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Cherenkov detector of ^{90}Sr based on aerogel as radiator

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ABSTRACT

^{90}Sr is a highly radiotoxic fission product, which may pollute the environment following an accident in a nuclear power plant. It is a pure β emitter and thus difficult to detect by standard methods. Recent progress in silica aerogel production, as well as the new multianode photomultiplier tubes (PMTs), offer possibilities for the detection of ^{90}Sr, based on Cherenkov radiation of β particles emitted by its daughter ^{90}Y. An appropriate choice of the aerogel refractive index (produced in the range between 1.005 and 1.06) determines the threshold for Cherenkov radiation and thus separates between higher and lower energy β particles. Multianode PMTs permit the determination of the Cherenkov photon yield, offering additional discrimination. An apparatus was constructed for the detection of the relatively higher energy β particles emitted by ^{90}Y ($E_{max} = 2.28$ MeV) and the detector performance was studied.

1. Introduction

Strontium ^{90}Sr is a very radiotoxic isotope because it accumulates in bone tissue. It has a rather long half-life of 28.2 years. Its daughter ^{90}Y emits β particles of 2.27 MeV end-point energy. It is a fission product, so it may pollute the environment as a result of either a nuclear power plant accident or a nuclear weapon explosion.

^{90}Sr and its daughter ^{90}Y are pure β emitters so they cannot be detected by standard and accurate methods of gamma ray spectroscopy. Other β emitters in the sample, with overlapping spectra, will lead to erroneous results in total beta counting or would complicate matters in the usual β spectroscopy. Cherenkov radiation offers the possibility of a well-defined β-energy cutoff by choosing an appropriate refractive index of the Cherenkov radiator. In addition, it has been demonstrated [1,2] that the counting efficiency rises steeply above threshold. Not very many isotopes have β end-point energies above 2 MeV, so ^{90}Y, the daughter of ^{90}Sr, with $E_{\gamma}^{max} = 2.27$ MeV, seems well suited for detection through Cherenkov radiation.

Recent progress in production techniques has led to improved properties of aerogels [3,4], most important of which is the greater transparency for Cherenkov photons in the wavelength region of highest photomultiplier sensitivity. On the other hand, multianode photomultipliers allow counting of the number of Cherenkov photons for each incident β particle. In the present paper we report on the results obtained with such an apparatus.

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2. The apparatus

The apparatus (Fig. 1) consists of sample holder attached to a multiwire proportional chamber (MWPC), a light reflector with an aerogel radiator, a multianode PMT array and a scintillation detector. All the parts are enclosed in a light tight box.

The $5 \times 5\,cm^2$ large MWPC consists of anode wire plane positioned between two aluminized mylar cathode planes. With such a light design, it has a high efficiency for charged particles (~99%) within the acceptance η_a and low efficiency for gamma rays (~0.1%). The acceptance η_a for electrons from sample amounts to 0.36. The MWPC signals a charged particle, distinguishing it from events where a gamma photon from the source generates an energetic electron in the aerogel Cherenkov radiator or in the PMT glass window.

The radiator consist of a block of $5 \times 5 \times 5\,cm^3$ aerogel with a refractive index of $n = 1.047$ and 40 mm transmission length at $\lambda = 400$ nm [6]. The electrons with kinetic energy above threshold (1.21 MeV) emit Cherenkov photons, which are collected by an array of 2×2 16 channel Hamamatsu R5900-M16 multianode photomultipliers with 18 mm × 18 mm active area each [5]. To increase the light yield, the radiator walls are covered with the aluminized mylar foil.

A 30 cm × 30 cm large scintillation detector is placed on top of the apparatus to detect and vetos background-contributing cosmic particles.

All the channels are amplified, discriminated and registered on the VME CAEN V673A multihit TDC unit. To reduce the number of electronic channels, four neighbouring channels from the multianode PMTs are connected together. The data are read out by a program running on the PC and stored on disk for further analysis.

The data acquisition is triggered by a hit in the MWPC.

