Research on Enhancing the Performance of Glass Scintillator

闪烁玻璃合作组
Glass Scintillator Collaboration

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The Institute of High Energy Physics, CAS

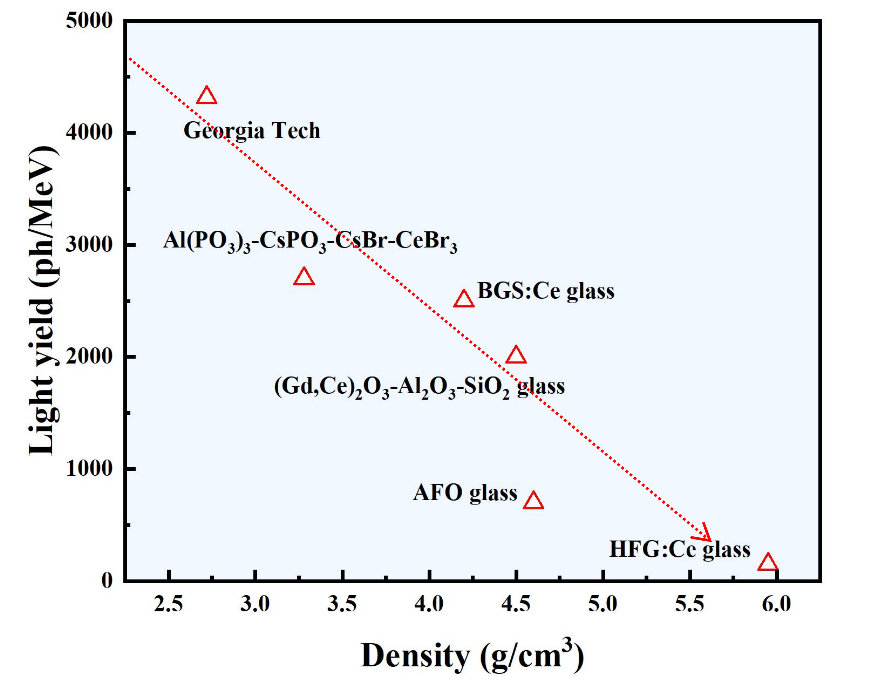
Outline

- 1. Status of Glass Scintillator（GFO）
  - 1.1. Performance Target
  - 1.2. Progress of High Density GS
  - 1.3. How to Improve the Light Yield
- 2. Challenges in Enhancing Light Yield
  - 2.1. Raw Material Purity
  - 3.2. Wavelength Shift
  - 3.3 Density, Light Yield and Decay Time
  - 3.4. Microcrystallization

1.1 Performance target of GS

	2021.09 (1st Meeting)	2024.05 (7th Meeting)	2024.10 (8th Meeting)	2025.09 (9th Meeting)	2026	
	Target	Realization	Target	Realization	Target (ECAL)	Target (HCAL)
Dimension (mm^3)	/	5 × 5 × 5	40 × 40 × 10	40 × 40 × 10	20 × 20 × 20	40 × 40 × 20
Density (g/cm^3)	6.0	5.93	6.0	>6.0	6.0	
Transmittance (%@400 nm)	>75	~70	>80	76	>80	
Emission peak (nm)	~400	~400	~400	390	~400	
Light yield (ph/MeV)	1000	985	1500	1408	2000	1000
Energy resolution (%@662keV)	/	30.3	/	28.7	<25	
Decay time (ns)	<100	35.8(10.7%), 105.1	<500	72.4 (10.5%),547.8	?	
Attenuation length (cm@400nm)	/	/	/	6.05	>10	

1.2 History of High Density GS（1）in Ref.



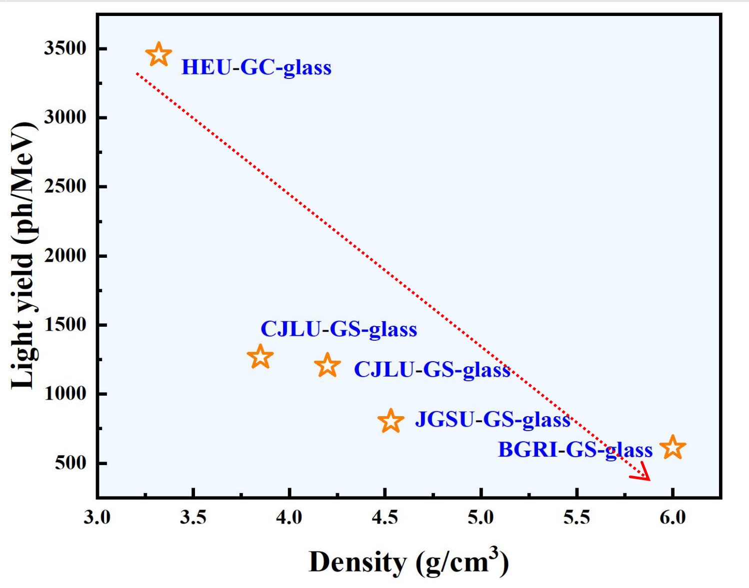
Scintillator	Density (g/cm^3)	Light yield (ph/MeV)	Year
$Li(Al_y,Gd_{1-x-y},Ce_x)Si(O,F,Br)$ glass [1] C. Struebing, et al., J. Am. Ceram. Soc., 2017, 101, 1116–1121.	2.72	4317	2017
$Al(PO_3)_3$-$CsPO_3$-CsBr-$CeBr_3$ [2] Y. Nakabayashi, et al., J MATER SCI-MATER EL, 2022, 33, 19846–19853.	3.28	2700	2022
DSB:Ce glass [3] V. Dormenev, et al., Nucl. Instrum. Methods Phys. Res. A, 2021, 1015, 165762.	4.2	2500	2015
$(Gd,Ce)_2O_3$-Al_2O_3-SiO_2 glass [4] A. Amelina, et al., J. Non-Cryst. Solids, 2022, 580, 121393.	4.5	2000	2022
AFO glass [5] C. Hu, et al., Nucl. Instrum. Methods Phys. Res. A, 2020, 954, 161665.	4.6	700	2020
HFG:Ce glass [6] E. Auffray, et al., Nucl. Instrum. Methods Phys. Res. A, 1996, 380, 524-536.	5.95	150	1996

- The introduction of heavy elements and structural densification： difficult to balance density and light yield

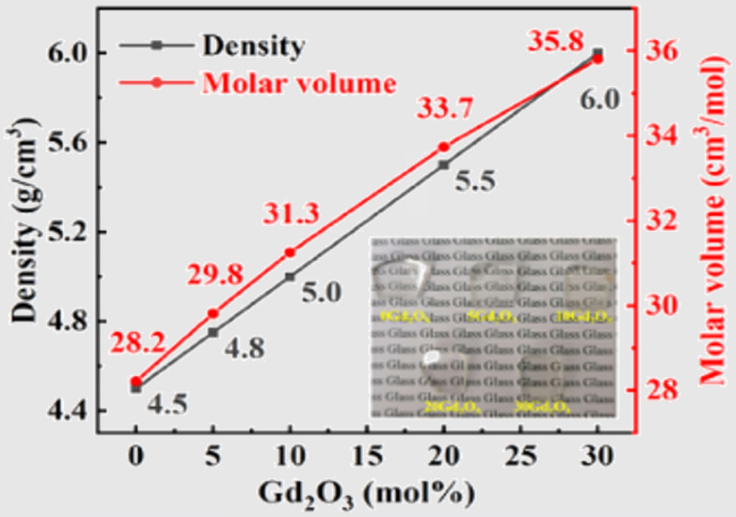
→ High Density → more severe Self-absorption → Low Light Yield

Is it possible to find a way to achieve both high density and high light yield in the Glass Scintiallator?

