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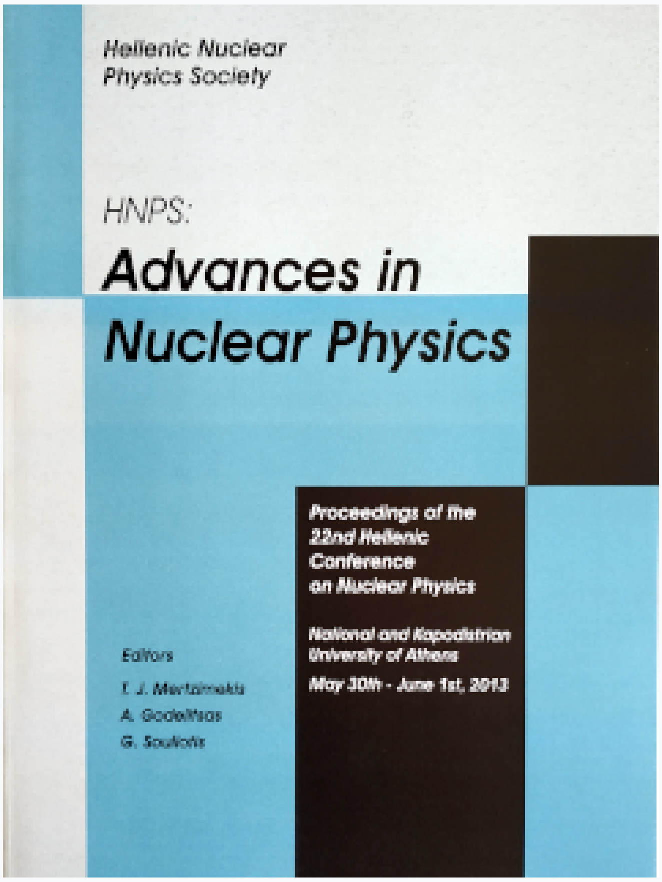

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Nuclear Reactor Neutrino Detection with the Spherical Proportional Counter

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Abstract

Nuclear Power Reactors are the most powerful neutrino sources as they emit large numbers of antineutrinos, at energies up to 10 MeV. The reactor neutrino detection is very important for fundamental physics goals, as well as for applications, among them being the possibility to determine the isotopic composition of the reactor's core. This could lead to application of neutrino spectroscopy for reactor monitoring, either for improving the reliability of operation of power reactors or as a method to accomplish certain safeguard and non-proliferation objectives. We present here the conditions on detecting neutrinos coming from nuclear reactors with the Spherical Proportional Counter (SPC), by exploiting the coherent neutrino-nucleus elastic scattering.

Keywords: Spherical Proportional Counter, SPC, Reactor neutrinos, neutrino detection

1. Introduction

Neutrino physics is a prominent research area incorporating novel and demanding experimental techniques. Neutrinos hide many answers for important questions in physics, such as the choice between cosmological models, supernova explosions, dark matter, etc. Furthermore, neutrino detection has many technological applications, such as the monitoring of nuclear reactors via detection of nuclear reactor neutrinos, allowing the determination of the isotopic composition of the reactors core. Here we study the conditions for the detection of nuclear reactor neutrinos through neutrino-nucleus coherent elastic scattering. Nuclear power reactors are copious neutrino sources. They emit large numbers of antineutrinos, about 5×10^{20} per second, broadly distributed over energies up to 10 MeV, with a peak at $0.5 - 1$ MeV [1]. The detection of nuclear recoils that are coming from the coherent elastic scattering demands a detector with ability of detection in the sub-keV region, very low noise and as much mass/volume as possible. A detector which is promising, in terms of the above, is the Spherical Proportional Counter (SPC)[2]. The SPC consists of a hollow sphere (usually copper), with a small ball (stainless steel or Si) in its center, as positive electrode. The diameters of the two spheres, as well as the voltage, the gas mixture and the detailed geometry of the central electrode, are all parameters to be optimized , depending on the experimental needs. In the simplest design, the SPC is a proportional amplification counter, with a volume of a diameter of some mm around the small central spherical electrode being the amplification region. Readout is by a single channel electronic chain. The SPC is proven to detect energy deposition below even 100 eV (very low detection threshold) and it has very low electronic noise because the capacity depends only from the small ball radius ($C = 4\pi\varepsilon_0 r^2$)[2]. As a matter of fact, large drift volumes can be built. All these attributes make the SPC a very good candidate for the detection of nuclear reactor neutrinos.