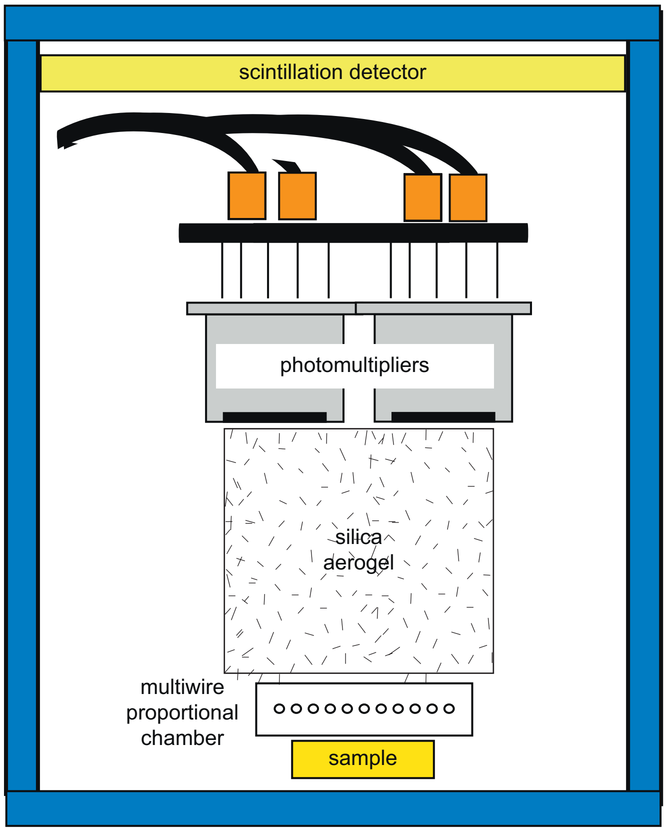

Fig. 1. The apparatus for measuring the ^{90}Sr activity.

3. Analysis and results

Cherenkov photons appear as peaks in the PMT-MWPC time difference of the first PMT hit (Fig. 2). The number of hit PMT channels is determined by counting the number of hits within a 90 ns time window, which corresponds to ($\pm 2\sigma$). An additional cut has been made on the time difference between the first hit and the concerned hit on the PMT (Fig. 3). Since all the Cherenkov photons are prompt, the off time hits which might be attributed to nonsimultaneous cross-talk hits are thus suppressed.

For ^{90}Sr source the distribution of a number of hit channels per event is shown in Fig. 4a. The number of random coincidences is consistent with an estimate based on the count rate on the MWPC and the dark current count rate on the PMTs (around 10 Hz per channel), and can be neglected. The apparatus is, however, also triggered by cosmic charged particles. While the particles within the geometrical acceptance are detected by the scintillation detector (70%), the others still contribute to the signal. To account for this, the data were also collected without the source. The distribution of the number of hit channels per event is shown for events without a signal in the scintillation detector in Fig. 4b. Note that it has a higher mean number of hits than the distribution of the ^{90}Sr source.

The resulting background rate of the events without the scintillation signal amounts to 40 events per hour and can be neglected for high activity samples, while it remains the reason for the relatively high minimum detectable activity [7]:

$$A_{\min} = \frac{3 + 3.29\sqrt{N_b t}}{\eta_a t} \tag{1}$$

which is determined for measurement time t, background rate N_b and MWPC geometrical acceptance η_a. For the case of realistic 3 h measurement it amounts to 0.3 Bq. The normalized background distribution should be thus subtracted from the low activity sample distribution.

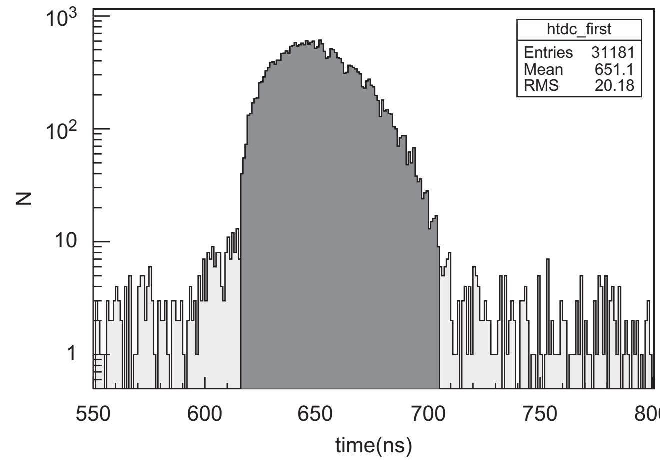

Fig. 2. Time difference of an individual channel between the PMT and MWPC signal. The shaded region indicates coincidence hits in the analysis.

