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Design studies on the 4π γ-ray calorimeter for the ETF experiment at HIRFL-CSR*

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Abstract: A high detection efficiency calorimeter which is used to detect γ-rays with energies from 1 MeV up to 10 MeV as well as light charged particles has been proposed. Design of the geometry, results of the crystal tests and Monte Carlo simulations are presented in this paper. The simulation results confirm that the calorimeter can obtain high detection efficiency and good energy resolution with the current designed geometry. And the calorimeter is competent for the future External Target Facility (ETF) experiments.

Key words: calorimeter, detector design, scintillator detector, ETF, simulation

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1 Introduction

During recent decades, the reactions induced by radioactive nuclei beams around several hundred MeV/u have become an important tool to explore the structure and reaction mechanism of complex nuclei far from stability [1, 2], as well as to probe the properties of nuclear matter under extreme conditions [3–6]. With the construction of the Cooling Storage Ring of the Heavy Ion Research Facility in Lanzhou (HIRFL-CSR) [7], much interest has been aroused in research on the structure of exotic nuclei and the equation of state (EOS) of dense nuclear matter [8–10]. For this research, an experimental setup, the External Target Facility (ETF), is under construction downstream of the second Radioactive Ion Beam Line in Lanzhou (RIBLL Ⅱ).

The ETF is a universal reaction experimental setup for completely kinematical measurements with high-energy radioactive beams, and it consists of many different sub-detector systems. Many experimental reaction studies removing one or several nuclei from the projectile [11–13], such as knockout reactions and Coulomb breakup reactions, need to measure γ-rays up to 10 MeV to get the necessary information. And the dipole resonance measurements are also concerned. For these purposes, a calorimeter is proposed for measuring gammas around the reaction target.

Different experiments may have different requirements of the detector. Therefore, as part of a universal setup, this calorimeter needs to measure not only the energies with enough resolution for a single γ-ray, but also the γ-ray multiplicities and the sum energy for each event. Obviously, high efficiency and good energy resolution are crucial for the planned measurements. Due to the proposed large angular coverage and the design for high energy reaction measurements, this calorimeter could also be used to measure the total energy of recoiling protons and other light

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charged particles produced in the collisions as well as γ-rays. This means that the detector must be able to resolve multiple hits distinctly, which requires both sufficient granularity and very high efficiency.

In this paper, we will present the design and the expected properties of the γ-ray calorimeter based on Monte Carlo simulations. We also show some test results for full size detector modules of the calorimeter at the end of this paper, which is very important to show the applicability of our simulation.

2 Design of the calorimeter

For γ-rays emitted by a fast moving particle, there is a Doppler Effect, the laboratory energy E_γ^{Lab} is associated with the centre-of-mass (CM) energy and the emitting angle by the Lorentz transformation

$$E_\gamma^{\text{Lab}} = \frac{E_\gamma^{\text{CM}}}{\gamma}\frac{1}{1-\beta\cos\theta}, \tag{1}$$

where E_γ^{CM} is the energy of γ-ray in the CM system, θ the emission polar angle, β the particle velocity and $\gamma = 1/\sqrt{1-\beta^2}$. Considering a 10 MeV γ-ray emitted from a particle with energies at about 600 MeV/u and 300 MeV/u, corresponding to β=0.79 and 0.65, respectively, its laboratory energy as a function of the polar angle is shown in Fig. 1(a). The energies of the γ-rays emitted in the forward region are increased by a factor of 2 or more in the laboratory system, thus the length of the detector modules in the forward region must be longer than those at the backward ones to get enough efficiency.

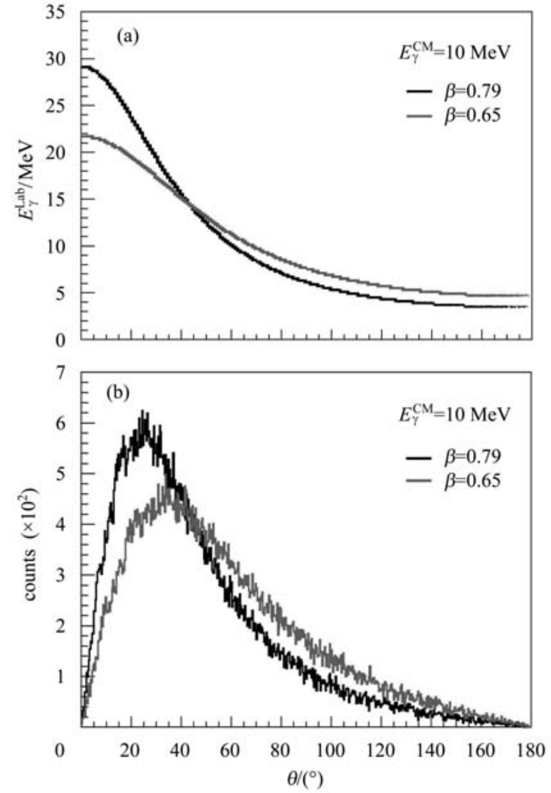

Fig. 1. Kinematical properties for γ-rays emitted by moving particles at different energies. (a) Laboratory energy of the γ-rays versus the emitted polar angle. (b) Angular distribution of isotropic emitted γ-rays.