1.2 History of High Density GS（2）in GS group

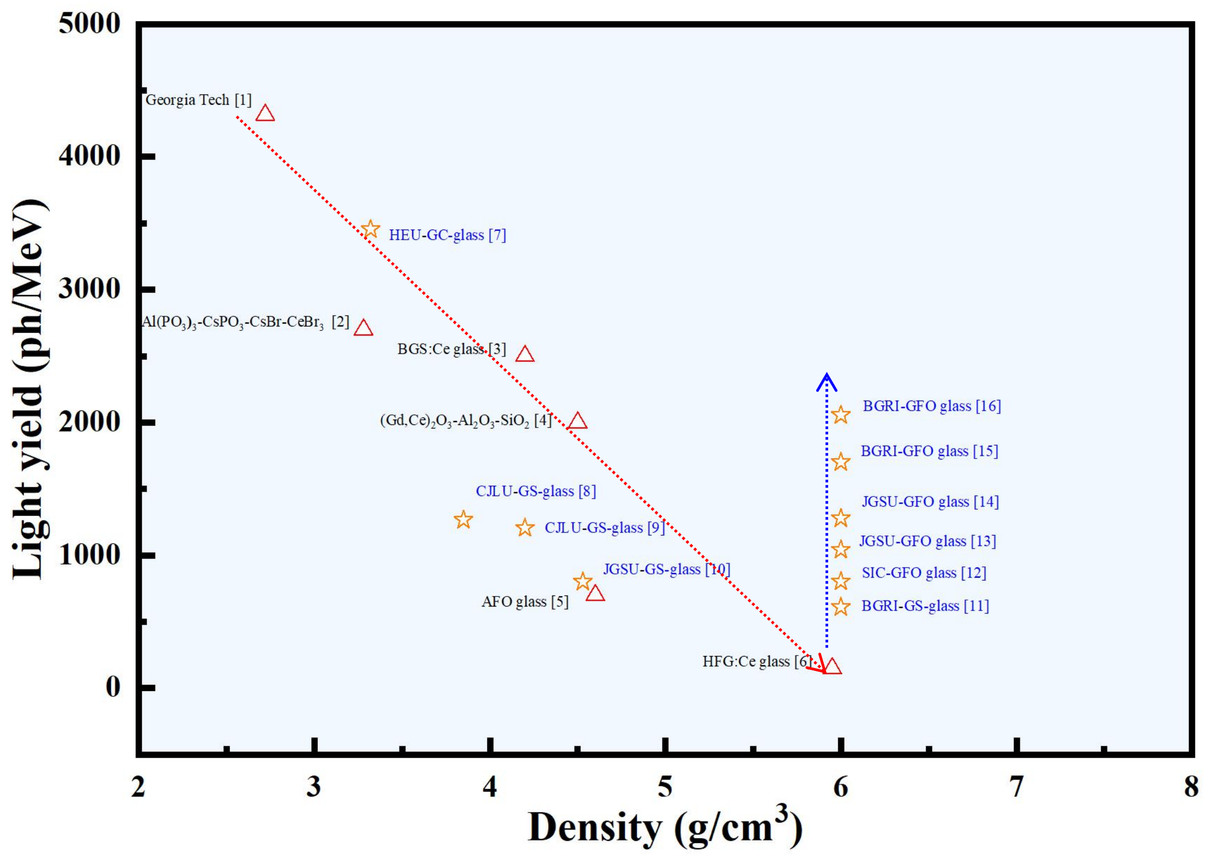


Scintillator	Density (g/cm³)	Light yield (ph/MeV)	Mean decay (ns)	Year
HEU-GC-glass [7] C.X. Luo, et al., ACS AMI, 2023, 15, 46226-46235.	3.32	3455	275.4	2023
CJLU-GS-glass [8] Z.H. Hua, et al., Ceram. Int., 2023, 49, 18844-18851.	3.85	1267	1730.4	2023
CJLU-GS-glass [9] T. Wu, et al., J. Am. Ceram., 2023, 106, 476-487.	4.20	1206	1363.6	2022
JGSU-GS-glass [10] G. Tang, et al., Opt. Mater., 2022, 130, 112585.	4.53	802	1059.9	2022
BGRI-GS-glass [11] Z.H. Hua, et al., PoS(ICRC 2023), 2023, 565.	6.0	611	1501.4	2023



- As Gd increases, the glass density gradually rises from 3.3 to 6.0 g/cm³.
- The self-absorption effect intensifies, light yield to decrease from 3455 to 600 ph/MeV.
- Incorporating a high concentration of heavy ions—inevitably introduces structural defects and energy quenching, which collectively result in a slower decay time.

Is it really no way to achieve both high density and high light yield in the GS?



Scintillator	Density (g/cm^3)	Light yield (ph/MeV)	Mean decay (ns)	Year
BGRI-GS-glass [11] Z.H. Hua, et al., PoS(ICRC 2023), 2023, 565.	6.0	611	1501.4	2023
SCI-GFO-glass [12] J.J. Hua, et al., Opt. Mater., 2024, 157, 116153.	6.0	804	804.0	2024
JGSU-GFO glass [13] X.Y. Sun, et al., COL, 2025, 23(12), 121602.	6.0	1043	458.5	2025
JGSU-GFO glass [14] X.Y. Sun, et al., JMCC, 2024, 12, 11149–11156.	6.0	1279	860	2024
BGRI-GFO glass [15] D. Yang, et al., Ceram. Int., 2025, 51 , 19780.	6.0	1702	1409.8	2025
BGRI-GFO glass [16] Z.H. Hua, et al., The Innovation, 2026.	6.0	2076	447.2	2026

GFO: Ce is a promising scintillator system capable of high density and high light yield.

1.3 How to Improve the Light Yield?

which then radiate scintillation photons. The light yield LY in terms of the number of scintillation photons produced per MeV of energy deposited in the crystal can be expressed as [64]

$$LY = 10^6\ S \cdot Q/(\beta \cdot E_g), \quad (35.3)$$

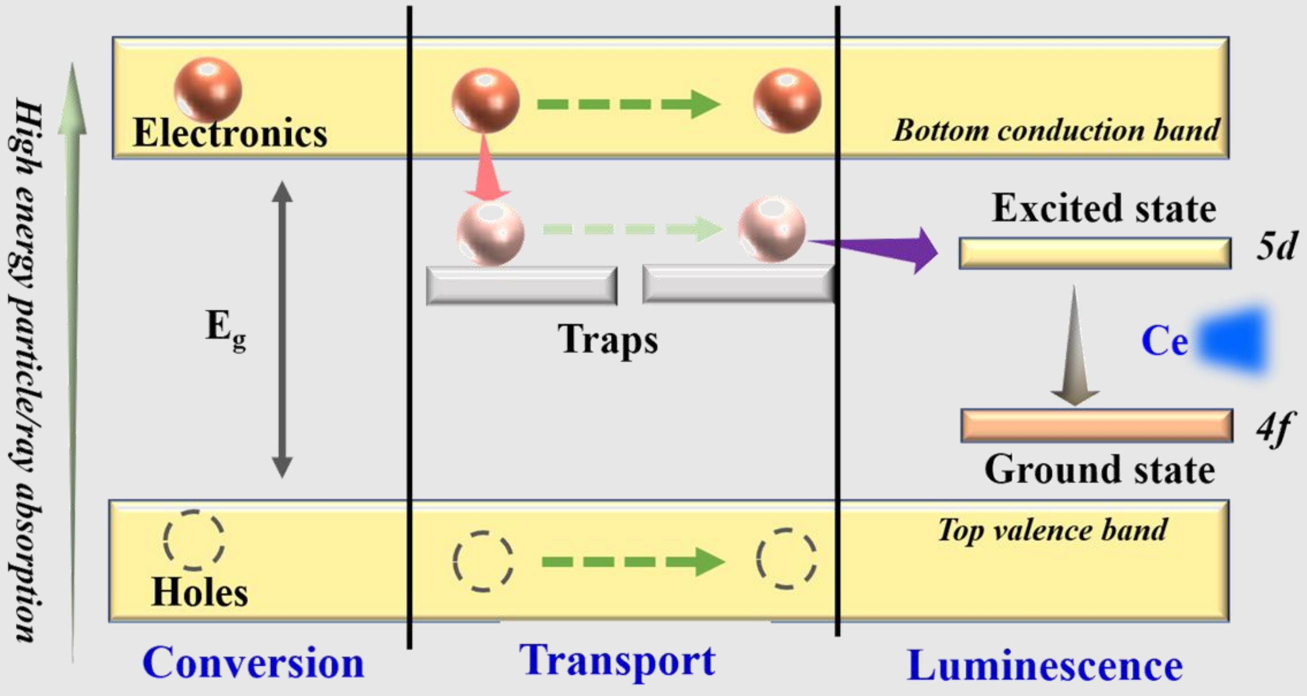
where $\beta \cdot E_g$ is the energy required to create an e-h pair expressed as a multiple of the band gap energy Eg (eV), S is the efficiency of energy transfer to the luminescent center and Q is the quantum efficiency of the luminescent center. The values of β, S and Q are crystal dependent and

