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Research on High-Precision Time-Resolved Detectors Coupled with fast Scintillation Crystals and fast PMTs

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Introduction

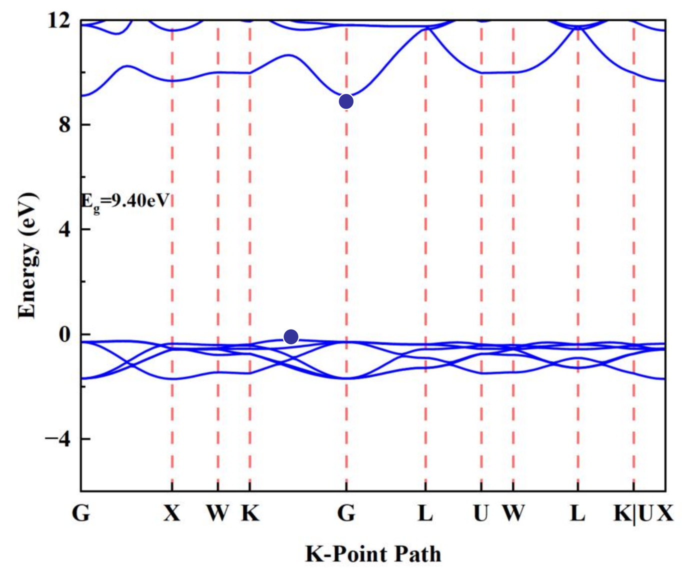
The performance of time-of-flight positron emission tomography (TOF-PET) critically depends on the coincidence time resolution (CTR). Achieving sub-100 ps CTR has become a key objective for next-generation systems. While widely used, scintillators like LYSO and LSO face limitations in practical applications due to their relatively slow decay time. BaF_2 crystals have advantages including high density, no intrinsic radioactivity, and ease of fabrication. However, their scintillation light is dominated by a slow component (~630 ns), with only a minor fast component (<0.6 ns), leading to limited CTR performance (>200 ps) under conventional readout schemes, which restricts their use in TOF-PET.

Cherenkov radiation, characterized by ultrafast emission (<10 ps) and the absence of decay time, provides a promising approach to improve CTR. BaF_2 crystals possess a moderate refractive index (n ≈ 1.56) and can generate considerable Cherenkov photon. Nevertheless, the strong temporal overlap between Cherenkov light and the fast scintillation component poses a major challenge for effective signal separation. In this study, we systematically investigated the characteristics of Cherenkov light in BaF_2 using Geant4 simulations and beam experiments, and developed a discrimination algorithm based on event selection and time-window optimization. Experimental results demonstrate that the Cherenkov-based approach achieves a CTR better than 30 ps (sigma), significantly outperforming traditional scintillation-based methods. This work offers a new pathway for the application of BaF_2 crystals in high-performance TOF-PET systems.

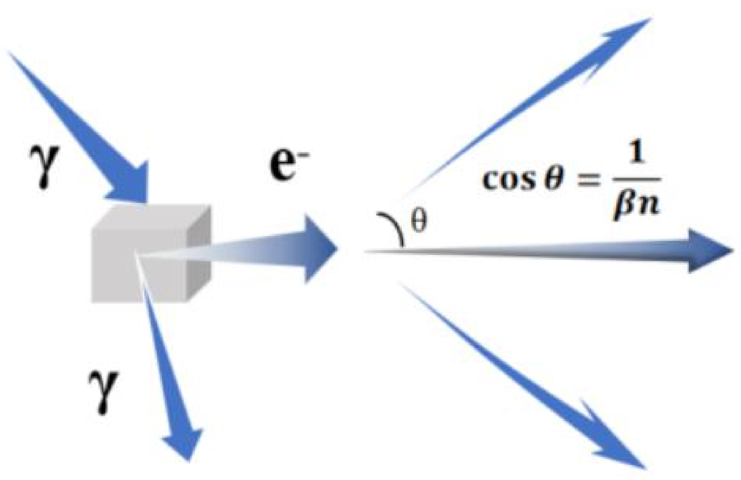
1.Capable of carrying structure and Cherenkov radiation

