Research progress of liquid xenon detection technology in medical imaging

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Abstract: Single photon emission computed tomography (SPECT) and positron emission tomography (PET) are important functional medical imaging technologies. Its function is to study the process of disease development and track radioactive labeled isotopes in organs, which can be used for early cancer screening, disease pathology research, and guidance for new drug development. Currently, most of the SPECT and PET systems used are crystal detectors with crystal scintillators as the medium. The detection technology based on liquid xenon is a new type of particle detection technology. Liquid xenon can generate both flash and ionization signals simultaneously. The performance of liquid xenon detection technology greatly exceeds that of traditional crystal detectors by combining optical signals and charge readout. We review the research progress of liquid xenon detection technology in medical imaging experiments in recent years.

Keywords: liquid xenon detection; Silicon photomultiplier tube; Medical imaging; Time projection room; Single photon emission computed tomography; Positron emission tomography imaging

1.Basic properties of liquid xenon

Xenon gas is an inert gas with a content of less than 0.1 ppm in the air. It can be prepared into high-purity xenon gas (99.999%) through air separation and further low-temperature distillation technology. High purity xenon gas is cooled to -100 ℃ by a refrigerator or liquid nitrogen refrigeration, forming liquid xenon (LXe) with a density of about 3 g/cm3 [5]. External incident particles scatter with xenon nuclei or outer electrons, and the scattered particles gain some kinetic energy, producing recoil. These additional energies are released in the form of scintillation photons and ionized electrons, generating flash and ionization signals in liquid xenon. Among all inert gases, xenon has the highest ionization yield and scintillation yield, meaning that the additional energy deposited inside can generate strong detectable flash and ionization signals. Except for the xenon 136 isotope with a half-life of up to 1021 years, xenon does not have any other long-lived radioactive isotopes, so pure xenon itself has a lower background. At room temperature, xenon is a gas and purification is relatively simple. Then, the high atomic number (54) and density (3 g/cm3) of liquid xenon make it highly effective in preventing penetrating radiation. Compared with crystal scintillators such as NaI (Tl) or semiconductors such as Ge, liquid xenon provides a good shielding effect, which is difficult for other scintillators to achieve. The characteristics of liquid xenon as a scintillator are summarized in Table 1, which has good advantages compared to commonly used crystals LSO and BGO [6]. As an excellent detection medium, liquid xenon has a high scintillation rate and fast scintillation decay time, making it more suitable for application in nuclear medicine. Moreover, liquid xenon is cheaper than current crystals and has significant advantages.

2.Positron emission tomography imaging

Positron emission tomography (PET) is an advanced diagnostic imaging technique. The principle of PET system is to inject drugs labeled with positron radioactive isotopes into the organism, embed them into specific molecules within the organism, and measure their uptake by different organs or cancer cells. By reconstructing the response lines of two 511 keV gamma photons flying in opposite directions generated during positron annihilation, an image displaying the position of positron emission radioactive isotopes can be obtained. When annihilation occurs within a few millimeters of the positron source, simultaneously detecting the coordinates of two photons and their interaction points in the detector can determine the position of the positron radiation source in the patient's body as a straight line. A set of such intersecting lines can perform three-dimensional reconstruction of the radiation source. Therefore, the main requirements for PET detectors are high photon detection efficiency, high energy resolution, high position resolution, and reduced false photon combination time resolution. The PET detector must detect 511 keV gamma rays very effectively and have a positional resolution of 1 mm. To limit the number of photon false combinations from different annihilation processes (known as random annihilation), a time resolution of 3 ns or more sensitive is usually required. The interaction of photons before entering the sensitive area of the detector can cause image distortion. These photons can be removed by depositing 511 keV in the detector. In order to limit the entry of most scattered photons into the detection sensitive area, an energy resolution of no less than 9% (FH WM) is required.

The liquid xenon detector used for improving medical imaging has rapidly developed, which is a practical application beneficial to the entire society. The use of liquid xenon detectors in high-speed and highly sensitive PET systems has potential importance for medical imaging. Compared with traditional systems, liquid xenon detectors have practical issues such as cost, safety, and complexity. In addition, there are other requirements such as fast image generation and complex Compton reconstruction. Therefore, more research is needed before this technology can be applied. In China, liquid xenon detection technology is becoming more mature in dark matter detection, but research in medical imaging is not yet in-depth. It is hoped that this study can play a certain role for domestic researchers.