Cite by S.E. Derenzo, W.-S. Choong and W.W. Moses, Phys. Med. Biol.59, 3261 (2014).

For inorganic **scintillation crystals**, the light yield can be enhanced by improving the intrinsic properties of the material:

1. Reducing the bandgap energy (**Eg**);
2. Improving the energy transfer efficiency (**S**) from the sensitizer to luminescent center (activator) ;
3. Increasing the quantum yield (**Q**) of the luminescent center.

How to Improve the Light Yield of Ce^{3+} Doped Glass



Ce^{3+} Doped Glass

- ✓ **5d–4f electric-dipole-allowed transition:** high transition probability, ns-scale decay time
- ✓ **Tunable emission wavelength:** better spectral matching with photodetectors.
- ✓ **Suitable for high-energy particle detection:** incorporated into a high density/atom number host

Breakthrough in glass scintillator: Defect Control is the key!

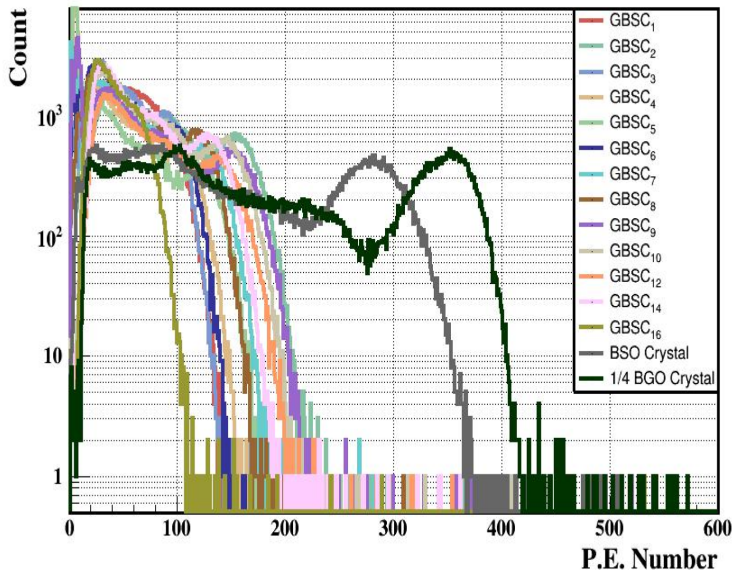
--**Purifying:** Using high-purity raw materials and reducing harmful defects, Fe(Ferric).

--**Doping (Co-doping):** Tuning energy transfer and luminescence process using:

Magnesium(Mg^{2+}), Manganese(Mn^{2+}), Ytterbium(Yb^{3+}), Lithium(Li^{+}) ,etc.

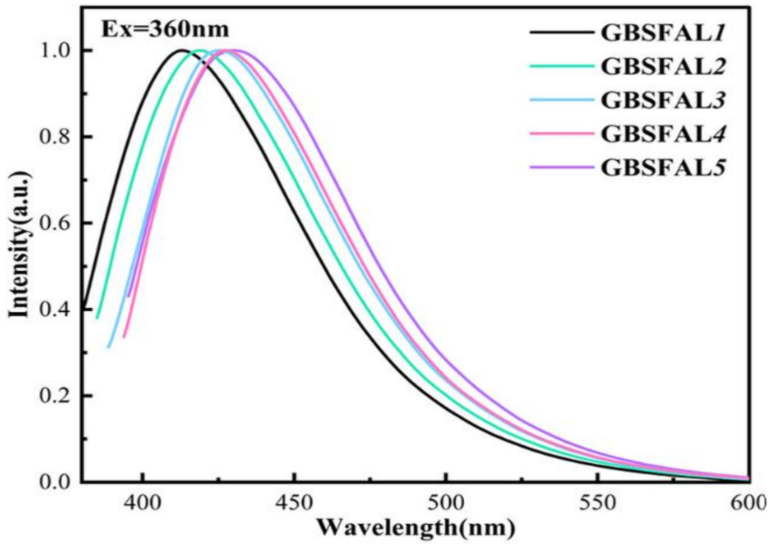
Light yield Enhancement—Doping, Co-Doping

➤ Effect of Ce^{3+} concentration on GFO



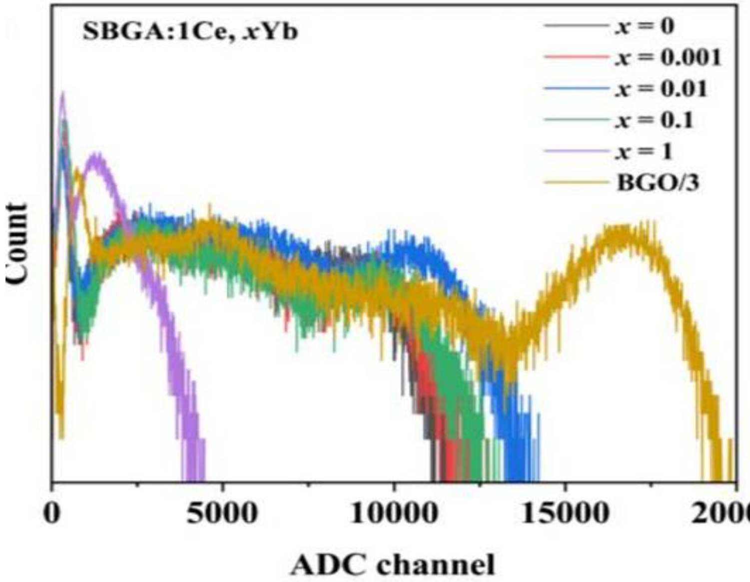
Ref. 2025 Chin. Opt. Lett, 23(12), 121602

➤ Effect of Li^{+} incorporation on GS



Ref. J. Am. Ceram. Soc., 2026, 109, e70997

➤ Effect of Yb^{3+} co-doping on GFO



Ref. Ceram. Int., 2026, 52, 26985–26993

- Ce^{3+} concentration regulates scintillation light yield and decay time.
- Optimized doping **enables intense luminescence with faster decay.**

- Li^{+} tunes the local coordination environment around Ce^{3+}.
- **The emission peak shifts toward the optimal SiPM PDE region.**

- Yb^{3+} reduces defect-related non-radiative energy loss.
- The light yield improves from ~1200 **to ~1500 ph/MeV.**

