR;

➢ Impact of Density

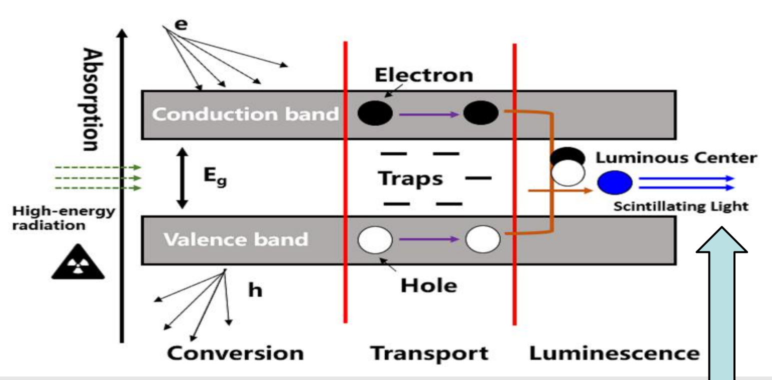


Glass density ~ 6 g/cm3 is a relatively reasonable target, which can guarante a good BMR (~3.3%) and feasibility in R&D

1.3 Target of Glass Scintillator

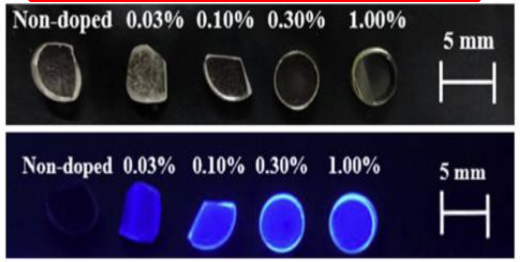
Key parameters	Value	Remarks
➢ Tile size	~30×30 mm^2	Reference CALICE-AHCAL, granularity, number of channels
➢ Tile thickness	~10 mm	Energy resolution, Uniformity and MIP response
➢ **Density**	**5-7 g/cm^3**	More compact HCAL structure with higher density
➢ **Intrinsic light yield**	**1000-2000 ph/MeV**	Higher intrinsic LY can tolerate lower transmittance
➢ Transmittance	~75%	
➢ MIP light yield	~150 p.e./MIP	Needs further optimizations: e.g. SiPM-glass coupling
➢ Energy threshold	~0.1 MIP	Higher light yield would help to achieve a lower threshold
➢ Scintillation decay time	~100 ns	Mitigation pile-up effects at CEPC Z-pole (91 GeV)
➢ Emission spectrum	Typically 350-600 nm	To match SiPM PDE and transmittance spectra

1.4 The Design of the Glass Scintillator



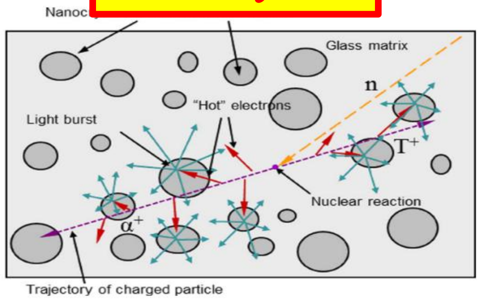
- Scintillation mechanism---- **Luminescence Center**
- **Conversion**—photoelectric effect and Compton scattering effect;
- **Transport**—electrons and holes migrate;
- **Luminescence**—captured by the luminescent center ions

Lanthanide elements



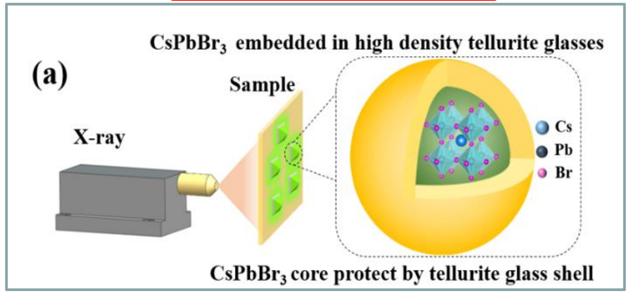
Journal of Alloys and Compounds 782 (2019) 859-864

Nanocrystals



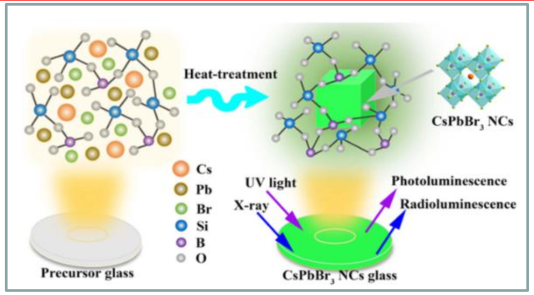
IEEE TNS 60 (2) 2013

Quantum Dots



Optics Letters 46(14) 3448-3451 (2021)

Lanthanide + Quantum Dots



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- High Light Yield: Lanthanide for the Luminescence Center: Cerium（Ce）；
- High Density and Low radioactivity background: Gadolinium（Gd）；

1.5 The GS R&D Collaboration Group

- GS Production
  - Development
  - Mass production
- GS Research
  - Optical test
  - Mechanical test
  - Irradiation test
- GS HCAL Design
  - Simulation
  - SiPM Research
  - Single Tile Test
- GS Application
  - Unclear Detection
  - Others

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China Building Materials Academy
中国建筑材料研究院

China Jiliang University
中国计量大学

Harbin Engineering University
哈尔滨工程大学

Harbin Institute of Technology
哈尔滨工业大学

Sichuan University
四川大学

Glass Scintillator Collaboration

闪烁玻璃合作组
Glass Scintillator Collaboration

-- The Glass Scintillator Collaboration Group established in Oct.2021；

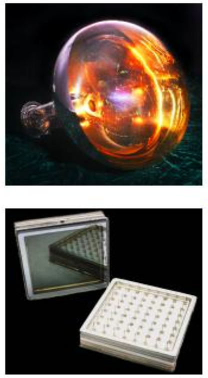
-- The Experts of the GS in the University, Institute and Industry are still welcomed to join us (qians@ihep.ac.cn).