2. Detecting neutrinos with the SPC

For relatively low energy neutrinos ($E < 30$ MeV), the energy transfer to the nucleus is small and the nucleus degrees of freedom are not excited. As a matter of fact, only the kinetic energy of the nucleus changes. The reaction we consider for the detection of the reactor neutrinos is the coherent neutrino-nucleus (A,Z) elastic scattering

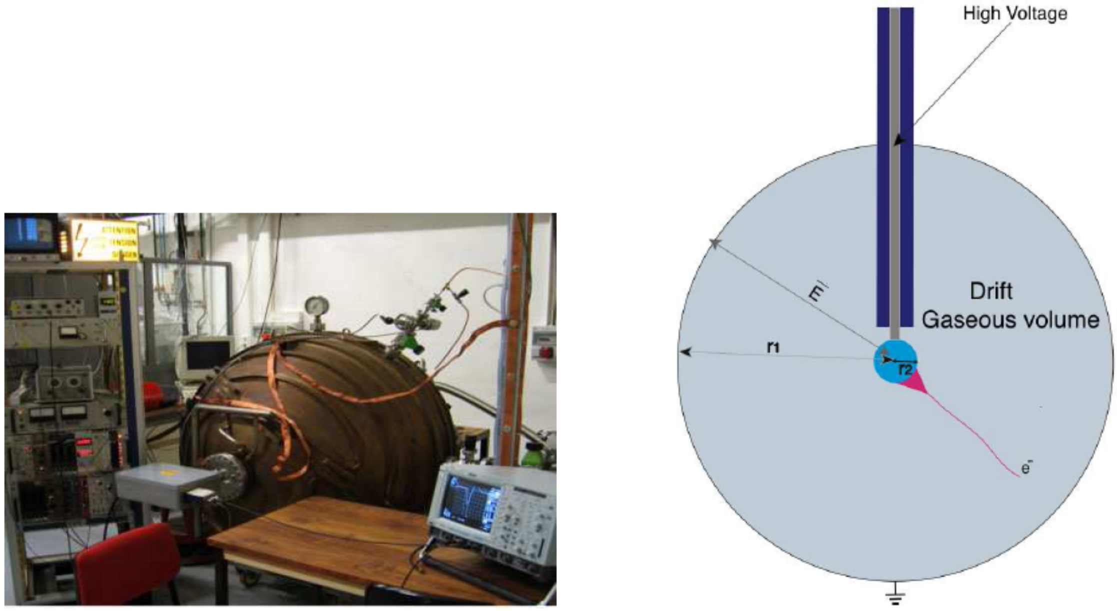

Figure 1: A positive High Voltage (HV) applied in the central electrode, produces a radial electric field in the inner spherical volume. An electron created in the gas volume drifts to the central electrode, producing an avalanche in the last few mm of its path. Positive ions moving backward are inducing a signal to the preamplifier.

$$\nu + (A,Z) \rightarrow \nu' + (A,Z)' \tag{1}$$

which is a neutral current weak interaction, with a small energy transfer and sensitive to all neutrino flavours. The cross section of the neutrino nucleus elastic scattering has the form:

$$\left(\frac{d\sigma}{dT_A}\right) = \frac{G_F^2 A m_N}{2\pi}(\frac{N^2}{4})F_{coh}(T_A, E_\nu) \tag{2}$$

with

$$F_{coh}(T_A, E_\nu) = F^2(Q^2)\left(1 + (1 - \frac{T_A}{E_\nu})^2 - \frac{A m_N T_A}{E_\nu^2}\right) \tag{3}$$

where m_N is the nucleon mass, A is the nuclear mass number, N is the neutron number, T_A is the kinetic energy of the recoiling nucleus, E is the neutrino kinetic energy, Q^2 is the square of the four-momentum transferred

$$Q^2 = \frac{2E_\nu^2 T_A M_A}{E_\nu^2 - E_\nu T_A} \tag{4}$$

and $F(Q^2)$ is the nuclear form factor. The effect of the nuclear form factor depends on the target, since the maximum recoil energy depends on the target.

3. Reactor neutrino spectra

The electron antineutrinos in a nuclear reactor, are produced dominantly by the beta decay of the fission products. In Table 1 the total number of $\bar{\nu_e}$ per fission above 1.8 MeV is given for the most common parent fissile nuclei .

