PROCEEDINGS OF THE YEREVAN STATE UNIVERSITY

Physical and Mathematical Sciences 2025, **59**(1), p. 20–31

Physics

STUDY OF $PbWO_4$ CRYSTAL FOR ePIC EmCal PROTOTYPE

A. S. HAKOBYAN* , D. G. KHURSHUDYAN**, A. H. MKRTCHYAN***

A. Alikhanian National Science Laboratory (AANL),
Yerevan Physics Institute, Armenia

The study presents the characterization of $PbWO_4$ crystals intended for the prototype of the EmCal electromagnetic calorimeter of the ePIC detector, which is being constructed at the Electron-Ion Collider in the Brookhaven National Laboratory at the USA. Measurements were performed on 20 crystals produced by "Crytur" company, each of which was then thoroughly examined under a microscope. Transversal transparency measurements were made at the center of the crystals, as well as at several fixed points equidistant from the center to the right and left sides to study uniformity. The average transparency of the crystals is 21.3%, 65.6%, and 71.7% for wavelengths of 360 *nm*, 440 *nm*, and 600 *nm*, respectively. The transmittance measurements repeated 10 times in the center of each crystal show that accuracy of our measurement is better than 10%. The light yield of $PbWO_4$ was estimated to be an average $16 pe/MeV$. The optical characteristics of Crytur crystals meet the requirements of the EIC electromagnetic calorimeter. After performing all the necessary measurements, 16 crystals in good condition were selected for the calorimeter prototype. A 4×4 prototype of EmCal was designed, constructed and tested with cosmic muons.

https://doi.org/10.46991/PYSUA.2025.59.1.020

MSC2020: 78-05, 78A40.

Keywords: $PbWO_4$ Crystals, Electromagnetic Calorimeter, ePIC Detector, Transparency Measurements, Light Yield, Radiation Hardness, Crystal Characterization, Electron-Ion Collider, Optical Properties.

Introduction. The Electron-Ion Collider (EIC) is a particle accelerator designed to study the quark-gluon structure of protons and nuclei, to clarify the origin of nucleon spin and mass, as well as to investigate physical phenomena related to dense gluon systems [1]. Before the design of the EIC, the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory was the main platform for studying quark-gluon plasma. Through collisions of polarized electrons with protons, deutrons and

* E-mail: argine.hakobyan1@edu.ysu.am
** E-mail: dianakhurshudyan36@gmail.com
*** E-mail: a.mkrtchyan@aanl.am

ions at EIC, scientists aimed to uncover the structure of proton spin, origin of nucleon mass, and many unsolved problems of physics beyond the Standard Model.

To address these challenges, as well as a number of other important issues, three different detector proposals were developed: ATHENA (A Totally Hermetic Electron Nucleus Apparatus) [2], ECCE (EIC Comprehensive Chromodynamics Experiment) [3], and CORE (a COmpact detectoR for the EIC) [4]. All three proposals were presented to the EIC Detector Proposal Advisory Panel (DPAP) and were thoroughly reviewed.

Following the DPAP recommendations (March 2022), all three collaborations united their efforts to form the ePIC (electron Proton/Ion Collider) collaboration, based on the ECCE detector proposal, in order to complete the design of the first detector for the EIC project.

The ePIC detector consists of three main components: the central detector (“barrel”), the forward endcap, and the backward endcap systems (Fig. 1). The ePIC central detector has a cylindrical geometry, based on the BaBar/sPHENIX superconducting solenoid magnet.

Experimental Part.

Problem Statement and Objective. The primary objectives of this work are:

• to study and evaluate the physical and optical properties of $PbWO_4$ crystals for their application in the electromagnetic calorimeter of the ePIC detector;

• to improve the efficiency of the equipment and enhance experimental precision.

The main focus is on assessing transparency, transverse optical properties, and the impact of radiation. These studies aim to address the challenges associated with the production, quality assurance, and experimental application of $PbWO_4$ crystals in high-energy physics experiments.