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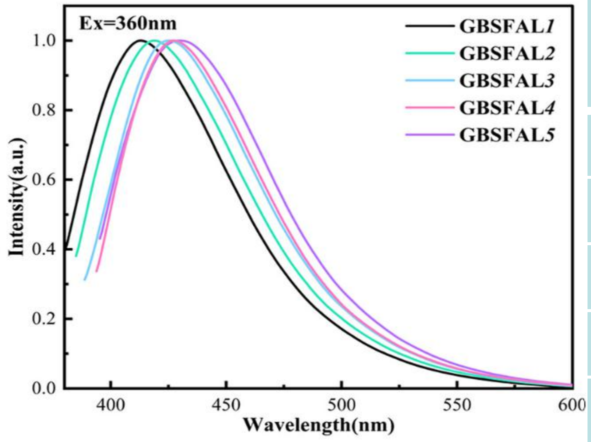
2.1 Raw material purity—Gd_2O_3

	Gd_2O_3 (%)	Price (RMB/kg)	LO (ph/MeV)	ER (%@662keV)	Decay time (ns)	XEL intensity
#121	99.9	~270	1279	29.8	81.0 (2.1%), 898.9	157512
#122	99.5	~220	1376	29.0	88.6 (2.2%), 913.7	159879
#123	99.99	~300	1488	28.2	84.5 (1.9%), 899.8	158017
#124	99.99	~280	1200	33.2	93.3 (3.3%), 906.4	157090
#125	99.999	~1000	1529	28.2	92.4 (3.0%), 916.5	163754

- Using higher purity Gd_2O_3 (99.9% → 99.999%) can increase the light output of scintillating glass from 1200 ph/MeV to 1500 ph/MeV;
- However, such a significant cost increase is difficult to afford in mass production;
- Therefore, achieving glass scintillators with superior performance through low-cost raw materials and preparation methods remains a major challenge in research.

2.2 Wavelength shift of GS

Doping **Li⁺** into GFO Glass

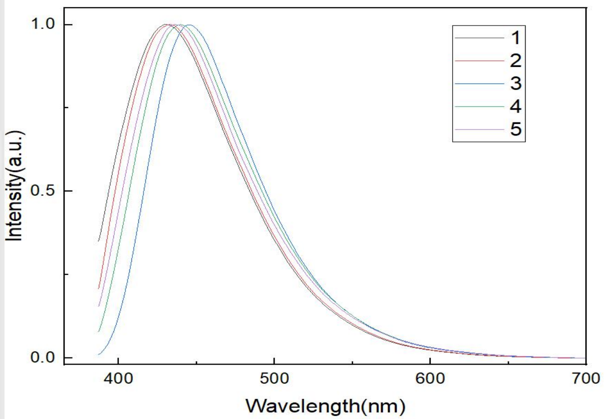


	Density (g/cm^3)	Emission peak(nm)	LO (ph/MeV)
GBSFAL1	5.58	407	1271
GBSFAL2	5.63	408	1360
GBSFAL3	5.68	409	1491
GBSFAL4	5.69	411	1116
GBSFAL5	5.70	420	1252

- After adding Li^+, the glass emission peak red-shifts from 390 nm to approximately 420 nm;
- As a strong network modifier, Li^+ increases the coordination field around Ce^{3+}, lowers its luminescence energy levels, and ultimately leads to a redshift of the emission peak and an increase in light output;

➢ 2026, J. Am. Ceram. Soc.

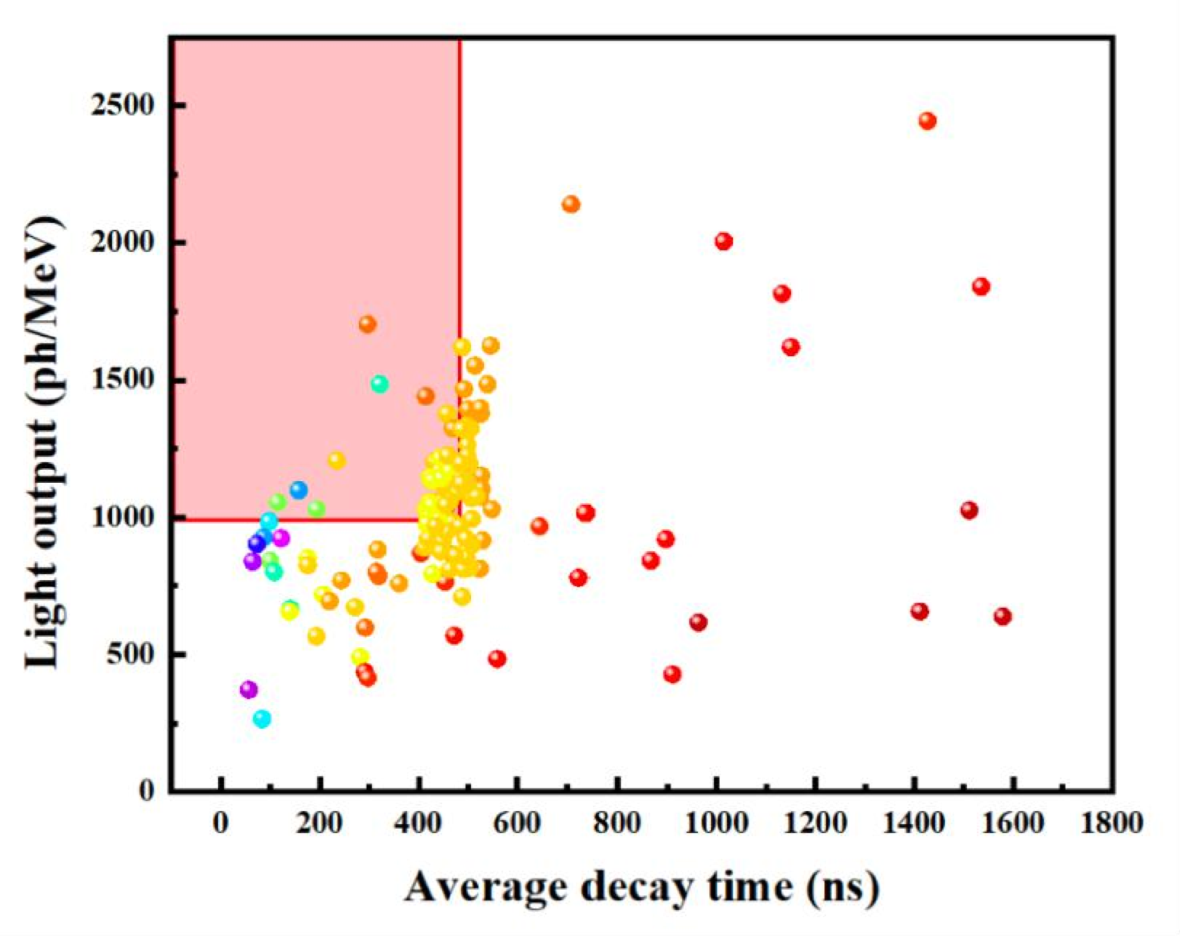
Doping **GdF_3** into GFO Glass



	Density (g/cm^3)	Emission peak (nm)	Light yield (ph/MeV)
1	5.49	429	?
2	5.61	433	
3	5.76	444	
4	5.93	440	
5	6.16	436	

- Further increasing the GdF_3 content in the glass can enhance its density; the emission peak red-shifts from 430 nm to 440 nm;
- However, the light yield and decay time of the glass have not yet been measured.