Accurate information on the anti-neutrino flux from ^{235}U, ^{239}Pu, and ^{241}Pu can be obtained by the measurement of the beta spectra from the exposure of these isotopes to thermal neutrons. These beta spectra

l	$\mathbf{N_l^{\nu}}$	$\mathbf{E_l}$
^{235}U	1.92 ± 0.019	201.7 ± 0.6
^{238}U	2.38 ± 0.020	205.0 ± 0.9
^{239}Pu	1.45 ± 0.021	210.0 ± 0.9
^{241}Pu	1.83 ± 0.019	212.4 ± 1.0

Table 1: Total number of $\bar{\nu}_e$ per fission above 1.8 MeV and energy release per fission for the isotopes relevant in nuclear reactors [10].

have to be converted into anti-neutrino spectra, taking into account the beta branches involved. The errors on these fluxes are at the level of a few percent. The antineutrino flux from all the fission products an isotope l is given by

$$\phi_l(E_\nu) = Exp\left(\sum_{k=1}^{K_l} a_{kl} E_\nu^{k-1}\right) \tag{5}$$

in units of anti-neutrinos per fission and in MeV. The coefficients a_{kl} are determined by a fit to the values, of the neutrino energy and the corresponding anti-neutrino flux, respectively [8].

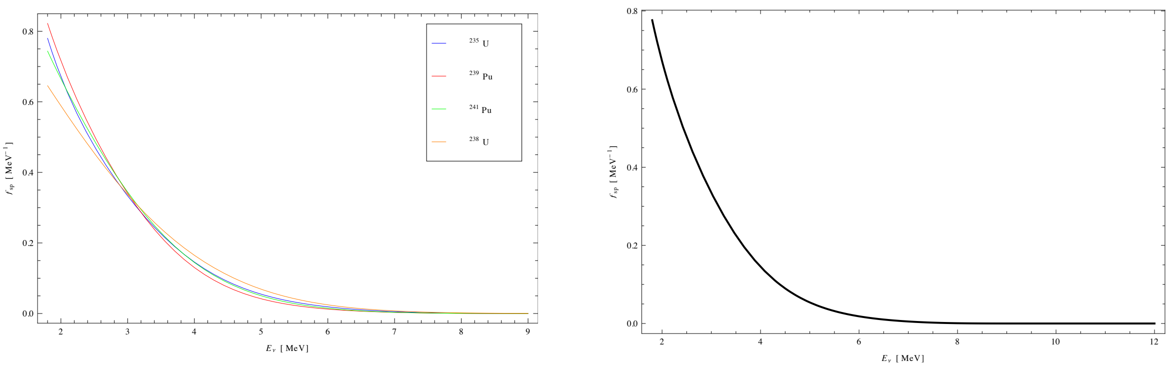

Figure 2: Calculated reactor antineutrino spectra, *Left*: antineutrino spectrum of each isotope, *Right*: total antineutrino spectrum. For $238U$, which does only undergo fast neutron fission, no similar measurements exist, and one has to rely on theoretical calculations.

The number of events we expect to count with our detector can be calculated by

$$N_{ev} = \frac{N_d}{4\pi L^2} \sum_l N_l^{fis} \int_{(T_A)_{thrs}}^{(T_A)_{max}} \int_{(E_\nu)_{min}}^{(E_\nu)_{max}} \frac{d\sigma}{dT_A} \phi_l(E_\nu) dE_\nu dT_A \tag{6}$$

Here N_d is the number density of the target nuclei in the detector and L is the distance between the reactor core and the detector. If the initial composition of the reactor fuel is known, the number of fissions per second N_l^{fis} of each isotope l can be calculated accurately (better than 1%) at each burn-up stage by core simulation codes.

(a)

$(T_A)_{thrs}$ $[eV]$	σ_{tot} $/10^{-41}$ cm^2
	$(T_A)_{max} = 0.36$ keV
0	8.825
100	4.551

(b)

$(T_A)_{thrs}$ $[eV]$	σ_{tot} $/10^{-41}$ cm^2
	$(T_A)_{max} = 0.115$ keV
0	107.65
100	0.2563

Table 2: Total cross section (a) Neutrino-Ar, (b) Neutrino-Xe interactions, for the total reactor anti-neutrino spectrum. The maximum neutrino recoil energies are also presented.