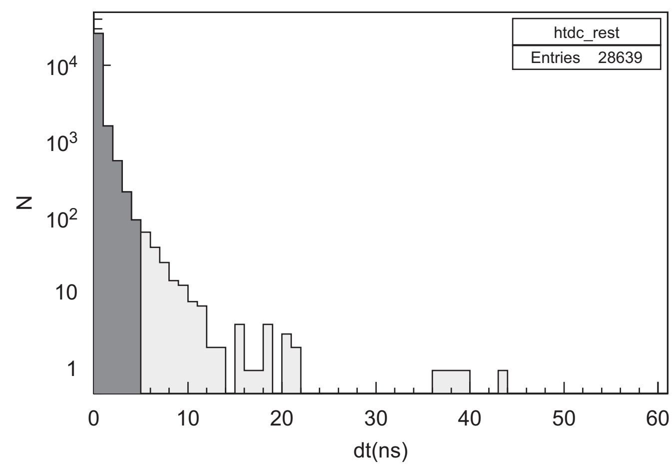

Fig. 3. Time difference between individual channels on the detector array. Only the hits with the time difference relative to the first hit of less than 5 ns are used in further analysis.

Four sources were used in order to calibrate the system. ^{42}K and ^{32}P were produced by neutron activation with the TRIGA reactor at the Jožef Stefan Institute, while ^{90}Sr/^{90}Y and ^{137}Cs were purchased from Amersham. Activities were estimated from data given by the producers as well as from the MWPC count rates and the corresponding solid angle. Among the sources used, ^{32}P are ^{90}Sr/^{90}Y are pure β-emitters, while ^{137}Cs and ^{42}K also emit the γ's. The resulting distribution of the number of hit channels per event is show in Fig. 5. All but the ^{137}Cs distribution agree with the simulation. Although the ^{137}Cs β end-point energy is below the Cherenkov threshold, some counts have been registered also for this isotope. They are due to photons coming from the radiator box, as has been verified by covering the aerogel photon exit window with black paper which resulted in a considerable reduction of the count rate.

The relative efficiency for the detection of particular source is determined by dividing the number of events with hits by the total number of events registered by the MWPC. The resulting efficiency for tested sources is shown in Fig. 6; for detecting ^{90}Sr it amounts to 0.024. Note that the efficiency is a steep function of the beta spectrum end-point energy.