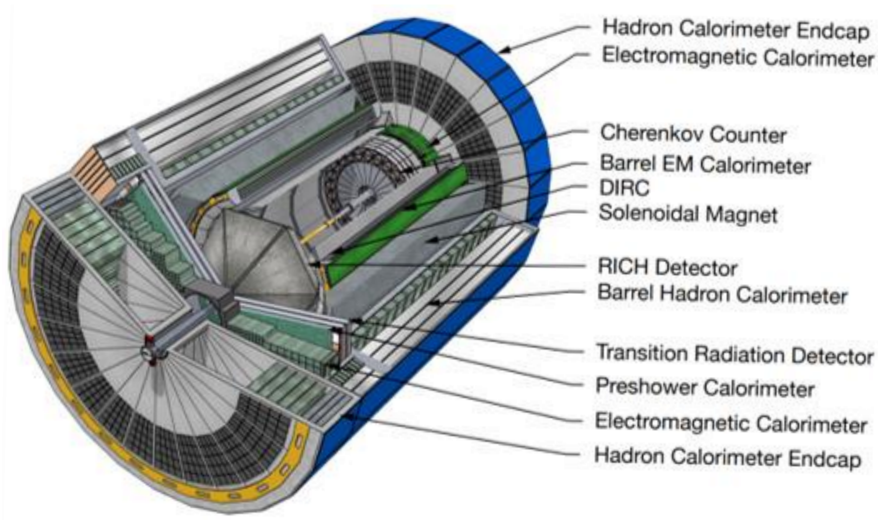

Fig. 1. The schematic diagram of the ePIC detector.

Description of $PbWO_4$ Crystals. The best resolution for electromagnetic calorimeters can be achieved through crystals. The general properties some of heavy crystals used in calorimetry are presented in Tab. 1. Based on the results of the many studies, the $PbWO_4$ crystal was selected for the EmCal.

Table 1

General properties of heavy crystals for calorimetry

Parameter	Lead Tungsten (PbWO4)	Lead Fluoride (PbF2)	Bismuth Germanate (BGO)	Luterium-Yttrium (LSO/LYSO)
Density (g/cm³)	8.28	7.66-7.77	7.13	7.2-7.4
Rad. length (cm)	0.89	0.93-0.95	1.10-1.12	1.16
Refractive index	2.20	1.82	2.15	1.82
Emission peak (nm)	420	~310, ~280	480	420
Moliere radius (cm)	2.19	2.22	2.15	2.07
Radiation type	Scint. (~13% Č)	Pure Čer.	Scint. (~1.6% Č)	Scintillation
Timing property τ (ns, %)	5 (73%); 14 (23%); 110 (4%)	Fast, <30	300	40-50
Effective Z	73	77	83	65
Hydroscopicity	No	No	No	No
Interact. Length (cm)	~20.7	~21	~22.7	~20.9
Rad. hardness (krad)	~20-50	~50	~1,000	>1,000
Light yield LY (photon/MeV)	~140-200	~2-6	~5,000-10,000	~5,000-30,000
d(LY)/dT (%/°C)	-2.0-2.5	No	-0.9	-0.2
Critical energy (MeV)	~9.6	8.6-9.0	7.0	9.6

Crystal calorimeters provide high resolution and detection efficiency, making them ideal for the EIC. Below are the summarized key physical and optical properties of $PbWO_4$ crystals [5], with more detailed information available in [6]. The selection of $PbWO_4$ for calorimetry is justified by several important factors that highlight its advantages over other materials, such as the remaining blocks. $PbWO_4$ is characterized by a small Molière radius ($R_M = 2.0\ cm$) and high density ($\rho = 8.3\ g/cm^3$), which enables high spatial resolution. In addition, the device has a very fast response time ($< 2\ ns$) and strong radiation resistance, which is extremely important in high-radiation environments. All these properties make $PbWO_4$ the best choice for calorimeters, ensuring fast and accurate data collection even under intense radiation conditions. Prior to constructing the calorimeter prototype, we studied the physical properties of the crystals and evaluated their quality control, as it is crucial to pre-examine, measure, and analyze the optical characteristics of the crystals used in calorimetry.

Crystal Characterization. The studies were conducted at the A. Alikhanyan National Science Laboratory (AANL). Measurements were performed on 20 crystals. The goal of measurements is to select the best crystals that meet the requirements for constructing the calorimeter prototype.

The following equipment was used during the work:

- Ocean Optics DH-mini Deuterium Halogen Light Source.
- Flame – the Next Generation of Miniature Spectrometers.
- DPX M80 Digital Microscope.