4. Experimental

The differential cross sections for Ar and Xe as target nuclei, are obtained after folding the cross section with the total reactor anti-neutrino spectra. The results are presented in the following sections, as well as the total cross sections of these interactions. The distance of the detector from the reactor core is considered as $L = 100$ m. The gas filling of the detector is at pressure $P = 10$ atm, at temperature of $T = 300$ K. The event rate is presented for SPC radii of 0.65, 4, 10 m and recoil thresholds of 0 and 100 eV. The reason we consider such a low threshold is that the total reactor anti-neutrino spectrum extends up to a few MeV and, therefore, the kinetic energy of recoiling nuclei limited well below 1 keV. We consider a Pressurized Water Reactor (PWR), with UOx fuel, the reactor type being N4 (with 4 steam generators), with a thermal power of 4.27 GW and electrical power of 1.5 GW. It is supposed that the reactor is in its initial burning cycle, with composition of 60.5% ^{235}U, 7.7% ^{238}U, 27.2% ^{239}Pu, and 4.6% ^{241}Pu.

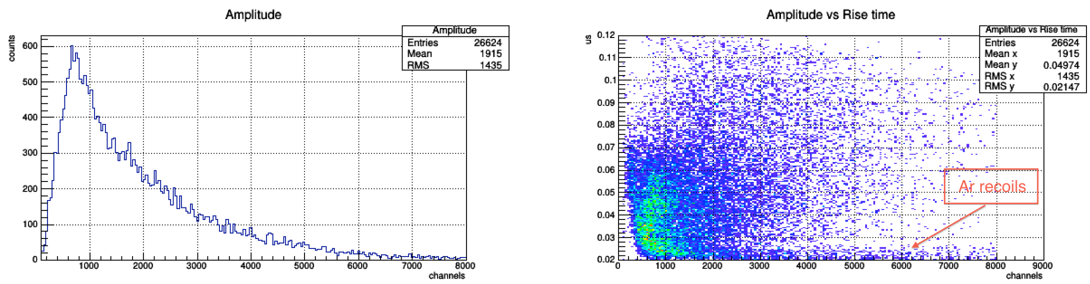

Figure 3: Experimental measurements of the nuclear recoils produced by the elastic scattering of the Ar atoms with the neutrons from an Am-Be source. The composition of the gas mixture is Ar (91%), CH_4 (5%) and N_2 (4%). We present *Left*: the amplitude and *Right*: the amplitude vs rise time of the pulse. The nuclear recoils are visible at the low rise time part of the left graph.

A spherical proportional counter with $R = 0.65$ m is under development in Thessaloniki, for reactor neutrino detection. To simulate the neutrino low energy recoils with the gas of the detector we measure the recoils produced by neutrons from an Am-Be neutron source. The rate of the source is 6.6×10^4 neutrons/s. In figure 3 are presented the signals of the detector with a gas mixture of Ar (91%), CH_4 (5%) and N_2 (4%). The Ar recoils signals have lower rise time and are well separated from the cosmic rays.

(a)

$(T_A)_{thrs}$ $[eV]$	Event rate /[yr]		
	$R = 0.65\ m$	$R = 4\ m$	$R = 10\ m$
0	130850	$3.050 \cdot 10^7$	$4.779 \cdot 10^8$
100	67485	$1.573 \cdot 10^7$	$2.462 \cdot 10^8$

(b)

$(T_A)_{thrs}$ $[eV]$	Event rate /[yr]		
	$R = 0.65\ m$	$R = 4\ m$	$R = 10\ m$
0	$1.596 \cdot 10^6$	$3.720 \cdot 10^8$	$5.823 \cdot 10^9$
100	3800	886023	$1.387 \cdot 10^7$

Table 3: Number of events, for an (a) Ar filled (b) Xe filled detector, for three different radii of the SPC, at $0, 100\ eV$ thresholds. The event rate is for a detector at 10 atm of pressure, at temperature of $300^o\ K$ and at a distance of 100 m from the reactor core.

5. Conclusions

From the calculations presented above, is obvious that it is possible to detect neutrinos coming from nuclear reactors by exploiting the neutrino-nucleus coherent elastic scattering. To do that we need a detector with very low detection threshold, less than $100eVs$. The SPC detector seems to fulfil this condition.

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Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης