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Optimization of the electron collection efficiency of a large area MCP-PMT for the JUNO experiment ☆

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A novel large-area (20-inch) photomultiplier tube based on microchannel plate (MCP-PMTs) is proposed for the Jiangmen Underground Neutrino Observatory (JUNO) experiment. Its photoelectron collection efficiency C_e is limited by the MCP open area fraction (A_{open}). This efficiency is studied as a function of the angular (θ), energy (E) distributions of electrons in the input charge cloud and the potential difference (U) between the PMT photocathode and the MCP input surface, considering secondary electron emission from the MCP input electrode. In CST Studio Suite, Finite Integral Technique and Monte Carlo method are combined to investigate the dependence of C_e on θ, E and U. Results predict that C_e can exceed A_{open}, and are applied to optimize the structure and operational parameters of the 20-inch MCP-PMT prototype. C_e of the optimized MCP-PMT is expected to reach 81.2%. Finally, the reduction of the penetration depth of the MCP input electrode layer and the deposition of a high secondary electron yield material on the MCP are proposed to further optimize C_e.

1. Introduction

The Daya Bay Neutrino Experiment is a China-based multi-nation particle physics project for neutrino physics research. In 2012, the Daya Bay Collaboration announced [1] a nonzero value for the neutrino mixing angle θ_{13} with a significance of 5.2 standard deviations. As a much larger follow-up, the Jiangmen Underground Neutrino Observatory (JUNO) is in development. It aims at determining the neutrino mass hierarchy and performing precision measurements of the Pontecorvo–Maki–Nakagawa–Sakata matrix elements [2,3]. As the key component of the main detector, the 15,000 photomultiplier tubes (PMTs) is critical to the experiment. Compared to the Daya Bay Neutrino Experiment, JUNO proposes more stringent requirements [4,5] for the PMTs. To match these requirements, a novel ellipsoidal PMT based on microchannel plate (MCP-PMT) is proposed.

Fig. 1 shows the 20-inch MCP-PMT prototype designed for JUNO. An ellipsoidal glass shell is used, resulting in a narrow transit time spread for the photoelectrons. Transmission and reflection photocathode layers are deposited on the inner face of the upper and lower semi-ellipsoidal glass shell respectively for the high quantum efficiency. Considering the difficulty of assembly and the assurance of a stable and high gain, dynodes in traditional PMTs are substituted by a pair of microchannel plates (MCPs).

Photoelectron collection efficiency (C_e) is a crucial parameter for the PMTs, which has a great impact on the detection efficiency and energy resolution. As a detector based on the MCP, C_e of the MCP-PMT is limited by the MCP open area fraction A_{open}. Considering the effective collection of photoelectrons and secondary electrons emitted by the electrons striking at the nickel-chromium

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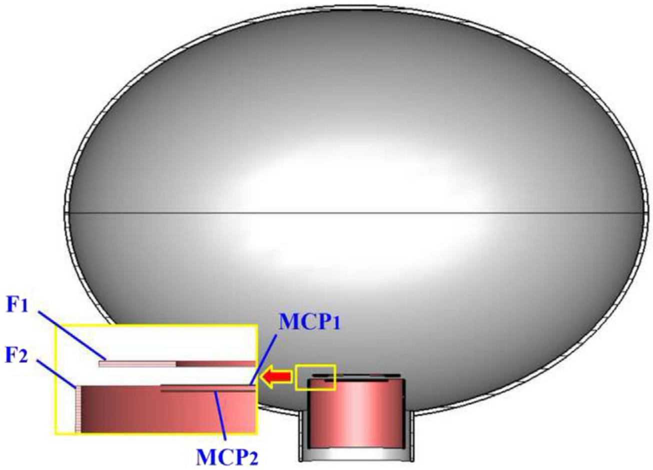

Fig. 1. Simplified prototype of the 20-inch MCP-PMT (model I). F_1 and F_2 represent two focusing electrodes.

electrode (MCP input electrode), dependence of C_e on the angular (θ) and energy (E) distributions of electrons in the input charge cloud and the potential difference (U) between the photocathode and the MCP input electrode are investigated using the simulation software, CST studio Suite [6]. Based on the simulation results, an optimized 20-inch MCP-PMT with higher C_e exceeding A_{open} is described. To further optimize the MCP-PMT performance, additional solutions applicable to the MCP are proposed.

2. Theory and computer simulation details

In this work, CST Studio Suite was used to build the model and calculate the resulting electric fields, electron trajectories, energies and velocities based on the Finite Integral Technique and Monte Carlo method.