Mechanical Dimensions. Longitudinal (Z) and transverse (X,Y) dimensions of the crystals were measured with a high-precision caliper (with accuracy better than 50 μm) and a Mituito Electric Digital Height Gage sensor (with accuracy of 3–5 μm). The measure geometric parameters of the 20 crystals are presented in Tab. 2.

Table 2

The average dimensions of 20 $PbWO_4$ crystals

Crystal ID	X (mm)	Y (mm)	Z (mm)
142656	20.52	20.50	199.95
062641	20.35	20.54	199.84
142642	20.43	20.53	199.98
012649	20.45	20.49	199.90
122648	20.44	20.43	199.98
182783	20.51	20.45	199.99
042779	20.52	20.53	200.01
122774	20.54	20.51	200.01
042617	20.52	20.54	200.02
062616	20.55	20.53	200.02
022752	20.50	20.50	200.00
162794	20.52	20.51	200.03
082647	20.50	20.48	200.01
182770	20.49	20.49	200.01
142762	20.48	20.53	200.02
202771	20.50	20.49	200.00
122787	20.51	20.49	199.99
072644	20.49	20.57	197.97
142788	20.46	20.48	199.98
122611	20.46	20.43	200.19

Visual and Microscope Inspection of Crystals. The crystals were rectangular, with nominal dimensions of $20.5 \times 20.5 \times 200$ mm^3.

Visual Inspection. The samples were inspected visually to identify macro defects and inhomogeneity that may be visible to the eye. All surfaces of the samples were polished and no further surface treatments, other than simple cleaning with alcohol, were carried out before the measurements. We did not find any crystal with significant defects, e.g., cracks or bubbles in the bulk volume.

Inspection under Microscope. After the visual inspection and dimensions measurements, all crystals were examined with a DeltaPix digital microscope. The DMPX ZOOM 8X system is equipped with a high-quality 8x magnification lens and an HDMI camera, along with compatible software, providing a powerful platform for precise measurements, image capture, recording, and smooth high-speed live image inspection and measurement. An example of the damaged surface of the crystal is shown in Fig. 2.

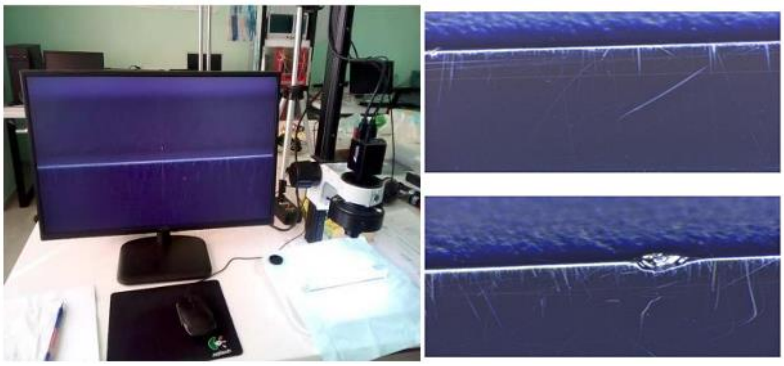

Fig. 2. The damaged surface of the crystal.

Optical Transmittance. The transversal transmittance of the crystals was measured using the 402 OCEAN-ART (FLAME-S-XR1) optical spectrometer. Its operational range encompasses ultraviolet to visible light (UV-Visible, λ =200–1025 *nm*). We used the OceanArt Software application, which allows for measurements of absorption, transparency, and reflection.

Transmittance Measurement Includes Three Simple Steps:

• Initial measurement (performed with the light on, without the crystal).

• Dark current measurement (with the light on, but the Shutter is closed).

• Transparency measurement (with the Shutter open, the crystal in place, between the input and output fibers).