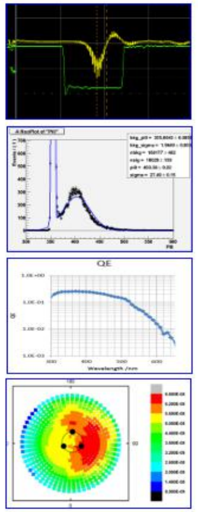
Outline

- 1. The Motivation and Design;
- 2. The Test Facilities for GS;
- 3. The Progress of GS;
- 4. Summary and Next plan;

2.1 Test Facilities -- the PMT Lab in IHEP

- PMT

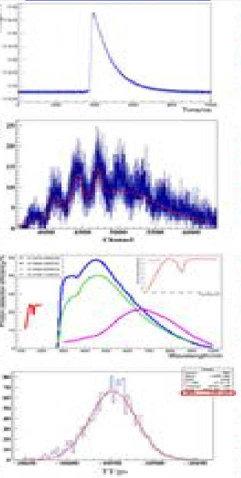




Others
……

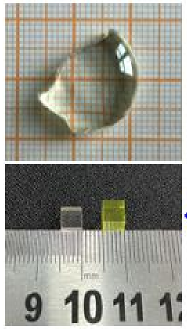
- Anode Pulse Rise Time;
- Pre/Late/After Pulse;
- Dark Count
- The Single Photoelectron Spectrum;
- The voltage distribution (BASE) ;
- The Supply voltage;
- Typical Gain Characteristic;
- Anode Dark Current
- Spectral Response;
- Wavelength of Maximum Response;
- Cathode Sensitivity: Luminous(2856K);
- Quantum efficiency with λ
- Photocathode efficiency Area;
- Photocathode efficiency Uniform;
- The position of the Sb, K, Cs;
- The linearity of the PMT
- Magnetic characteristics;
- Transit Time Spread (FWHM)

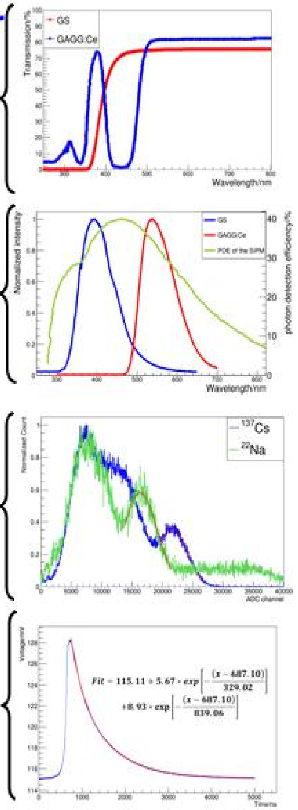
- SiPM



- Pixel Number;
- Photosensitive Area;
- Breakdown Voltage;
- Over Bias
- Typical Gain Caracteristic;
- Dark Count;
- Optical Crosstalk;
- Dynamic Range and Linearity
- The Single Photoelectron Spectrum;
- Photon Detection Efficiency;
- Pulse Width;
- Amplitude
- Pulse Rise Time;
- Fall Time;
- Transit Time;
- Transition Time Spread

- The Scintillator Test System





- Density;
- Elastic Modulus;
- Refractive Index;
- Transmission Spectrum
- Absorbance;
- Excitation Spectrum;
- Emission Spectrum;
- PL QY
- Light Yield;
- Energy Resolution;
- Decay time;
- Afterglow
- Coincidence Time Resolution;
- Neutron/Gamma Discrimination;
- Irradiation Damage