Inspired from previous researches [7–14], the present simulations have the following considerations: (i) The electrostatic lens effect at the MCP channel entrances is simulated in detail, which evaluates the electron trajectories more accurately. (ii) The contribution of secondaries excited by the primary electrons striking the input (nickel-chromium) electrode [15–17] to C_e is considered. (iii) Three components of secondary electrons are well simulated: Electrons backscattered elastically on the impacted surface referred to as backscattered electrons. Electrons scattered from atoms inside the material and reflected back out referred to as rediffused electrons. True-secondary electrons are produced by electrons interacting with the material [18]. (iv) Energy conservation which prevents the aggregate energy of the emitted electrons from exceeding the primary electron energy is applied.

Considering secondary electron emission from the MCP input electrode (nickel-chromium electrode), the electron collection process is complex. As shown in Fig. 2, dotted arrow shows a primary electron entering the channel entrance directly, and this is referred to as the primary electron contribution (C_p). Solid arrows represent trajectories of primary electrons striking the input electrode layer. These primaries excite secondary electrons. Dashed-dotted arrows show secondaries which fly away or are absorbed by the MCP input electrode without emission. They make no contribution to C_e. Dashed arrows show generations of secondaries returning to the channels by an appropriate electric field. These secondaries make contributions to C_e, and are referred to as the secondary electron contribution (C_s). C_e can be written as the sum of two components

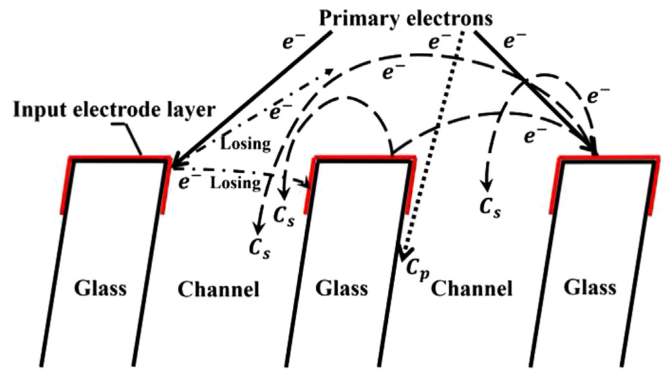

Fig. 2. Electron collection process of MCP. A dotted arrow is referred to as the primary electron contribution (C_p). Solid arrows represent trajectories of primary electrons which either make no contribution to C_e (dashed-dotted arrows) or generate secondaries that are further collected (dashed arrows). These latter are referred to as the secondary electron contribution C_s.

$$C_e = C_p + C_s \tag{1}$$

C_p is greatly affected by the angle of incidence θ (relative to the MCP input surface normal) of incoming electrons. The electric field upon the MCP input face affects the trajectories of secondaries, and consequently C_s. In addition, a higher secondary yield δ_e increases the probability to collect secondaries, which increases C_s. Nickel-chromium has a maximum secondary electron yield at normal incidence

$$(\delta_e)_{max} \approx 1$$

for primary energy $E \approx 500$ eV [19,20]. δ_e is related to E and θ and has been investigated experimentally [21–23] and theoretically. According to the Furman model [18], the electron yield (δ_{bs}) for the backscattered electrons is given by

$$\delta_{bs}(E,\ \theta) = \delta_{bs}(E, 0)[1 + e_1(1 - cos^{e_2}\ \theta)] \tag{2}$$

where $\delta_{bs}(E,\ 0)$ is the form for $\delta_{bs}(E,\ \theta)$ at normal incidence (θ=0), e_1 and e_2 are two adjustable parameters. The rediffused electrons yield (δ_{rd}) is expressed as

$$\delta_{rd}(E,\ \theta) = \delta_{rd}(E, 0)[1 + r_1(1 - cos^{r_2}\ \theta)] \tag{3}$$

where $\delta_{rd}(E,\ 0)$ is the form for $\delta_{rd}(E,\ \theta)$ at normal incidence (θ=0), r_1 and r_2 are two adjustable parameters. The true secondary electron yield (δ_{ts}) is

$$\delta_{ts}(E,\ \theta) = \hat{\delta}(\theta) D\left(\frac{E}{\hat{E}(\theta)}\right) \tag{4}$$

The scaling function $D(x)$ is chosen to ensure that δ_{ts} reaches a peak value $\hat{\delta}$ at an energy $\hat{E}$, namely,

$$D(x) = \frac{sx}{s - 1 + x^s} \tag{5}$$

where s is an adjustable parameter required to be greater than 1.

Generally, C_p is greatly affected by θ. θ and E determine δ_e mostly, and consequently C_s. C_s also depends on the electric field at the MCP input face. The collection efficiency C_e of the 20-inch MCP-PMT prototype can be recognized as a function of θ, E and the electric field at the MCP input face. The investigation of the dependence of C_e on the three factors can be resorted to simulations. It is however impossible to implement millions of MCP channels in the simulation model of a 20-inch PMT. According to this reality, simulations proceed in two steps. Firstly, a simplified model of the 20-inch MCP-PMT (model I) in which the MCPs are replaced by two perfect electric conductors (PEC) is built (see Fig. 1) to