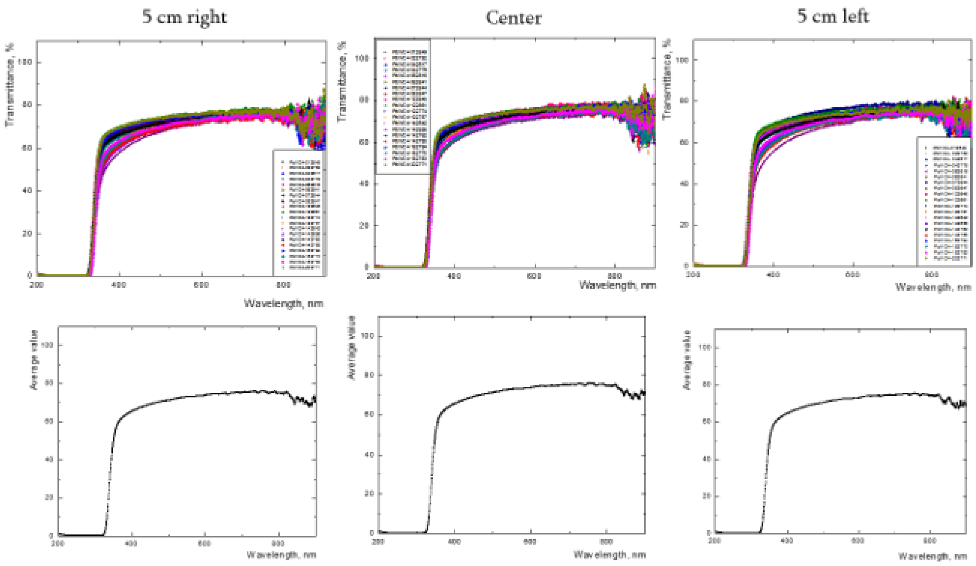

Fig. 3. The results of our transparency measurements of 5 $PbWO_4$ crystals and their averaged results.

For each crystal, measurements were taken 5 *cm* from the right, 5 *cm* from the left, and from the center of the crystal. The obtained data were then averaged.

The results of our transparency measurements of 5 $PbWO_4$ crystals and their averages are shown in Fig. 3.

The systematic uncertainties of the measurements were determined by repeating multiple transparency measurements in the same position for the same crystal. In our case, the crystal was $PbWO_4$-202771 and the transverse transparency was measured 10 times at the center of the crystal. To estimate the relative error of the measurements, we divided all the data (T_i) is based on the average value of transparency $\bar{T}$, $T_i/\bar{T}$, where $\bar{T}$ is calculated as

$$\bar{T} = \frac{T_1 + T_2 + T_3 + \cdots + T_{10}}{10}.$$

The data presented in Fig. 4 show that the measurement accuracy is better than 10%. The homogeneity of the crystal was evaluated by recording the variation in its transversal optical transparency near the wavelength corresponding to the transparency value of $T = 50\%$. The transversal transparency of the crystal (2 *cm* thick) was measured at several points, at distances ranging from 5 to 195 *mm* from its front surface. The average transparency of the crystals is 21.3%, 65.6%, and 71.7% for wavelengths of 360 *nm*, 440 *nm*, and 600 *nm*, respectively. The results show that the crystal is homogeneous.The optical characteristics of most Crytur crystals meet the requirements of the EIC calorimeter.

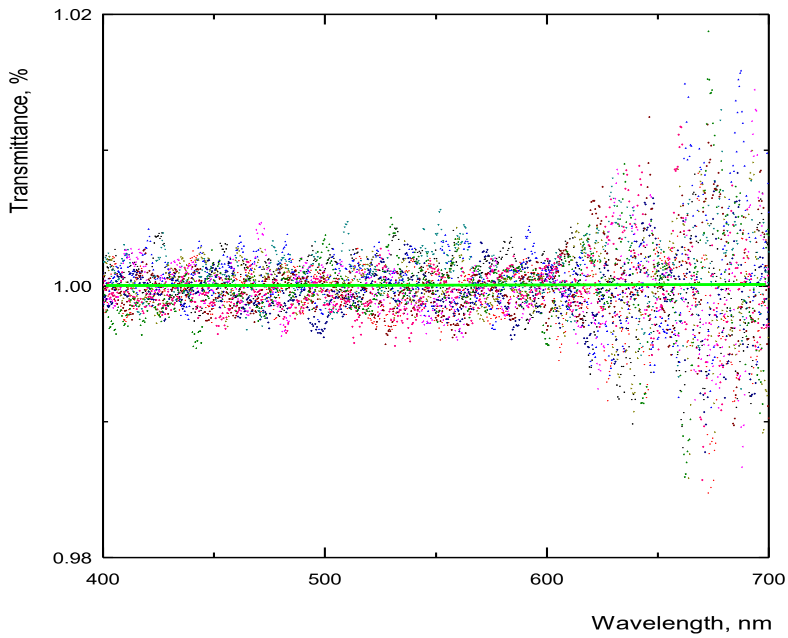

Fig. 4. The relative accuracy of the transparency measurements of the crystals.