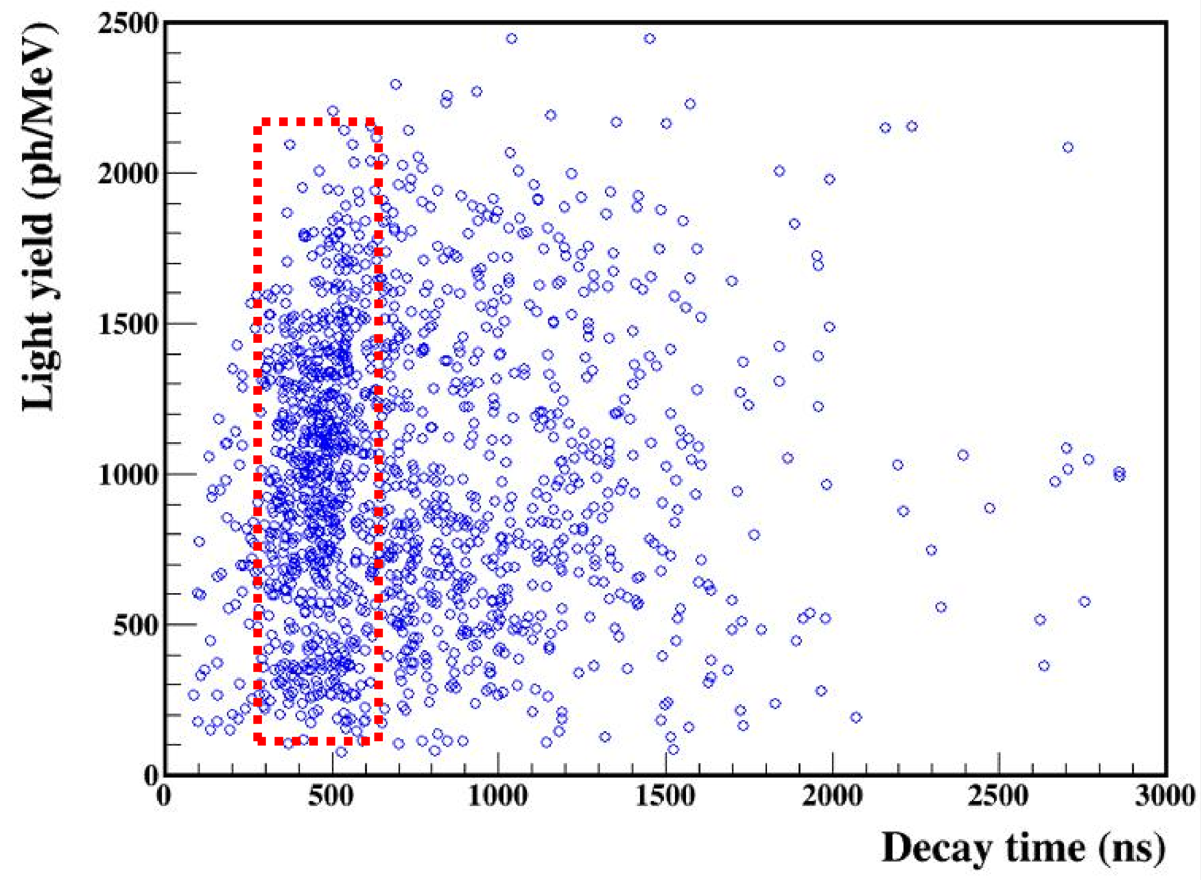
2.3 Decay time VS Light output 20251025



- GS group has achieved mass production of GS with a light yield of 1000 ph/MeV and a decay time of 500 ns;
- Decay time of the GS, determined by physical properties: 100ns -> 300ns -> 500ns;
- Typical results show that decay time and light yield tend to be positively correlated: a higher light yield generally implies a slower decay time;
- Only a small number of GS samples meet all three performance criteria: density > 6.0 g/cm³, light yield > 1500 ph/MeV, and decay time < 500 ns.

We really need the decay time of GFO less than 500ns? What about 1us? or others?

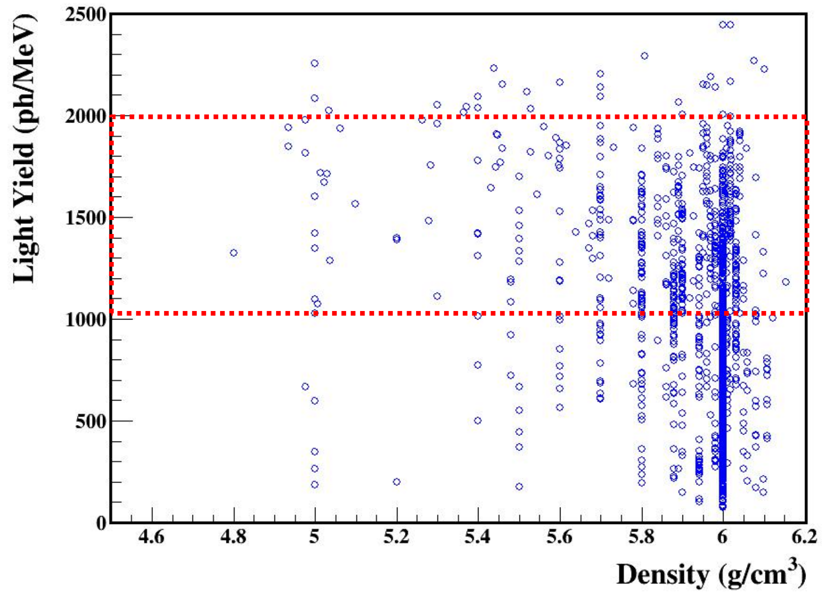
Decay time VS Light output 20260729



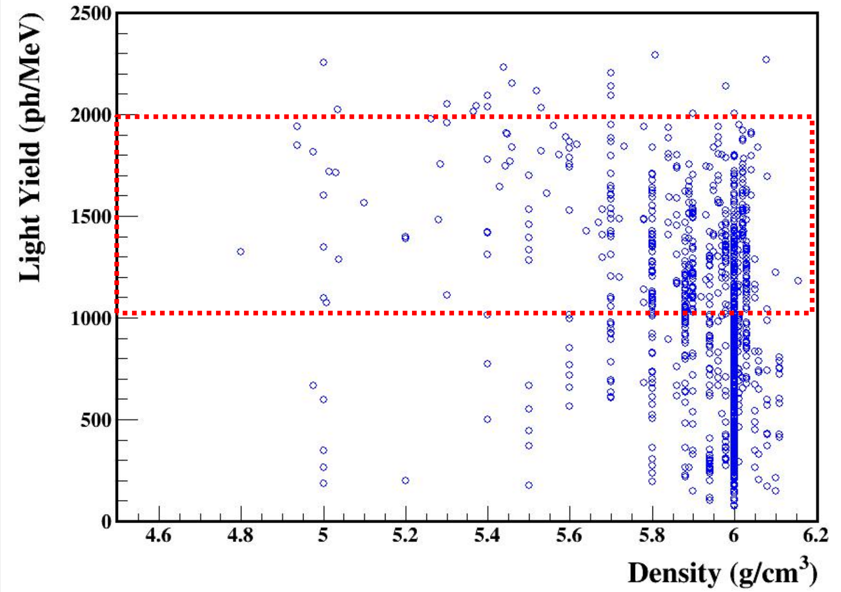
- A light yield of 1000 ph/MeV corresponds to 500 ns. What decay time corresponds to a light yield of 2000 ph/MeV?
- Decay time of the GS, determined by physical properties: 100ns -> 300ns -> 500ns;
- Typical results show that decay time and light yield tend to be positively correlated: a higher light yield generally implies a slower decay time;
- Only a small number of GS samples meet all three performance criteria: density > 6.0 g/cm^3, light yield > 1500 ph/MeV, and decay time < 500 ns.