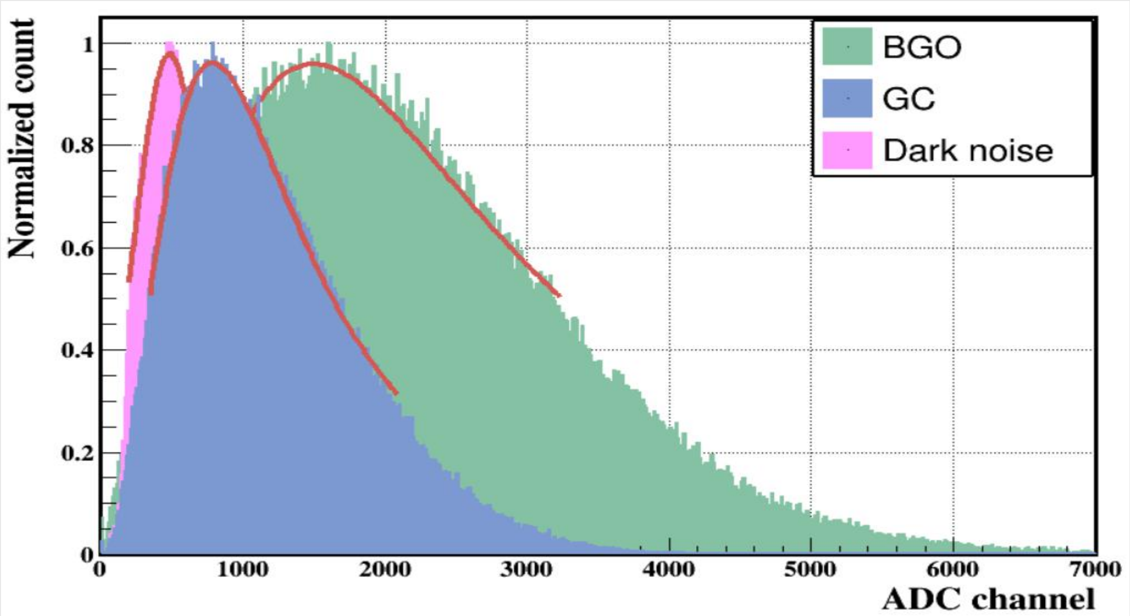
Others
……

- XPS
- XRD

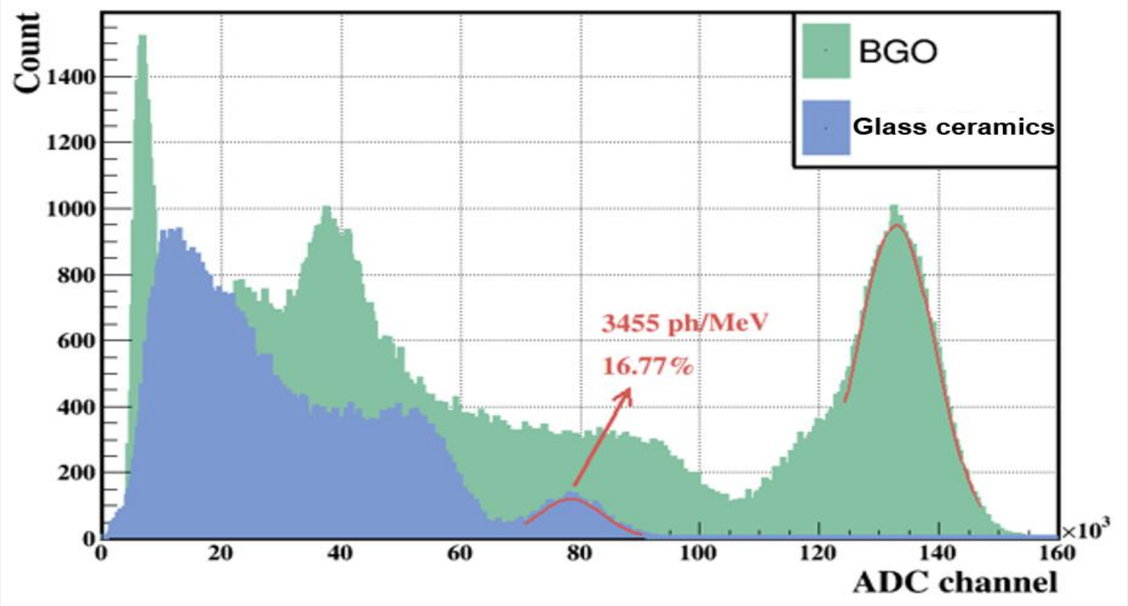
2.2 The Light Yield Test （1）--Energy Spectra

Light Yield @gamma-ray VS @ X-ray

➢ X-Ray Energy Spectra



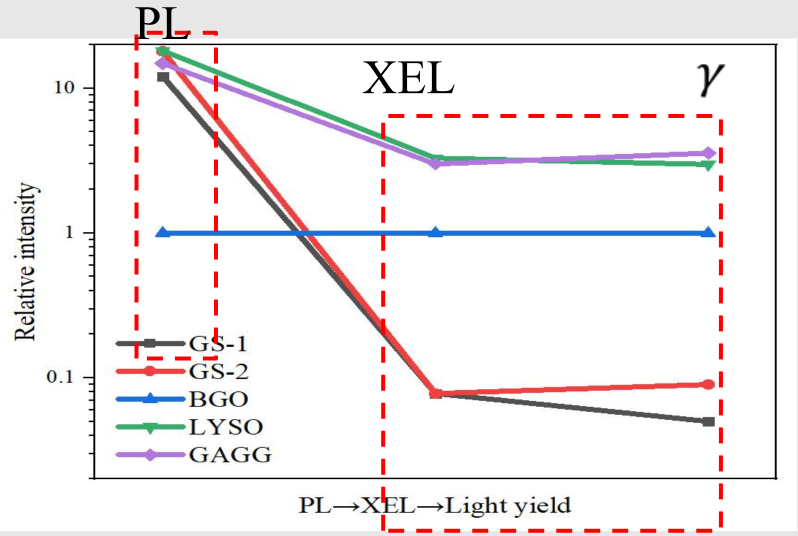
➢ ^{137}Cs γ-Ray Energy Spectra

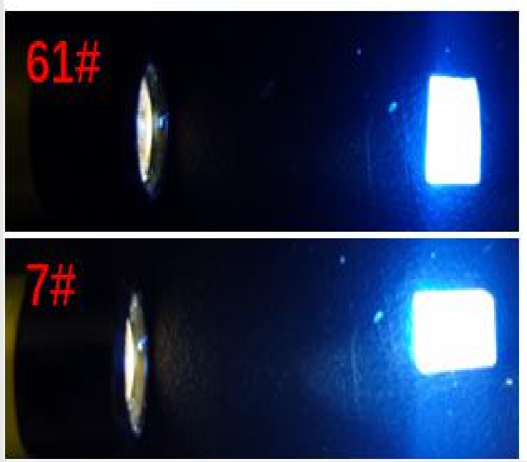


- Under X-ray, the photon number of the Gass Ceramic detected by SiPM is about **32%** of BGO crystal;
- Under ^{137}Cs, the photon number of the Gass Ceramic detected is about **59%** of BGO crystal;
- Therefore, the relative light yield of glass scintillator under X rays is not equal to γ rays.

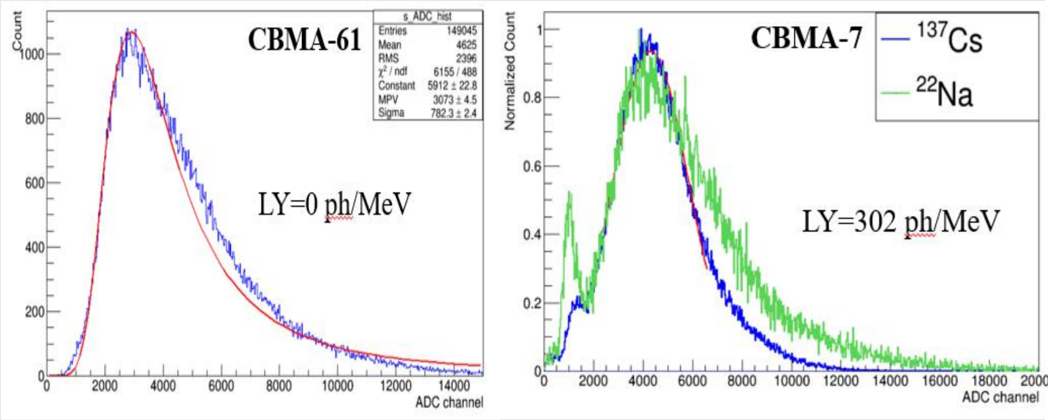
2.2 The Light Yield Test （2）--Emission Spectra