In Fig. 5, the measurement results of $PbWO_4$ crystals are presented (transmittance as a function of wavelength):

a) CMS ECAL PWO crystals (2005);

b) AANL EmCal prototype PbWO crystals (2022).

This comparison demonstrates that our data align with the results of the 2005 CMS collaboration studies, confirming the consistency of modern production processes with earlier research findings.

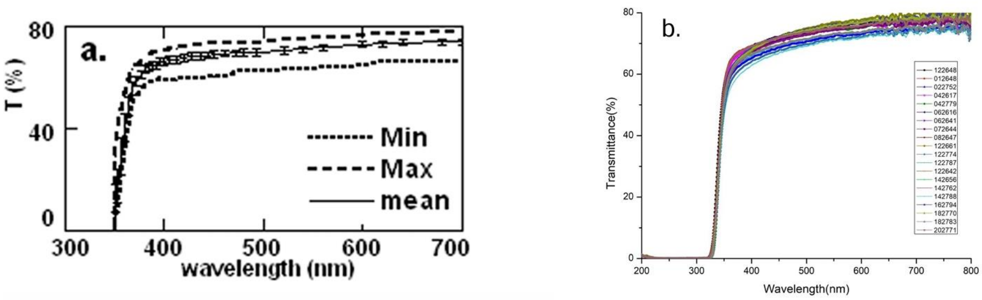

Fig. 5. Transmittance of a) CMS ECAL PWO crystals (2005) [8];
b) AANL EmCal prototype PbWO crystals (2022).

Light Yield. The light yield (LY) is measured by the number of photoelectrons registered for 1 MeV of energy absorbed in the crystal (pe/MeV) (Fig. 6). At the AANL, the light yield of the $PbWO_4$ crystal was estimated using cosmic muons passing perpendicularly through its 2 cm thick surface. The light yield of $PbWO_4$ was estimated to be an average 16 pe/MeV. One of the front surfaces of the crystal was coupled to the input window of a photomultiplier tube (PMT) with Bicron BC-630 optical grease, while all other surfaces were wrapped with one layer of ESR reflective film and one layer of black Tedlar film. The light yield measurements were conducted using two different PMTs, Hamamatsu H6533 and Hamamatsu R4125.

The measurements revealed that the photocathode of both PMTs only partially covered $(\backsim 50\%)$ the front surface of the crystal $(4\ cm^2)$. Therefore, this must be taken into account when comparing with other known data.

To generate triggers from cosmic muons, two identical scintillation counters were used, positioned at a small distance from each other (the active dimensions of the scintillator are $1.0 \times 1.0 \times 5.0\ cm^3$.

The signals from these counters, passing through a threshold of 20 mV on the “CAEN 16 Channel N843 CFD” module, generate NIM standard signals with a duration of 40 ns, which in the subsequent “N455 Logic Unit” coincidence module create a gate (Gate) of 150 ns width for the QDC charge-to-digital converter. The anode signals from the PMT were directly digitized using the charge-sensitive 12-bit integrating type CAEN V792N QDC analog-to-digital converter.

The data acquisition and recording program is based on CAEN The general code written in the C programming language for the company is intended to work with QDC, TDC, and discriminators through the “CAEN VME to USB 2.0/Optical Link Bridge” module that controls the electronic system. In our case, the program is adapted to work with the QDC. It is located on a computer running the Fedora Linux operating system, connected to the control module via a USB cable. Data recording is activated as soon as the QDC emits a LAM signal. All 16 channels of the QDC are read, and the data is written to a file in text format.

Fig. 6. The light yield (LY) is measured by the number of photoelectrons registered.

This output file is subsequently read by a program operating under the ROOT data processing software package, which generates histograms of the QDC signal distribution. The data can be processed in parallel with the collection.

Design and Construction of EmCal Prototype. A prototype calorimeter consisting of 4×4 $PbWO_4$ crystals is being designed, constructed and preliminarily tested at the AANL (Fig. 7).

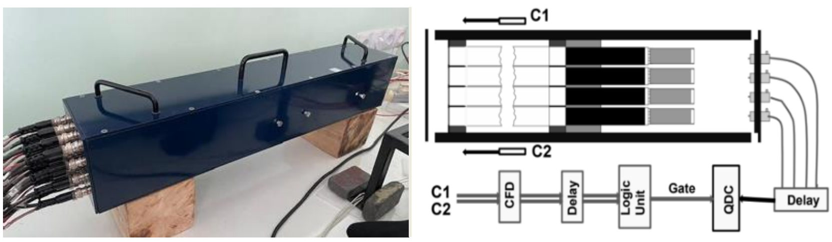

Fig. 7. Schematic diagram of the calorimeter prototype and some of construction parts.

After measuring the light yield, we tested the PMTs and their high-voltage dividers for the selected $PbWO_4$ crystals. The side surfaces of the crystals are wrapped with one layer of high- quality ESR reflective film and one layer of black light-isolating Tedlar paper. One of the two open front surfaces will be optically coupled with R4125 photomultiplier tubes (PMTs) using optical grease, while the opposite side will be used for the LED light monitoring system. The crystals are placed very close to each other ($100-200$ μm apart), and their positions are fixed by two plastic grids made with a 3D printer, one at the front and the other at the end of the crystals. Following this is the iron part that holds the 16 PMTs, with hole diameters of 19.5 mm, allowing the R4125 PMTs, wrapped with electrical insulation paper and magnetic shielding μ-metal sheet, to easily slide into the hole and be pressed against the crystal. Signal and high-voltage cables, as well as the necessary electronics and DAQ systems for prototype testing, are being prepared. The prototype was tested by cosmic muons. Muons, passing through all four layers of the calorimeter, lose a total energy of $\sim$ 100MeV ($\sim$ 25 MeV in each block). As a result, they generate $\sim$ $700-800$ photoelectrons, which is $\sim$ $7-8$ pe/MeV. This value is almost two times less than the measured value of the light output of $PbWO_4$ [9] because of the partial coverage of the end surface of the crystal with the PMT R4125 photocathode.

In Fig. 8 are shown the distributions of the total number of photoelectrons produced by muons in the prototype, derived with such calibration.

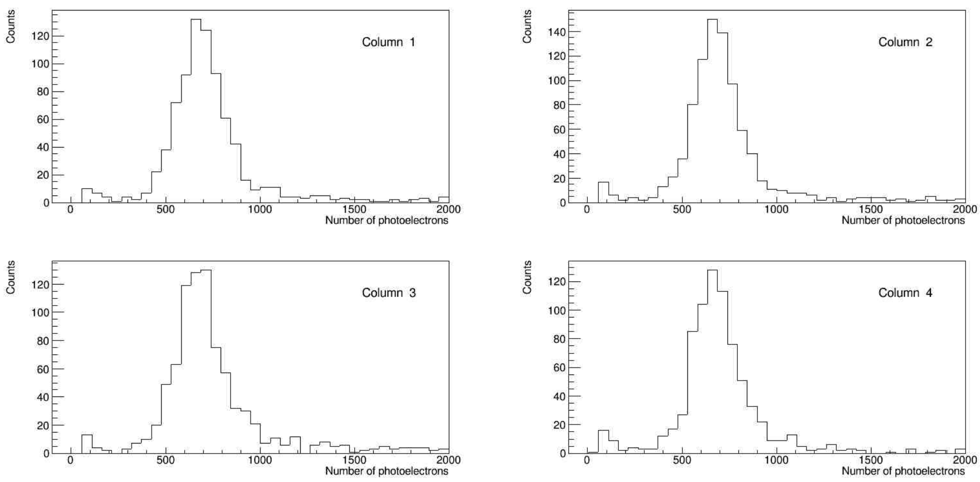

Fig. 8 Distributions of the total number of photoelectrons produced by cosmic muons in 4 columns of the prototype.

Summary and Outlook. The detailed studies of $PbWO_4$ crystals presented in this work show that they meet the stringent requirements for the construction of the electromagnetic calorimeter of the ePIC detector. The measurements of transmittance, uniformity, and light yield conducted during the research are crucial for accurate energy measurements in the calorimeter. Measurement accuracy is better than 10%. The light yield of $PbWO_4$ was estimated to be an average 16 pe/MeV.