First-principles method: Utilizing HSE06 to calculate the band structure of BaF_2:

- The indirect band gap inhibits the radiative recombination rate at the band edge, resulting in slow-flashing light.
- Ba-5p core level enables ultrafast scintillation kinetics on a sub-nanosecond scale.
- Cherenkov radiation signal overlaps with fast scintillation; slow scintillation is naturally filtered out by readout window.



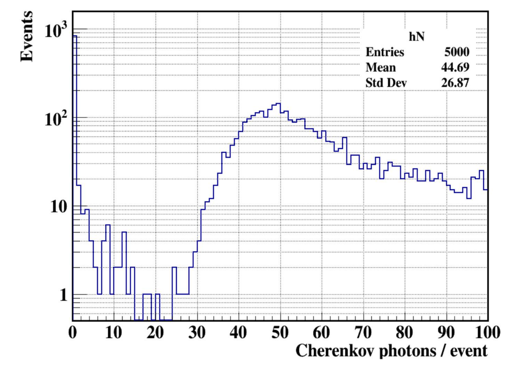
➢ Band structure



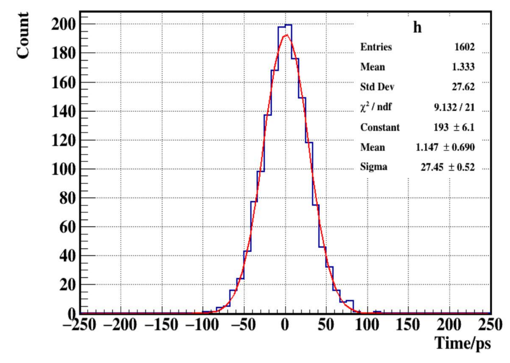
➢ Cherenkov radiation mechanism

2. Geant 4：CTR of BaF_2-FPMT

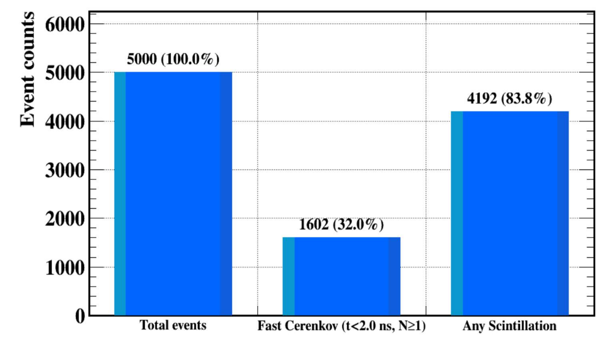
- Simulation process: Conduct a detailed simulation of the entire process of photon generation, propagation, reflection, refraction and detection within the crystal, precisely replicating the experimental conditions.