Density VS Light output VS Decay time

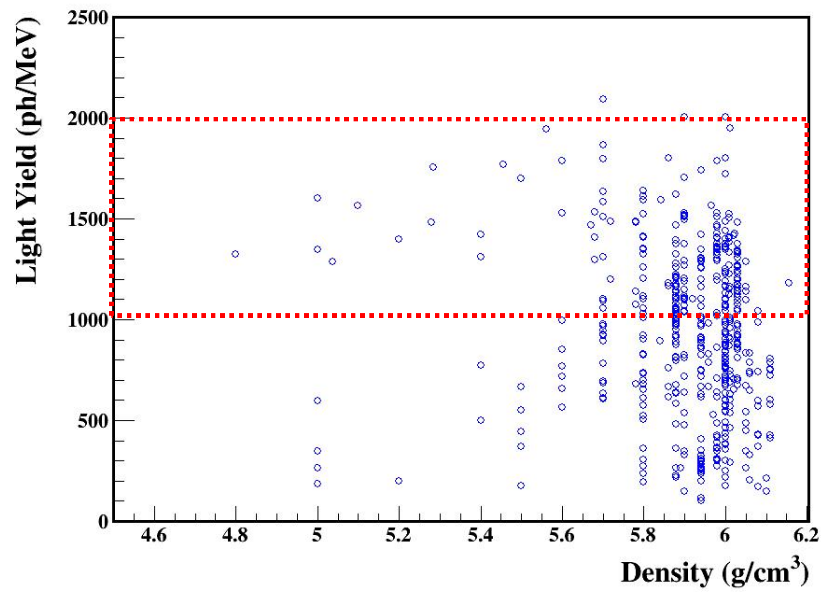
Decay time < 2us



Decay time < 1us



Decay time < 500ns

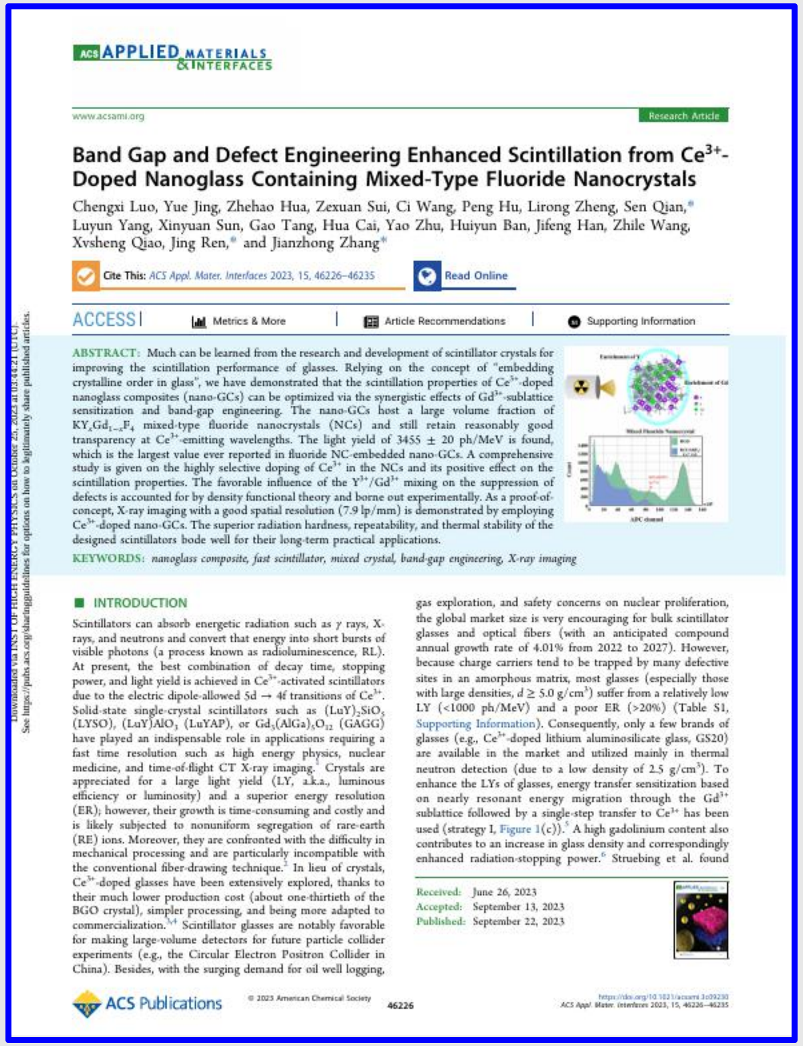


In the absence of decay time constraints, GS Group has successfully fabricated laboratory-scale samples with a density approaching 6 g/cm^3 and a light yield exceeding 2000 ph/MeV;

However, when the decay time<1000 ns, achieving a light yield of 2000 ph/MeV becomes challenging. Decay time<500 ns, the light yield can only be maintained at ~1500 ph/MeV.

Must the density of GFO be greater than 6? Light yield above 2000 ph/MeV? Decay time below 500 ns?

2.4 Microcrystallization



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Band Gap and Defect Engineering Enhanced Scintillation from Ce^{3+}-Doped Nanoglass Containing Mixed-Type Fluoride Nanocrystals

Chengxi Luo, Yue Jing, Zhehao Hua, Zexuan Sui, Ci Wang, Peng Hu, Lirong Zheng, Sen Qian,* Luyun Yang, Xinyuan Sun, Gao Tang, Hua Cai, Yao Zhu, Huiyun Ban, Jifeng Han, Zhile Wang, Xvsheng Qiao, Jing Ren,* and Jianzhong Zhang*

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ABSTRACT: Much can be learned from the research and development of scintillator crystals for improving the scintillation performance of glasses. Relying on the concept of "embedding crystalline order in glass", we have demonstrated that the scintillation properties of Ce^{3+}-doped nanoglass composites (nano-GCs) can be optimized via the synergistic effects of Gd^{3+}-sublattice sensitization and band-gap engineering. The nano-GCs host a large volume fraction of $KY_xGd_{1-x}F_4$ mixed-type fluoride nanocrystals (NCs) and still retain reasonably good transparency at Ce^{3+}-emitting wavelengths. The light yield of 3455 ± 20 ph/MeV is found, which is the largest value ever reported in fluoride NC-embedded nano-GCs. A comprehensive study is given on the highly selective doping of Ce^{3+} in the NCs and its positive effect on the scintillation properties. The favorable influence of the Y^{3+}/Gd^{3+} mixing on the suppression of defects is accounted for by density functional theory and borne out experimentally. As a proof-of-concept, X-ray imaging with a good spatial resolution (7.9 lp/mm) is demonstrated by employing Ce^{3+}-doped nano-GCs. The superior radiation hardness, repeatability, and thermal stability of the designed scintillators bode well for their long-term practical applications.

KEYWORDS: *nanoglass composite, fast scintillator, mixed crystal, band-gap engineering, X-ray imaging*

INTRODUCTION

Scintillators can absorb energetic radiation such as γ rays, X-rays, and neutrons and convert that energy into short bursts of visible photons (a process known as radioluminescence, RL). At present, the best combination of decay time, stopping power, and light yield is achieved in Ce^{3+}-activated scintillators due to the electric dipole-allowed 5d → 4f transitions of Ce^{3+}. Solid-state single-crystal scintillators such as $(LuY)_2SiO_5$ (LYSO), $(LuY)AlO_3$ (LuYAP), or $Gd_3(AlGa)_5O_{12}$ (GAGG) have played an indispensable role in applications requiring a fast time resolution such as high energy physics, nuclear medicine, and time-of-flight CT X-ray imaging.[1] Crystals are appreciated for a large light yield (LY, a.k.a., luminous efficiency or luminosity) and a superior energy resolution (ER); however, their growth is time-consuming and costly and is likely subjected to nonuniform segregation of rare-earth (RE) ions. Moreover, they are confronted with the difficulty in mechanical processing and are particularly incompatible with the conventional fiber-drawing technique.[2] In lieu of crystals, Ce^{3+}-doped glasses have been extensively explored, thanks to their much lower production cost (about one-thirtieth of the BGO crystal), simpler processing, and being more adapted to commercialization.[3,4] Scintillator glasses are notably favorable for making large-volume detectors for future particle collider experiments (e.g., the Circular Electron Positron Collider in China). Besides, with the surging demand for oil well logging, gas exploration, and safety concerns on nuclear proliferation, the global market size is very encouraging for bulk scintillator glasses and optical fibers (with an anticipated compound annual growth rate of 4.01% from 2022 to 2027). However, because charge carriers tend to be trapped by many defective sites in an amorphous matrix, most glasses (especially those with large densities, $d \geq 5.0$ g/cm^3) suffer from a relatively low LY (<1000 ph/MeV) and a poor ER (>20%) (Table S1, Supporting Information). Consequently, only a few brands of glasses (e.g., Ce^{3+}-doped lithium aluminosilicate glass, GS20) are available in the market and utilized mainly in thermal neutron detection (due to a low density of 2.5 g/cm^3). To enhance the LYs of glasses, energy transfer sensitization based on nearly resonant energy migration through the Gd^{3+} sublattice followed by a single-step transfer to Ce^{3+} has been used (strategy I, Figure 1(c)).[5] A high gadolinium content also contributes to an increase in glass density and correspondingly enhanced radiation-stopping power.[6] Struebing et al. found