Light Yield @gamma-ray VS @ PL



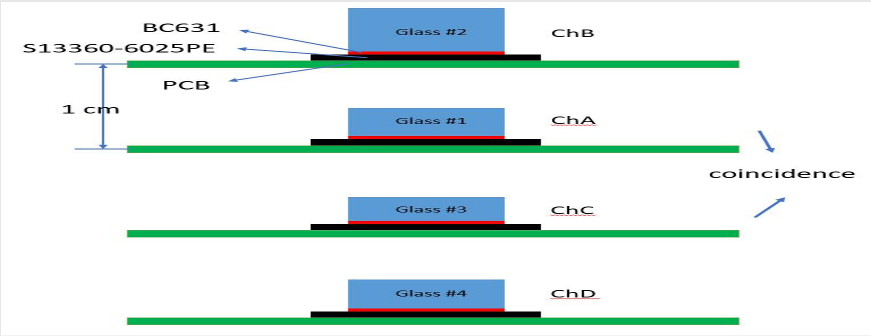


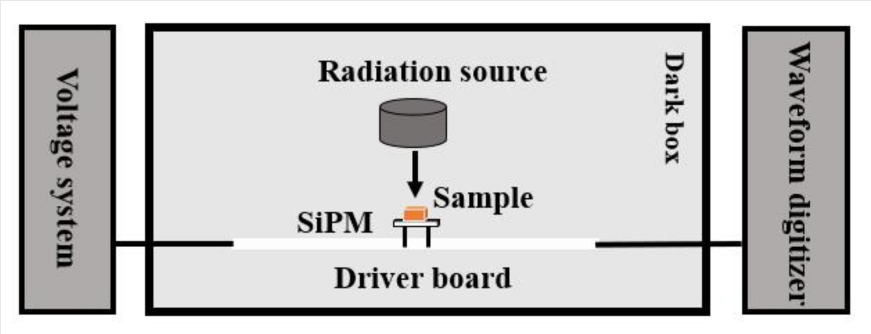
➢ γ-Ray Energy Spectra

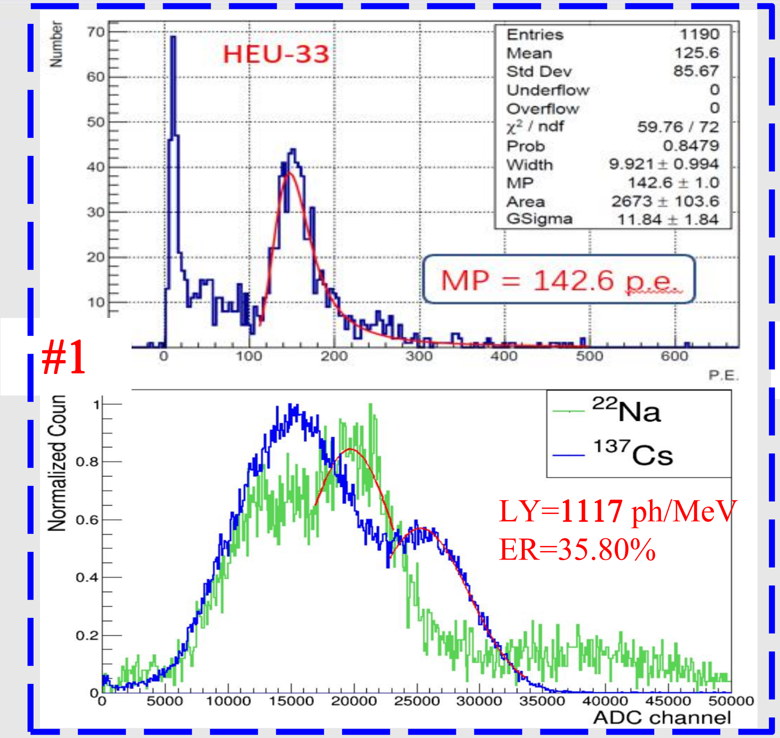


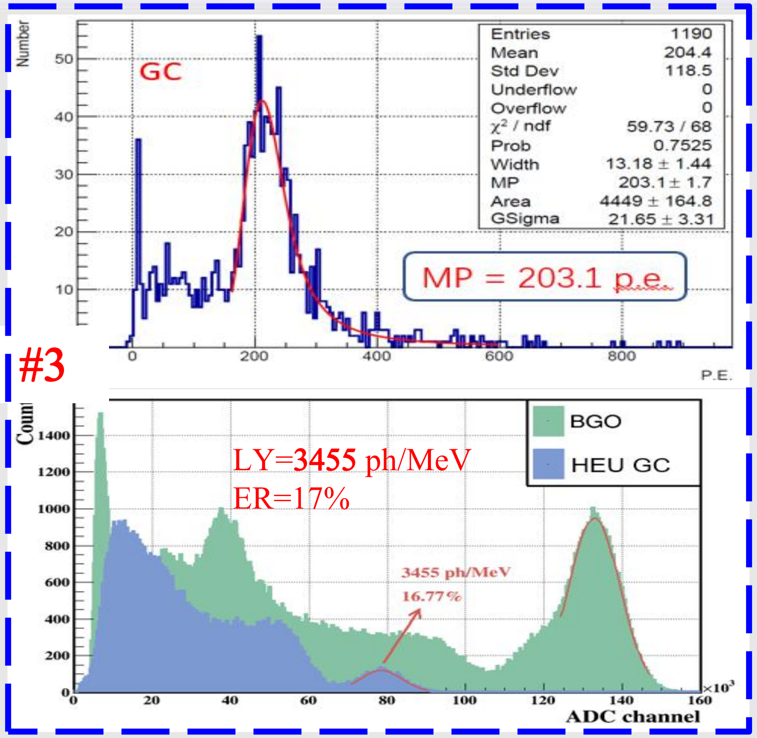
- In a crystal, the XEL intensity is equal to light yield under γ-ray. But its not the case with glass scintillators due to defects and broken bonds.
- Photoluminescence(PL) is not related to its scintillation properties；
- We can obtain high yield glass scintillator in fast, avoid the wrong direction of research， only test the light yield@gamma-ray .