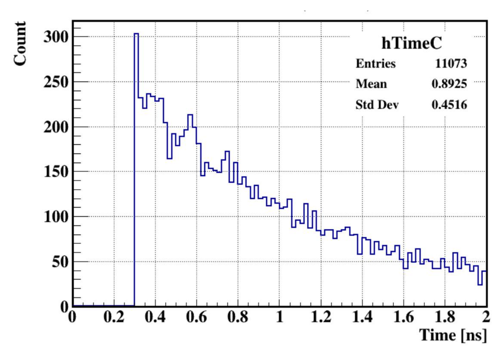
➢ Cherenkov photons for each Event

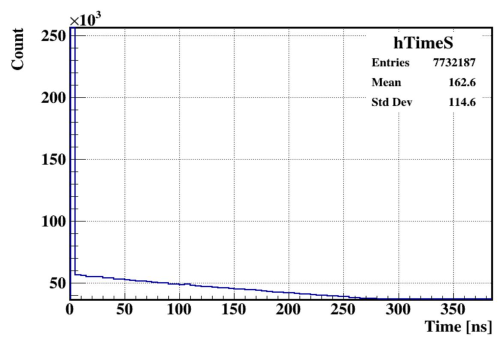


➢ CTR of BaF_2-FPMT



➢ Events Classification Results





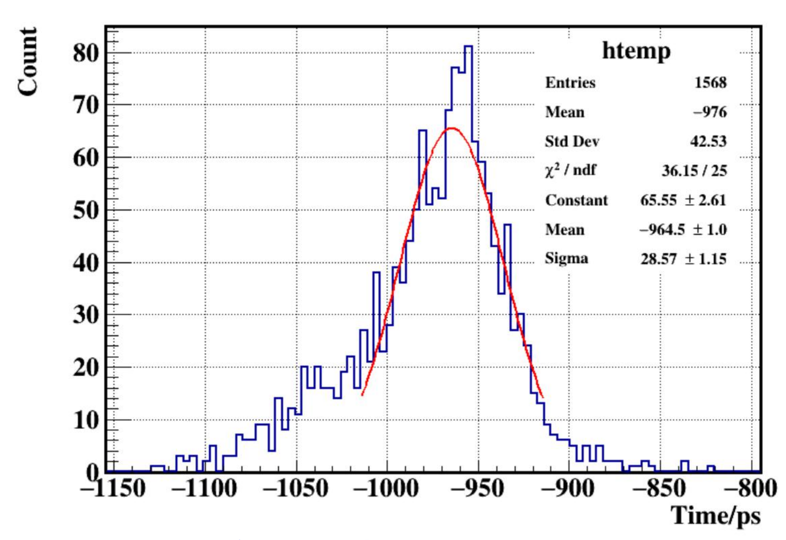
- Total events：5000
- Detected 58.93 Cherenkov photons per event.
- Pure Fast Cherenkov：1602
- Geant 4：CTR=27.45 ps (sigma)

➢ Time distribution of Cherenkov photons ➢ Time Distribution of Fluctuating Photons

3. Beam experiment：CTR of BaF_2-FPMT

- Event selection algorithm: By taking advantage of the extremely short time response of Cherenkov radiation and the small difference in the fast component of the scintillation light (~0.6 ns), an event selection algorithm was developed, successfully selecting 1568 pure Cherenkov events from the massive data.
- Conforming to time resolution calculation: Based on the selected pure Cherenkov events, CTR was accurately calculated. The results showed that the CTR reached 28.57 ps (sigma).

➢ The beamtest setup schematic



➢ CTR of BaF_2-FPMT

Project	Parameter
Beam	KEK-PF-AR 5 GeV electron beam, spot σ ≈ 2 mm, single bunch 10^3 e^-
Crystal	Two BaF_2 crystals (5×5×5 mm), with both ends polished, and the sides fully wrapped with 0.1 mm Teflon.
Photo electricity	Each crystal is coupled to a FPMT (σ_{TTS} 25 ps) on one end, for a total of two channels; The trigger is generated by the coincidence of the two FPMT channels themselves.
Data collection	A 20 GS/s oscilloscope records the waveforms from the two FPMT channels, with offline extraction of the first photon arrival time and calibration using the single-photon peak.
Process	A total of 5000 events met the criteria, supporting the Cherenkov-Fluorescence separation and <30 ps CTR measurement.

4. Conclusions

- Our study confirms the distinguishability of Cherenkov and scintillation light in BaF_2 with a CTR of ~28 ps, surpassing conventional performance metrics.
- These results establish a strong theoretical basis for the use of BaF_2 in TOF-PET systems with picosecond-level timing resolution, charting a course for cost-efficient, high-performance detector technology.
- Future research will optimize photon collection and dual-readout configurations to boost BaF_2's role in TOF-PET, advancing precise medical imaging and physics research.

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