Comparing our measurements to the studies conducted in 2005 by the CMS ECAL group (see [8]), we can conclude that our results align with the main findings of that research: Optical Transmission: Similar to the 2005 studies, our measurements indicate that $PbWO_4$ crystals exhibit high transparency of approximately 80% for wavelengths beyond 400 *nm*, meeting the crystal requirements. LY-T Correlation: Our results confirm the existing correlation, particularly around the 360 *nm* region, where a strong relationship between the light yield of the crystals and their optical transmission is observed. Variation Analysis: Likewise, our measurements validate that the efficiency of light production in the crystals fluctuates around the average value by approximately 25%. For homogeneous batches, these fluctuations reduce to around 5%. This comparison demonstrates that our data are consistent with the findings of the 2005 studies, affirming the compatibility of contemporary production processes with earlier research. Furthermore, it supports the quality control processes of CMS ECAL crystals.

We also aim to conduct detailed testing with cosmic muons in the future, followed by experiments using the LUE-75 electron beam and the C18 cyclotron's proton beams. The LUE-75 electron linear accelerator, operated at the AANL is the only electron accelerator in Armenia and neighboring countries that functions in the energy range of 15 to 75 *MeV* [7]. Linear accelerators, including the LUE-75, have a straight linear design where particles are accelerated step by step. This structure ensures more efficient energy transfer and enables the achievement of high velocities in a very short time.

No studies have yet been conducted below the 80 MeV energy range, and our research will be among the first to address this issue. Our primary objective is to irradiate the crystals with an electron beam, investigate how energy resolution changes in the low-energy range, and calculate the energy lost by the incident electrons within the crystals.

The analysis of the results demonstrates that the crystals exhibit excellent optical uniformity and stability, ensuring consistent measurements. The selection of the crystals and the construction of the prototype reinforce the possibility that the ePIC detector will achieve the necessary accuracy and efficiency for measuring complex processes in electron-ion collisions and for exploring new physical phenomena.

We express our heartfelt gratitude to our supervisors, Hamlet Mkrtchyan, Hrachya Marukyan, and Vardan Tadevosyan, whose invaluable guidance and support greatly contributed to the successful completion of this research. Their dedication and professional expertise not only enhanced the quality of our work, but also inspired and motivated us to achieve the highest standards. This work would not have been possible without their encouragement and constructive feedback.

We also extend our deepest gratitude to the ARPA Foundation for their support and for standing by us.

Received 30.01.2025
Reviewed 17.02.2025
Accepted 03.03.2025

REFERENCES

1. Khalek R.A., et al. Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report. *Nuclear Physics A* **1026** (2021).
https://doi.org/10.1016/j.nuclphysa.2021
2. Adam J., et al. ATHENA Detector Proposal-a Totally Hermetic Electron Nucleus Apparatus Proposed for IP6 at the Electron-Ion Collider. *Journal of Instrumentation* **17** (2022), P10019.
https://doi.org/10.1088/1748-0221/17/10/P10019
3. Bylinkin A., et al. Detector Requirements and Simulation Results for the EIC Exclusive, Diffractive and Tagging Physics Program Using the ECCE Detector Concept. *Nucl. Instrum. Meth. A* (2023).
https://doi.org/10.48550/arXiv.2208.14575
4. Alarcon R., et al. CORE-a Compact DetectoR for the EIC. e-Print: 2209.00496 [physics.ins-det]
5. Adzic P., Andelin D., Almeida N. The CMS Electromagnetic Calorimeter Group Radiation Hardness Qualification of $PbWO_4$ Scintillation Crystals for the CMS Electromagnetic Calorimeter.
https://doi.org/10.1088/1748-0221/5/03/P03010
6. Annenkov A.A., Korzhik M.V., Lecoq P. *Nuclear Instruments and Methods in Physics Research A* **490** (2002), 30–50. Lead Tungstate Scintillation Material.
7. Hakobyan A. Status of Electron Linear Accelerator LUE-75 of the A. Alikhanyan National Science Laboratory and Stability of Electron Beam Energy. *J. Contemp. Phys. (Armenian Ac. Sci.)* **56** (2021), 169.
https://arar.sci.am/dlibra/publication/309999
8. Dafinei I. Optical and Scintillation Properties of Lead Tungstate Crystals: A Statistical Approach. *CERN Technical Report* (2006), 019.
9. Horn T., Berdnikov V.V., et al. Scintillating Crystals for the Neutral Particle Spectrometer in Hall C at JLab. *Nucl. Instrum. and Methods* **A 956** (2020), 163375.
https://doi.org/10.1016/j.nima.2019.163375