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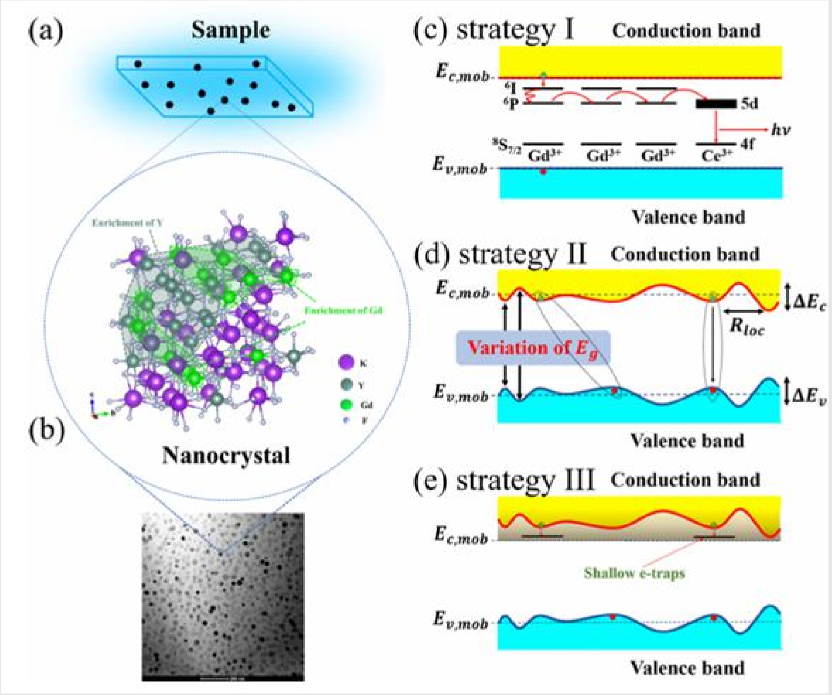
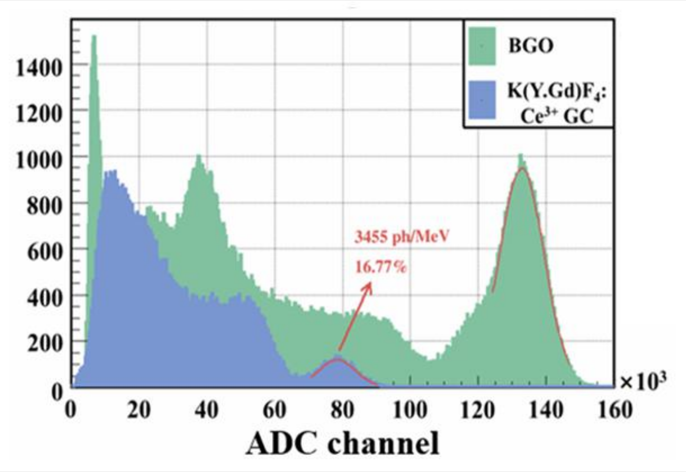
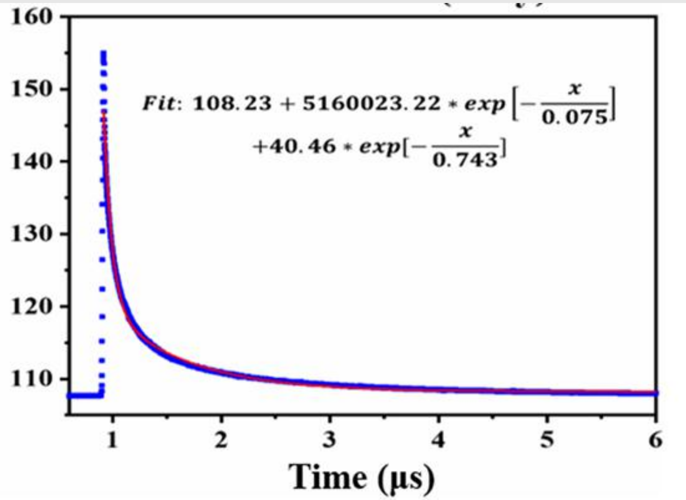




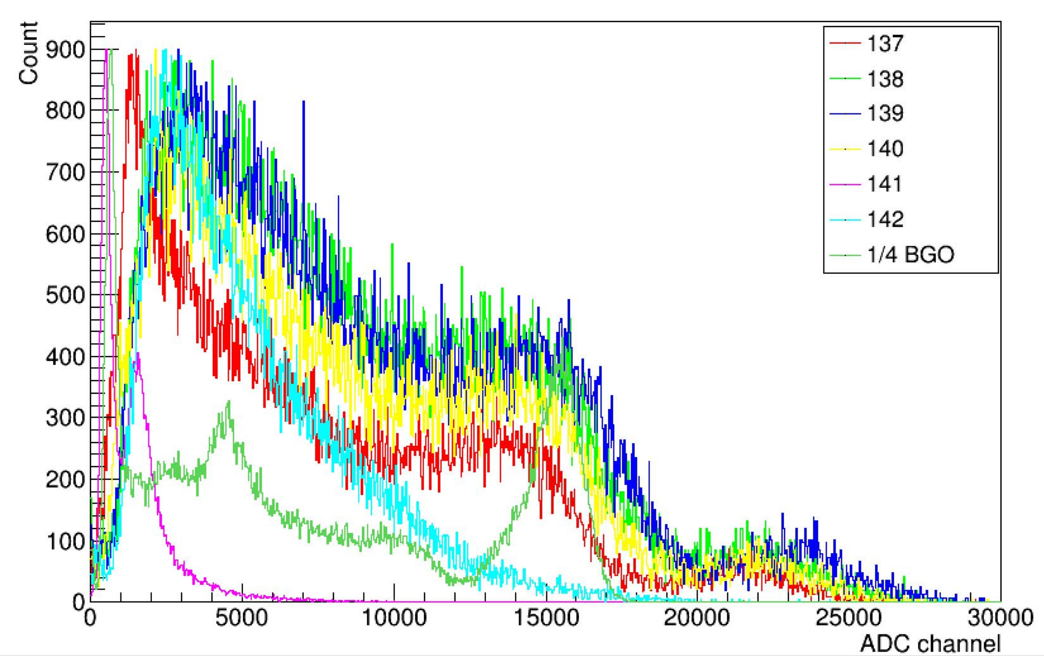


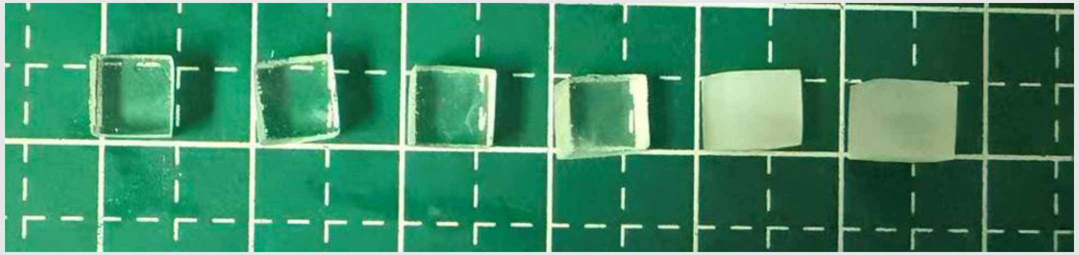
- Density=3.32 g/cm^3
- LY=3455 ph/MeV
- Energy resolution=16.8%@662keV
- Decay=75 (70%) ns, 743(30%) ns