2.2 The Light Yield Test （3）--Cosmic Ray Test









- Considering the density and thickness of the glasses, the MIP response by the cosmic ray is consistent with the light yield of the glass scintillator by gamma ray.

	MIP（p.e.）	LY（ph/MeV）	Thicknes（mm）	Density（g/cm³）	mip/(Thi*Den)	LY/MIP
#1	143	1117	2.6	5.4	10.2	**110**
#3（GC）	203	3455	2	3.3	30.6	**113**

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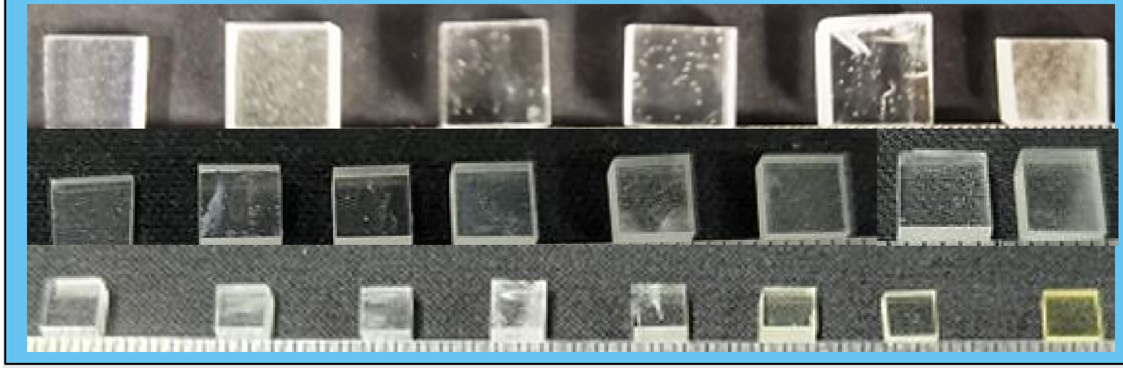
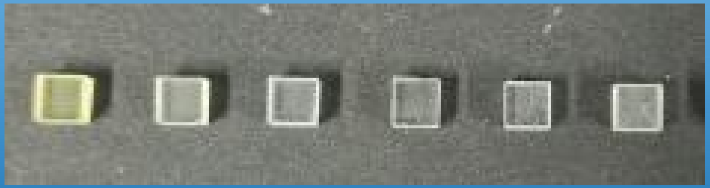
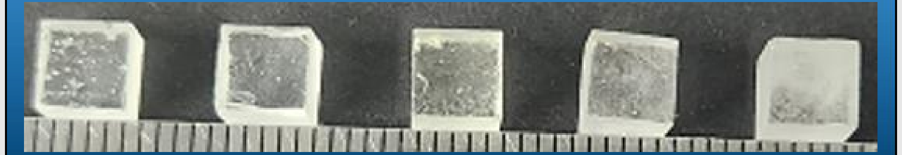
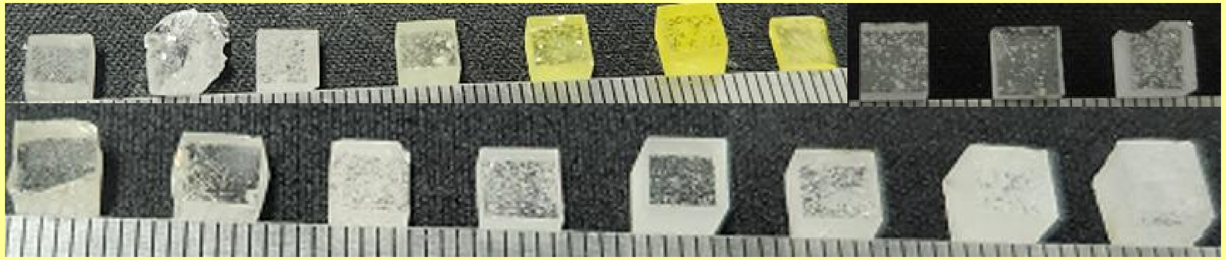
3.1 The GS Samples produced in one year（>200）



Gd-Ga-B-Ce^{3+} glass
20mm*20mm*12mm

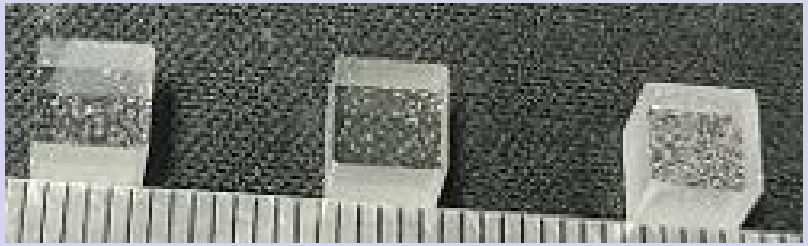






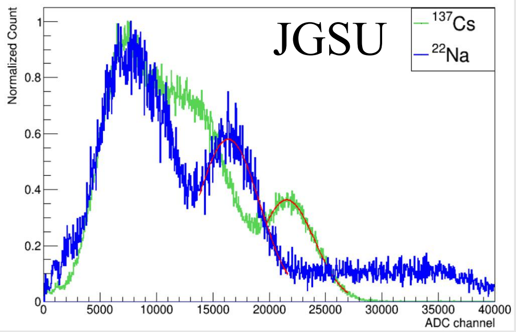
Gd-Al-B-Si-Ce^{3+} glass
42mm*51mm*10mm

Gd-Al-B-Si-Ce^{3+} glass
37mm*30mm*9mm



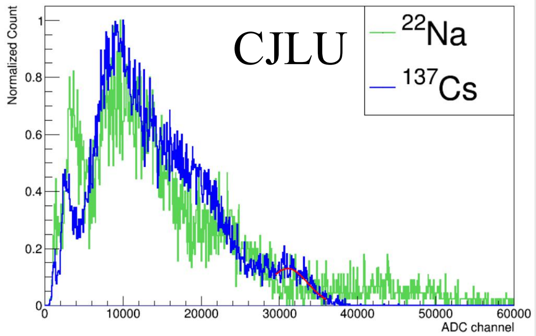
3.2 Borosilicate Glass（Gd-Al-B-Si-Ce^{3+}）