Ա. Ս. ՀԱԿՈԲՅԱՆ, Դ. Գ. ԽՈՒՐՇՈՒԴՅԱՆ, Ա. Հ. ՄԿՐՏՉՅԱՆ

$PbWO_4$ ԲՅՈՒՐԵՂԻ ՈՒՍՈՒՄՆԱՍԻՐՈՒԹՅՈՒՆ ePIC EmCal ՆԱԽԱՏԻՊԻ ՀԱՄԱՐ

Հետազոտությունը ներկայացնում է $PbWO_4$ բյուրեղների բնութագրումը, որոնք նախատեսված են ePIC դետեկտորի EmCal էլեկտրամագնիսական կալորիմետրի նախատիպի համար, որը կառուցվում է ԱՄՆ-ի Բրուքհավենի ազգային լաբորատորիայի Էլեկտրոն-իոնային կոլայդերում։ Չափումներ են կատարվել "Crytur" ընկերության կողմից արտադրված 20 բյուրեղների վրա, որոնցից յուրաքանչյուրն այնուհետ մանրակրկիտ հետազոտվել է մանրադիտակի տակ։ Լայնակի թափանցիկության չափումներ են կատարվել բյուրեղների կենտրոնում,

ինչպես նաև կենտրոնից դեպի աջ և ձախ կողմեր հավասար հեռավորության վրա գտնվող մի քանի ֆիքսված կետերում՝ միապեսակությունը ուսումնասիրելու համար: Բյուրեղների միջին թափանցիկությունը կազմում է 21,3%, 65,6%, և 71,7% 360 *nm*, 440 *nm* և 600 *nm*: Յուրաքանչյուր բյուրեղի կենտրոնում 10 անգամ կրկնվող հաղորդունակության չափումները ցույց են տալիս, որ մեր չափումների ճշգրտությունը ավելի լավ է, քան 10%: $PbWO_4$-ի լույսի ելքը գնահատվել է միջինը 16 pe/MeV: "Crytur" բյուրեղների օպտիկական բնութագրերը համապատասխանում են EIC էլեկտրամագնիսական կալորիմետրի պահանջներին: Բոլոր անհրաժեշտ չափումները կատարելուց հետո կալորիմետրի նախատիպի համար ընտրվել են լավ վիճակում գտնվող 16 բյուրեղներ: EmCal-ի 4×4 նախատիպը նախագծվել, կառուցվել և փորձարկվել է տիեզերական մյուոններով:

А. С. АКОБЯН, Д. Г. ХУРШУДЯН, А. Г. МКРТЧЯН

ИССЛЕДОВАНИЕ КРИСТАЛЛА $PbWO_4$ ДЛЯ ПРОТОТИПА ЭЛЕКТРОМАГНИТНОГО КАЛОРИМЕТРА EmCal ДЕТЕКТОРА ePIC

В исследовании представлена характеристика кристаллов $PbWO_4$, предназначенных для прототипа электромагнитного калориметра EmCal детектора ePIC, который строится на электронно-ионном коллайдере в Брукхейвенская национальной лаборатории в США. Измерения проводились на 20 кристаллах, произведенных компанией "Crytur", каждый из которых затем был тщательно исследован под микроскопом. Измерения поперечной прозрачности проводились в центре кристаллов, а также для изучения однородности в нескольких фиксированных точках, равноудаленных от центра в правую и левую стороны. Средняя прозрачность кристаллов составляет 21,3; 65,6 и 71,7% для длин волн 360, 440 и 600 *nm* соответственно. Измерения пропускания, повторенные 10 раз в центре каждого кристалла, показывают, что точность наших измерений превышала 10%. Световой выход $PbWO_4$ оценивался в среднем 16 pe/MeV. Оптические характеристики кристаллов "Crytur" соответствуют требованиям электромагнитного калориметра EIC. После проведения всех необходимых измерений были отобраны 16 кристаллов в хорошем состоянии для прототипа калориметра. Был спроектирован, построен и испытан с космическими мюонами прототип EmCal размером 4×4.