The Doppler Effect will also influence the angular distribution of emitted γ-rays in the laboratory system. Considering an isotropic distribution in the CM system, the corresponding distribution in the laboratory system is shown in Fig. 1(b). This shows that the angular distribution is not isotropic anymore, but concentrates at around 25°, and drops drastically for emission angles larger than 90°. This result suggests that the high efficiency can be achieved without covering the full solid angle. For example, if the calorimeter can cover the polar angles between 6° and 130°, a geometrical efficiency around 95.1% can be achieved for a 500 MeV/u γ-ray emitter.

For a γ-ray measured at an angle θ, the resolution of its energy in the CM system is dependent not only on the measurement resolution of energy in the laboratory system, but also on the angle uncertainty $\sigma(\theta)$ with the relationship

$$\sigma^2(E_\gamma^{\text{CM}}) = \gamma^2\beta^2 E_\gamma^{\text{Lab}} \sin^2\theta\sigma^2(\theta). \tag{2}$$

Then the relative energy resolution of the CM energy is given by the expression:

$$\frac{\sigma(E_\gamma^{\text{CM}})}{E_\gamma^{\text{CM}}} = \frac{\beta\sin\theta}{1-\beta\cos\theta}\sigma(\theta). \tag{3}$$

Because the angular uncertainty $\sigma(\theta)$ comes from the actual size of the detector modules, a high detector granularity is crucial to the reconstruction of gamma energies in the CM system.

In other words, for a given requirement of $\sigma(E_\gamma^{\text{CM}})/E_\gamma^{\text{CM}}$, we can get the limits for the angular uncertainty by the expression

$$\sigma(\theta) = \frac{\sigma(E_\gamma^{\text{CM}})}{E_\gamma^{\text{CM}}}\frac{1-\beta\cos\theta}{\beta\sin\theta}. \tag{4}$$

The angular uncertainty requirements for three different CM energy resolutions are shown in Fig. 2. From these curves, we know the influence of the polar angle coverage of each module on the energy resolution. The straight line in Fig. 2 shows the contributions of the proposed detector modules in different parts of the calorimeter, and all of them are better than 2% for the CM energy resolution.

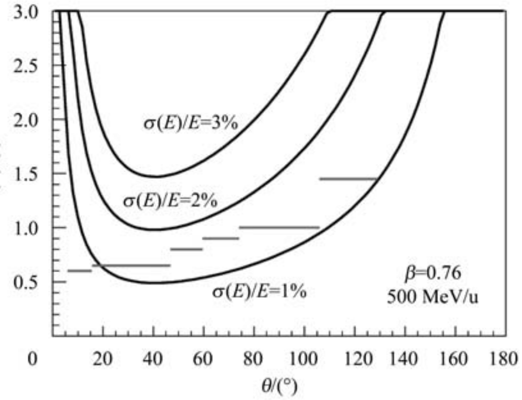

Fig. 2. Polar angular uncertainties for the proposed crystals, compared with the theoretical polar angular uncertainties for a given relative resolution on the CM energy, with β=0.76.

Considering all of this information, we get the design for the calorimeter based on a precise Monte-Carlo simulation, which will be described in the next section. The calorimeter consists of 4608 single modules with an inner radius of 30 cm for the barrel region in order to contain the reaction target and other detectors inside. The CsI(Tl) crystal is finally chosen to be the detector crystal after comparing with many other materials, and a large area avalanche photodiode (APD) will be used as the readout device. The APD has high quantum efficiency, especially for small signals from coupled CsI(Tl) crystals. Each crystal module is designed as a frustum for collecting the scintillation light, and the end part of the crystal is shaped into a light guide to fit the size of the APD. The calorimeter will cover a polar angle region from 6° to 129.2°, and the lengths of the modules are decreased from 18 cm to 11 cm with the increasing polar angles.

3 Monte Carlo simulation

To obtain the performance of the calorimeter and optimize the detector design, a Monte Carlo simulation was implemented. The simulation results could give the efficiency and resolution for the chosen geometry, and check the effects of the Doppler shift and broadening on the energy reconstruction. The simulation code is based on Geant4 [14], with the output exporting to ROOT [15] for data analysis. Different crystal sizes can be defined in the simulation code for testing the effects on detection efficiency, which is helpful to determine the crystal length in the final design of the calorimeter.