- Density~4.5 g/cm^3
- LY=802 ph/MeV
- ER=26.77%



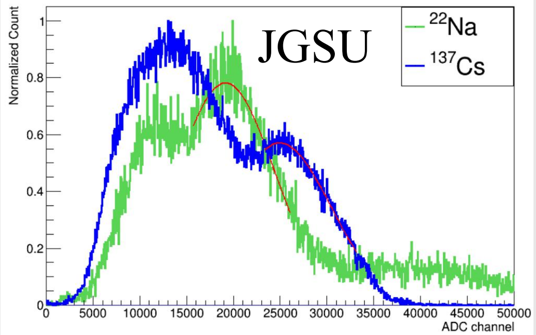
2021.11

- Density~4.0 g/cm^3
- **LY>1200 ph/MeV**
- ER=23.22%



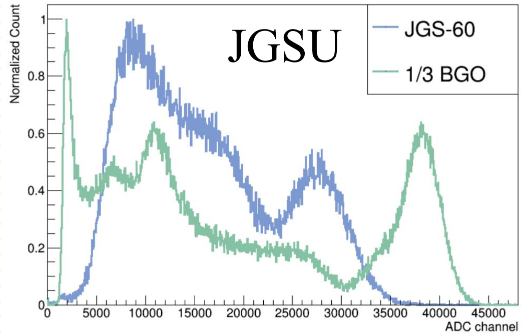
2022.06

- **Density~6.0 g/cm^3**
- LY>1000 ph/MeV
- ER=49.55%

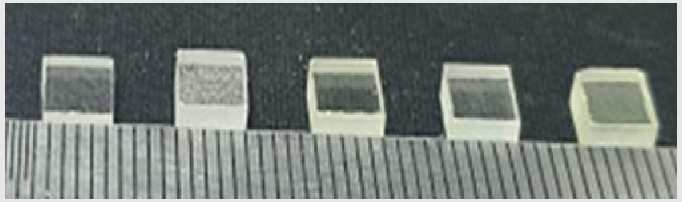
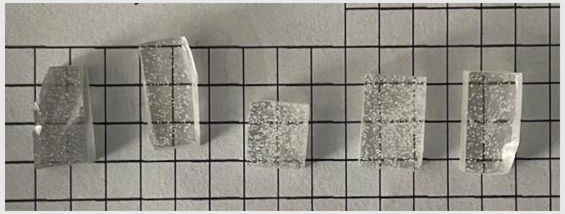
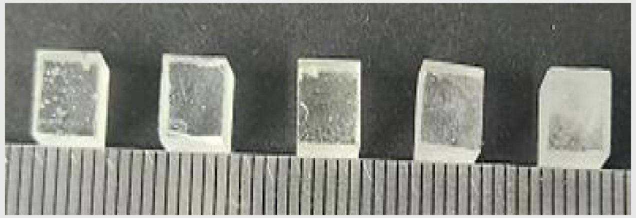
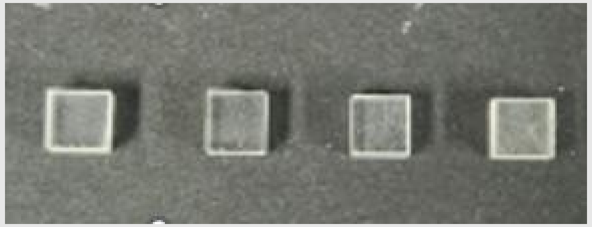


2022.11

- Density~6.0 g/cm^3
- LY>1200 ph/MeV
- **ER=27.12%**



2023.02

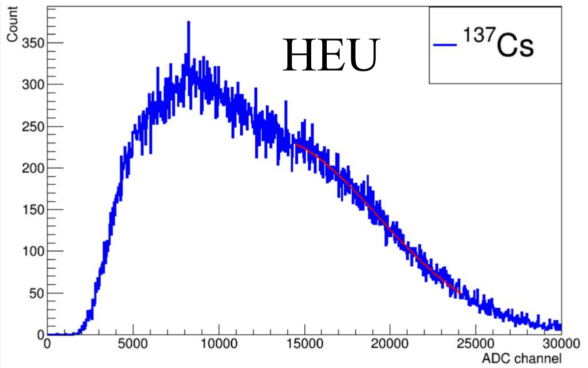





(2022.05)Opt. Mater. 2022(130): 112585

3.3 Glass Ceramic（Gd-Y-K-Si-Ce^{3+}）

About Glass Ceramic could be seen in these Ref.
(2021.07) Opt. Lett. (2021), 46(14), 3448;
(2021.11) J. Mater. Chem. C, 2021, 9, 17504;
(2022.11) J. Eur. Ceram. Soc., 2022;

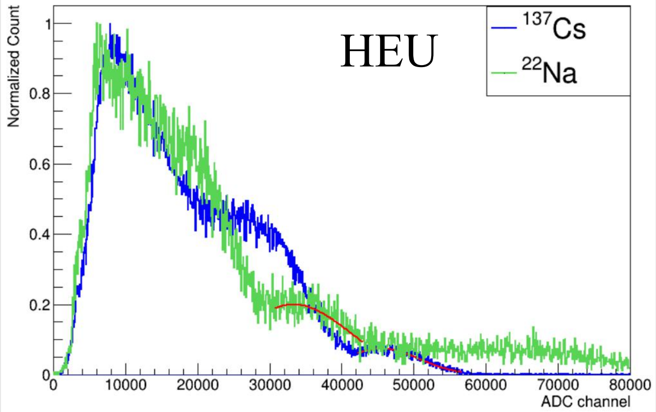
- Density~ 3.3 g/cm^3
- LY=519 ph/MeV
- ER=None