- 2023, ACS Appl.Mater. Interfaces

Ce^{3+}-doped Nanoglass

Microcrystallization in GS Group



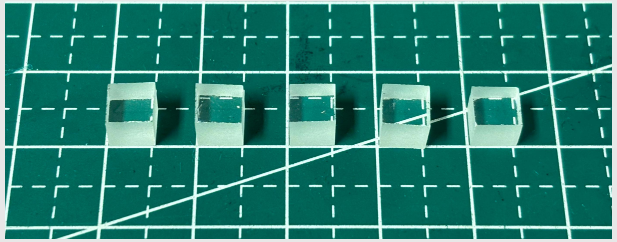


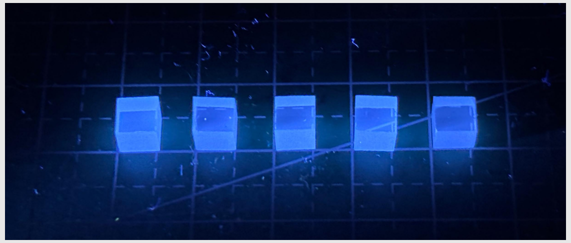
Sample	Density (g/cm³)	LY（photons/MeV）	E.R (%)	Decay time(ns)		
137	~3.0	3066	18.3%	78.1	43.8%	407.1
138	~3.0	3123	16.7%	75.5	46.9%	381.4
139	~3.0	3234	17.2%	75.6	46.6%	379.8
140	~3.0	3201	17.3%	75.8	47.0%	378.5

- By incorporating a nucleating agent system into the glass and subjecting it to heat treatment to induce microcrystallization;
- **The light yield of the glass can reach up 3000 ph/MeV, while the decay time can be controlled within 300 ns;**
- The heat treatment process is currently undergoing further optimization；
- However, the density of microcrystalline glass still remains difficult to increase.

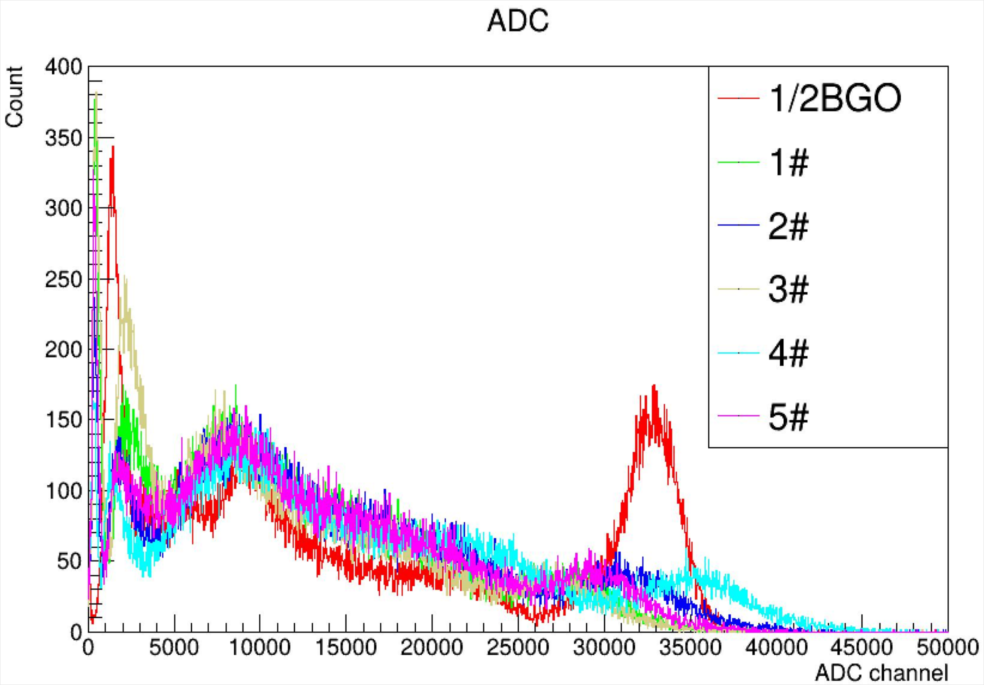
Microcrystallization in other University

- Samples:





- γ-ray spectra:



	LY (ph/MeV)	ER (% @662keV)	Density (g/cm^3)	Decay Time (ns)
1#	3619.86	24.2	4.2	698.95(18.4%), 4418.32
2#	4019.58	24.9	4.4	721.49(15.8%), 4791.96
3#	3451.02	29.0	4.6	575.23(12.1%), 3708.28
4#	4514.02	23.7	4.4	674.27(14.8%), 4368.02
5#	3768.71	24.4	4.6	734.03(16.3%), 4520.95
BGO	8544.45	10.9	7.1	69.4(5.5%), 313.6

Summary

1. We try our best to Enhance the Light Yield;
   - Purity: purity of raw materials VS performance VS cost.
   - Density: We really need the density of GFO larger than 6g/cc?
   - Decay Time: We really need the decay time of GFO less than 500ns?
   - Wavelength Shift:
   - Co-doping: We need time and funding to find the new materials;

2. How to conrol the cost of GFO Glass.

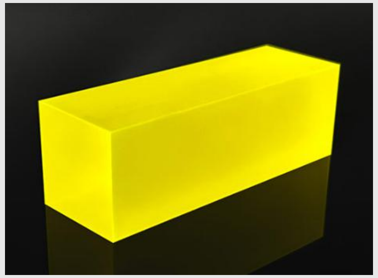
See the unseen
change the unchanged

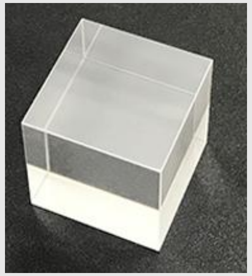
The Innovation

THANKS

2.4 GFO:Ce glass to GAGG and GSO crystal

Parameters	Unit	GAGG	GSO	GFO:Ce
Density	g/cm³	6.63	6.71	6.0
Melting point	℃	1850	1950	1150
Radiation Length, X_0	cm	1.63	1.38	1.64
Molière radius	cm	2.20	2.96	2.50
Nuclear interaction length	cm	21.5	20.6	24.1
Z_{eff}	--	50.6	58.0	56.9
dE/dX	MeV/cm	8.96	8.5	8.0
Emission peak	nm	540	430	390
Refractive Index	--	1.92	1.85	1.76
Light yield, LY	ph/MeV	60,000	8,000	~ 2,000
Energy resolution, ER	%662keV	5.0	9.2	25.8
Decay time	ns	100, 600	28, 260	~500
d(LY)/dT	%/℃	/	/	/
Cost	$/cc	/	/	<1.0


GAGG


GSO

- $Gd_3(Al_xGa_{1-x})_5O_{12}$:Ce **(GAGG)**
- Gd_2SiO_5:Ce (GSO)
- GFO:Ce Glass

have the similar compositions;

represent the ultimate performance goal.