Each crystal with genuine structure is constructed individually in the code, and the calorimeter without crystal wrappings and support mechanicals is shown in Fig. 3. The energy resolution of each crystal is taken into account by introducing a Gaussian smearing with the standard deviation extracted from the experimental data. The standard deviation of the Gaussian depends on the deposited energy $E_{\rm dep}$, as shown in Eq. (5), where $\Delta E/E$ is the realistic energy resolution measured at energy E. In this work, a conservative value of 7% (FWHM) for $\Delta E/E$ is assumed at E=662 keV,

$$\sigma=\left(\frac{1}{2.36}\frac{\Delta E}{E}\right)\sqrt{E}\times\sqrt{E_{\rm dep}}. \qquad (5)$$

In order to simplify the work, an isotropic distributed γ-ray source in the CM system is used as the event generator in the code instead of a real physics generator, which has no influence on the detector performance of interest. In order to reconstruct the CM energies, the emission polar angle is extracted from the polar angle of the axis of the crystal having the largest energy deposition, and the detected energy is calculated from the sum of the energy deposited on several adjacent crystals around the largest energy deposited crystal.

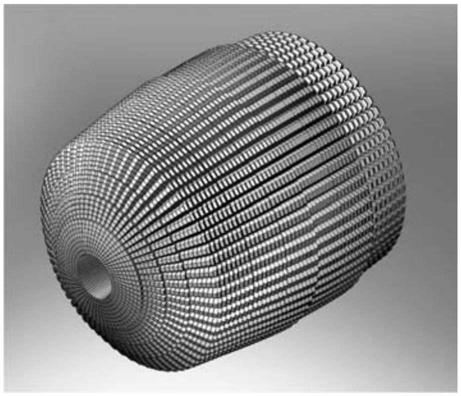

Fig. 3. Schematic view of the geometry of the γ-ray calorimeter.

A systematic study of the performance of the calorimeter has been carried out with this code, and some parameters of the design are modified accordingly. As an example, Fig. 4 shows some simulation results with a series of gamma energies (0.5, 1, 2, 5 and 10 MeV in the CM system), and a beam energy of 500 A MeV (β=0.76) is assumed to check the influence of the Doppler shift. Fig. 4(a) is the detection efficiency of the calorimeter at different gamma energies, and Fig. 4(b) is the energy resolution after reconstruction in the CM system. From the charts, one can see that a detection efficiency greater than 82% is achieved with this design, and a best resolution of 4.57% (FWHM) is obtained for 5 MeV gammas.

The good performance of the calorimeter with the present design has been proved by the simulation results, and high detection efficiency and good energy resolution are expected for the calorimeter in future ETF experiments.

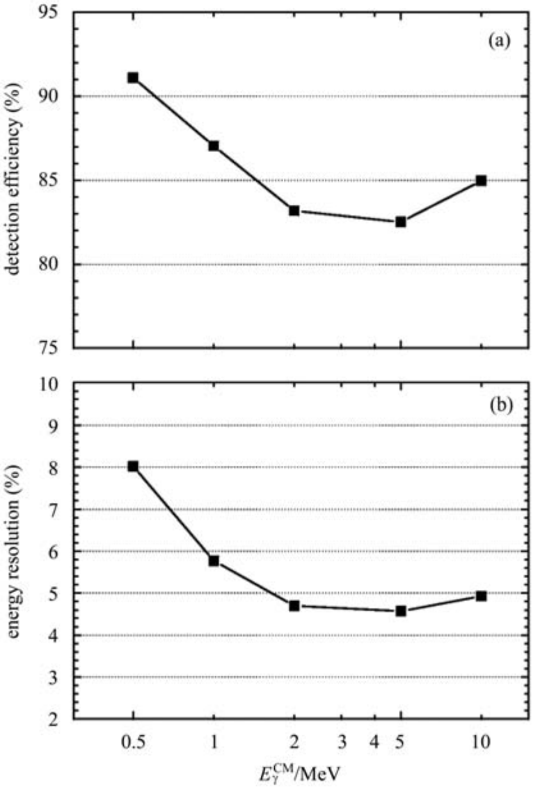

Fig. 4. Simulation results for different γ-ray energies. (a) Detection efficiency. (b) Reconstructed energy resolution.

At the present stage, crystal wrappings and support structures were not concerned in the simulation code. Accordingly, the backscattering photons or electrons coming from these materials may be lost in the crystals, which will cause the simulation result of the detection efficiency to become imprecise. In future work, we could add the support materials in the code to check the influence of this part on the simulation results.