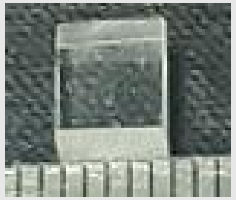
2022.04

(2022.10) J. Mater. Chem. C, 2021, 9, 17504

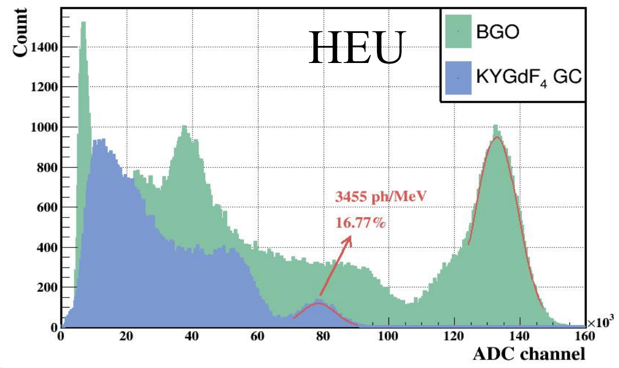
- Density~ 3.3 g/cm^3
- LY>1600 ph/MeV
- ER=27.27%



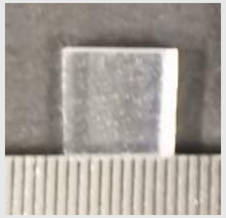
2022.10



- Density~3.3 g/cm^3
- **LY>3400 ph/MeV**
- ER=16.77%



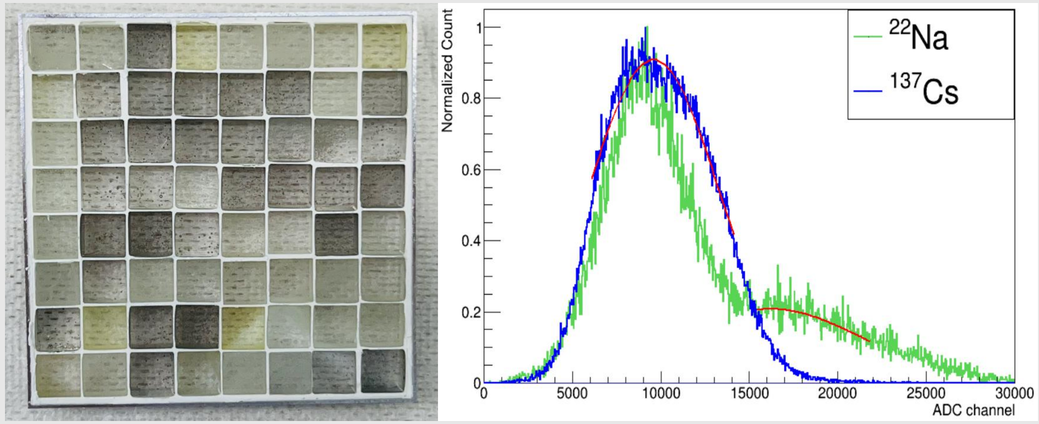
2022.11



3.4 The Bottleneck

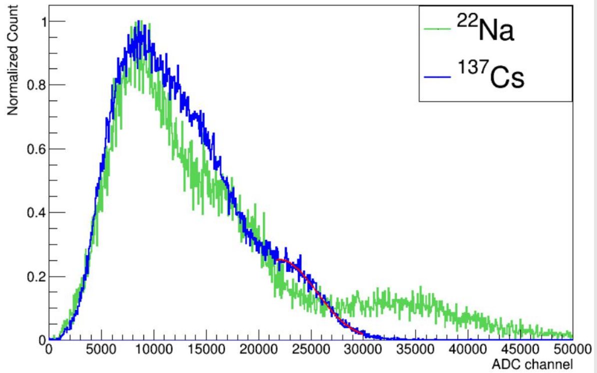
➢ Sample Array in Factory

to be more: The Uniformity ?



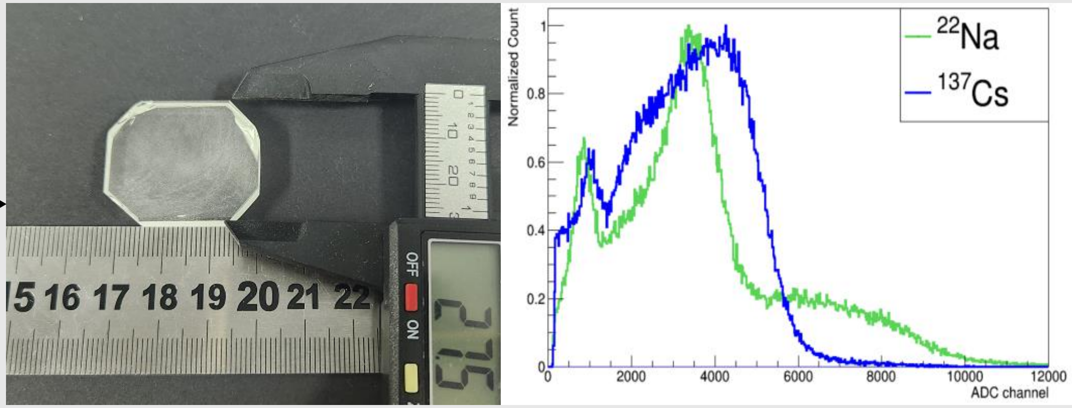
LY=346 ph/MeV

➢ Small Sample in the Collage Lab



LY=923 Ph/MeV； ER=37.12%

➢ Large Sample in Factory



to be Large: The Repeatability ?