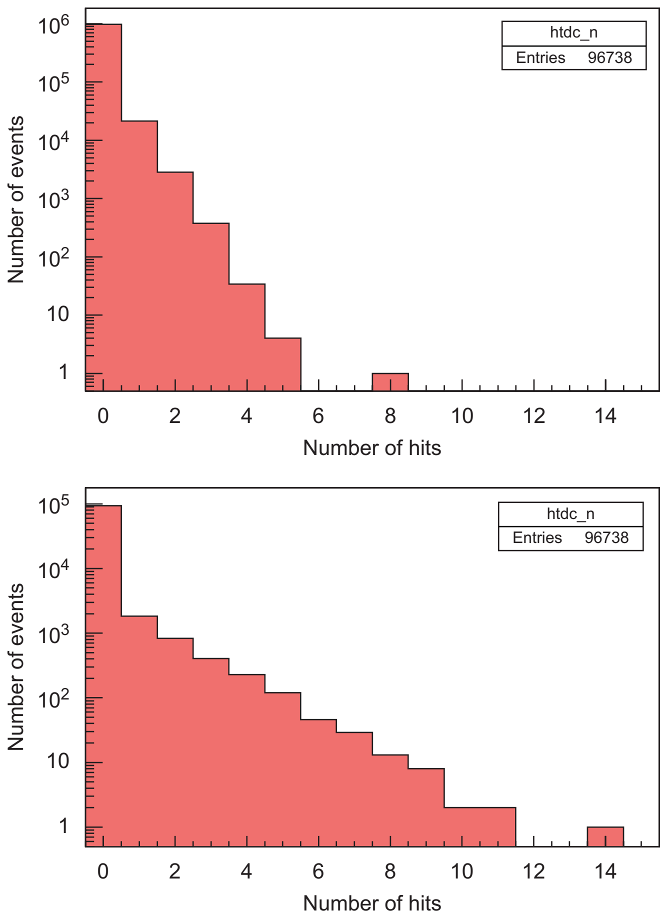

Fig. 4. Distribution of the number of the hit channels for the ^{90}Sr source (top) and for the background events (bottom).

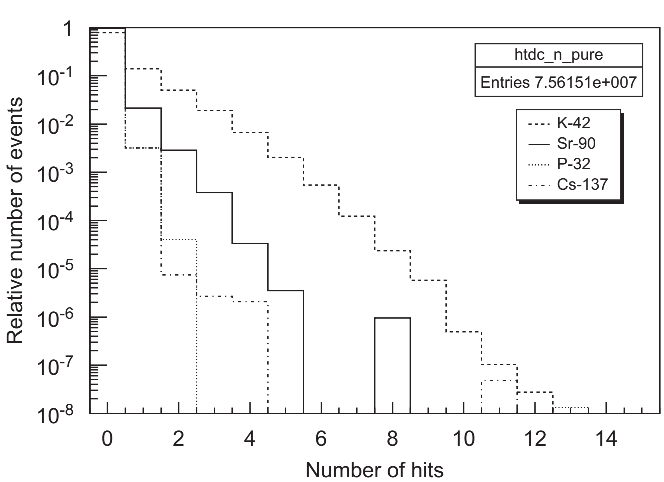

Fig. 5. Distribution of the background subtracted number of the hit channels per event for the 1 mio. of ^{90}Sr, 42 mio. of ^{42}K, 19 mio. of ^{32}P and 75 mio. of ^{137}Cs events. The distributions are all normalized to the same number of events.

4. Conclusions

An apparatus was constructed for the detection of ^{90}Sr/^{90}Y in environmental samples with Cherenkov radiation of β-particles in silica aerogels. The Cherenkov photon detection is performed with a multianode photomultiplier (Hamamatsu R5900-00-M16). With the signal from a thin wire chamber in coincidence and a cosmic ray background veto from a scintillation counter, the efficiency for the detection amounts to 0.024 with the minimal detectable activity of about 0.3 Bq.

To further remove the cosmic ray background, a larger scintillator should surround the MWPC and the aerogel. We expect that such an apparatus would be an efficient detector of ^{90}Sr of activity below 0.1 Bq.

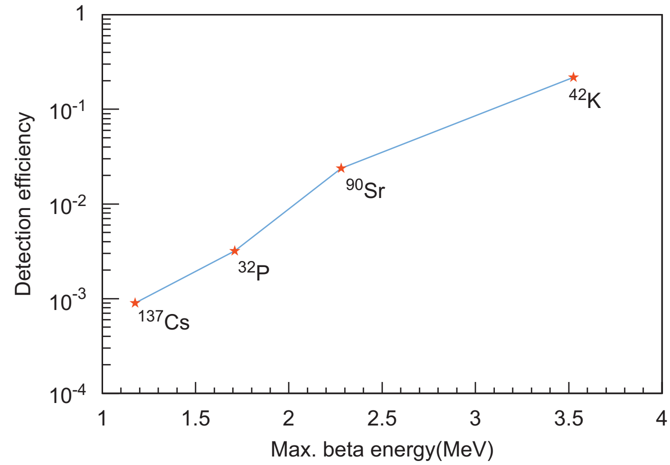

Fig. 6. Efficiency defined as count rate divided by appropriate activity as a function of beta spectrum end-point energy.

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