4 Detector module tests

The performance of the calorimeter is based on the single crystal module used, so knowledge about the actual performance of the designed modules is important, especially in our case, because many of them are very long in comparison with their sectional dimension ratio, which is disadvantageous for light transfer. In order to check this, a set of full-sized CsI(Tl) crystals were made and tested in the laboratory. Fig. 5 shows the energy spectrum of γ-rays from a collimated ^{137}Cs source measured with a CsI(Tl) crystal module at room temperature (+20 ℃). This module will be used at a polar angle of 17.6° in the calorimeter, and it has a length of 170 mm with a cross-section of 14.3 mm×10.5 mm. The CsI(Tl) crystals were manufactured by the Institute of Modern Physics, the Chinese Academy of Sciences [16], wrapped with Vikuiti Enhanced Specular Reflector (ESR) film [17] and aluminized mylar. The Hamamatsu S8664-1010 APD [18] was used for readout, and the signals from the APD were input into an ORTEC 142B preamplifier and an ORTEC 572A spectroscopy amplifier for shaping. An optimized shaping time constant of 6 μs was used, and an energy resolution of (6.20±0.11)% (FWHM) was obtained from fitting the full-energy peak.

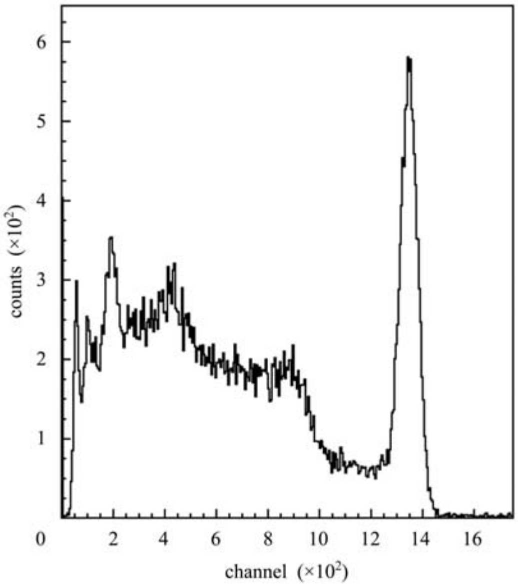

Fig. 5. Energy spectrum obtained by a Hamamatsu S8664-1010 APD coupled to a CsI(Tl) crystal module wrapped with ESR film and aluminized mylar. The energy resolution from fitting the photopeak is (6.20±0.11)%.

Non-uniformity of light collection is one of the factors affecting the energy resolution of scintillator detectors, especially when the crystals are shaped into a finger-like dimension. To evaluate the light collection non-uniformity, measurements were performed with a full-sized calorimeter module, which has a well polished surface and is coated with different kinds of wrapping materials, like teflon, Tevek, ESR film and aluminized mylar.

The pulse heights were recorded at 6 different positions along the crystal by using a collimated ^{137}Cs source. The quantification of light collection non-uniformity can be expressed by the G factor,

$$G=\frac{P_{\max}-P_{\min}}{P_{\text{ave}}}, \qquad (6)$$

where $P_{\max}$ and $P_{\min}$ are the maximum and minimum of the peak values among the 6 test points, and P_{ave} is the average of all the measured peak values.

In Table 1, the results of the G factor for two different crystal dimensions are presented. Type 1 is the crystal sample located at 35.8° and Type 2 is located at 17.6°, which is slimmer and longer than Type 1. The results show that the best non-uniformity of light collection and energy resolution are obtained from both crystal samples wrapped with ESR film.

These test results make sure that the performance values for a single module used in the Monte-Carlo simulation are realistic.

Table 1. Light collection non-uniformity and energy resolution obtained for gamma-ball crystals with different wrappings using Hamamatsu APDs.

wrapping	Type 1 (polar angle 35.8°)		Type 2 (polar angle 17.6°)	
	G(%)	$\Delta E/E$(%)	G(%)	$\Delta E/E$(%)
ESR	0.75	6.64	0.99	6.20
Teflon	1.62	6.77	16.23	8.30
Tevek	4.20	12.66	–	–

5 Conclusions

In this paper, we have presented the design, the Monte-Carlo simulations and some module test results for a highly efficient γ-ray calorimeter. The calorimeter will be constructed at the ETF of HIFIL-CSR for exotic nuclei studies. To reconstruct the energies of γ-rays in the CM system of the rest fragment, both the laboratory energy and the emission polar angle should be measured accurately. Therefore the critical point of the calorimeter design required by these aspects is described in the paper. A Monte Carlo simulation and the crystal tests were implemented to optimize the calorimeter design. The results of the simulation confirm that the calorimeter may have high detection efficiency and good energy resolution for reconstructed gamma energies. And the calorimeter is expected to perform well in future ETF experiments.

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