LY=466 ph/MeV

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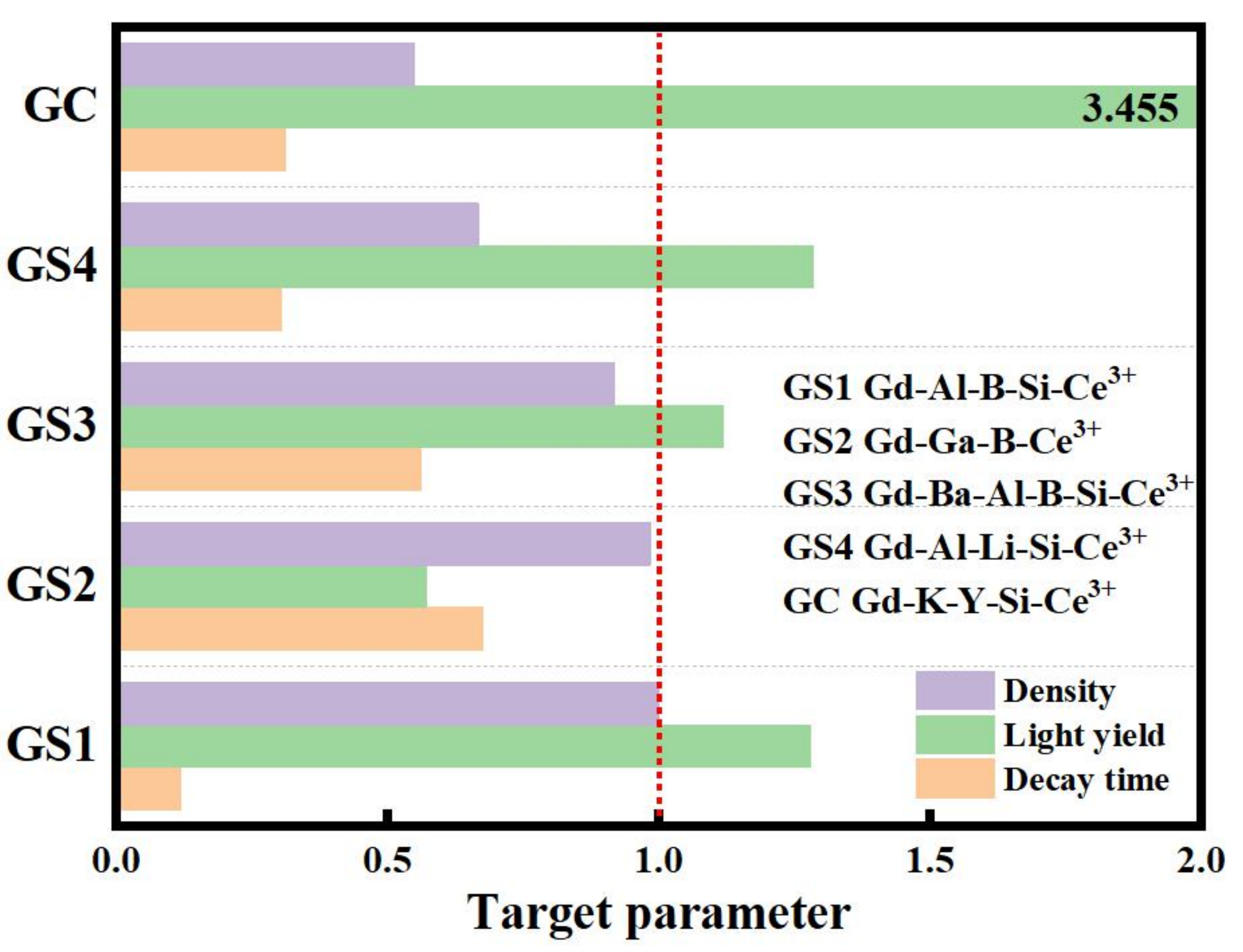
4.1 Summary



Glass scintillator of good Energy Resolution, High Density and High Light Yield

- **6.0 g/cm³ & 1279 ph/MeV with 27.12% @662keV — Gd-Al-B-Si-Ce^{3+} glass**
  - Ultra-high density **Tellurite Glass**—6.6 g/cm³
  - High light yield **Glass Ceramic**—3500 ph/MeV
  - Fast scintillating Decay Time—100 ns
  - Large size Glass—42mm*51mm*10mm

4.2 The Scintillator data

Typy	Composition	Density (g/cm^3)	Light yield (ph/MeV)	Decay time (ns)	Emission peak(nm)	Price/1 c.c (RMB)
Glass Scintillator in Paper	Ce-doped high Gadolinium glass[1]	4.37	3460	522	431	~10
	Ce-doped fluoride hafnium glass[2]	6.0	2400	23.4	348	150
Plastic Scintillator	BC408[3]	~1.0	5120	2.1	425	60
	BC418[3]	~1.0	5360	1.4	391	80
Crystal	GAGG:Ce[4]	6.6	50000	50	560	2400
	LYSO:Ce[5]	7.1	30000	40	420	1200
	BGO[6]	7.3	8000	300	480	800
Glass Scintillator for CEPC	?	>6	>1000	< 100	350-500	~1
Stuaus of Glass Scintillator	?	>6	>1000	< 200	350-500	~?

[1] Struebing, C . Journal of the American Ceramic Society, 101(3). [2] Zou, W. Journal of Non-Crystalline Solids, 184(1), 84-92 . [3] Plastic Scintillators | Saint-Gobain Crystals. [4] Zhu, Y. Qian, S. Optical Materials, 105, 109964. [5] Ioannis, G. Nuclear Instruments & Methods in Physics Research. [6]Akapong Phunpueok, et al. Applied Mechanics and Materials, 2020,901:89-94.

4.3 Next Plan

Gd-(Ba/Al)-B-Si -Ce^{3+} glass will be the focus of future research.

- The glass scintillators were prepared repeatedly to ensure its performance stability;
- The properties of the glasses will be further improved through **raw material purification;**
- To reduce the scintillation decay time of the glasses (<100 ns);
- To produce the large size and mass preparation samples;
- Test the radiation resistance and mechanical properties of the glasses;
- Explore the structural properties of the glasses.

闪烁玻璃合作组
Glass Scintillator Collaboration

See the unseen
change the unchanged

The Innovation

THANKS