Background simulation for the Spherical Proportional Counter and its use for the detection of optical photons

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Abstract. The recently developed Spherical Proportional Counter [1] allows to instrument large target masses with good energy resolution and sub-keV energy threshold. The moderate cost of this detector, its simplicity and robustness, makes this technology a promising approach for many domains of physics and applications, like dark matter detection and low energy neutrino searches. Detailed Monte Carlo simulations are essential to evaluate the background level expected at the sub-keV energy regime. The simulated background here, it refers to the contribution of the construction material of the detector and the effect of the environmental gamma radiation. This detector due to its spherical shape could be also served as an optical photon detector provided it is equipped with PMTs, for Double Beta decay and Dark Matter searches. All calculations shown here are obtained using the FLUKA Monte Carlo code.

1. Introduction

The development of massive detectors with a low energy threshold and low noise, remains generally a daunting challenge for present-day and future low-background experiments. The search for WIMP (Weakly Interacting Massive Particles) dark matter is under intense development and relies on the detection of low energy (keV scale) recoils produced by the elastic interaction of WIMP’s with the nuclei of the detector [2-5]. The question of detecting and exploiting neutrinos from both terrestrial and extra terrestrial sources has become central to physics and astrophysics. Coherent neutrino-nucleus scattering is a famous but as yet untested prediction of the Standard Model [6,7]. Despite having relatively high rates, neutrino-nucleus scattering is difficult to observe because its only signature is a small nuclear recoil of energy ~ keV (for MeV neutrinos). Because the neutrino is light, the nuclear recoil energy is extremely small leading to a signal below threshold for conventional solid or liquid state detectors. Thus, the challenge is to achieve a very low energy threshold (typically below 100 eV). Now thanks to the innovative Spherical Proportional Counter (SPC), very low energy depositions can be measured. Radioactive background studies taking into account the effect of the shield and radioactive contributions from used materials are necessary for the final design and construction for the project that the SPC will be used. In addition, detailed Monte Carlo simulations...
will be essential to confirm understanding of detector behaviour and response to electron and nuclear recoils, including at the lowest energies and to evaluate the background level expected at the sub-keV energy range relevant for each project.

**Figure 1.** The rise time (rt) versus the amplitude (in ADC) for a gas mixture of Ar-CH\(_4\) 2% where a UV lamp is attached on the sphere.

### 2. Detector description

The detector consists of a large spherical copper vessel 1.3 m in diameter and a small metallic ball 16 mm in diameter located at the center of the drift vessel, which is the proportional counter. The ball is maintained in the center of the sphere by a stainless steel rod and is set at high voltage. A second electrode (umbrella-shaped) that is placed 24 mm away from the ball along the rod, is powered with an independent but lower high voltage, serving as electric field corrector. The detector operates in a seal mode: the spherical vessel is first pumped out and then filled with an appropriate gas at a pressure from few tens of mbar up to 5 bar. Detailed description of the detector, its electronics, its operation and its performance could be found in references [6-8]. Ultra low energy results taken with this counter were presented in reference [1,11], showing an energy threshold as low as 25 eV and a single electron detection sensitivity. The benchmark result is the observation of a well resolved peak at 270 eV due to carbon fluorescence, which is a unique performance for such large massive detector. The main analysis method is to apply fiducial cuts for background rejection. For example, a run is performed with the present detector installed at ground (Saclay), using a gas filling of Argon with 2% admixture of CH\(_4\) and having a UV flash lamp installed in one of the sphere openings [12]. The scatter plot of the rise time (rt) versus the amplitude of the signal is shown in Figure 1. The rise time of the signal actually provides the depth of the ionized electrons produced in the gas. By applying a cut at \(rt < 0.009\) ms, we keep only volume events achieving a spectacular background reduction. For underground tests another similar detector of 1.3 m in diameter has been installed in the LSM laboratory in Modane (Frejus) under 1700 m of rock (4800 m water equivalent) providing protection from cosmic rays. Comparisons between measurements in the sub-keV energy region taken with both detectors need to carried out in order to understand the background level and optimize the detector in terms of sensitivity and noise background. In this work we will focus our studies to simulate the background.

### 3. Background simulations

3.1. FLUKA Monte Carlo code

FLUKA is a fully integrated particle physics Monte Carlo simulation package [13]. It has many applications in high energy experimental physics and engineering, shielding, detector and telescope design, cosmic ray studies, dosimetry, medical physics and radio-biology. For our simulations presented here, the EM-CASCA defaults card is used which provides the defaults for pure electromagnetic (EM) cascades. Its main features are: - Electromagnetic interactions are on - Rayleigh
scattering and inelastic form factor corrections to Compton scattering and Compton profiles activated. Detailed photoelectric edge treatment and fluorescence photons activated. Restricted ionisation fluctuations for EM. Both explicit and continuous heavy particle bremsstrahlung and pair production inhibited. The present lowest transport limit for electrons and photons is 1 keV.

3.2. Effect of cobalt-60

The spherical vessel of the SPC is made by copper which is not particularly pure and clean. Among the probable contaminants, the most potentially dangerous is the radioactive isotope cobalt-60 which has half-life 5.27 years and produces 2 gammas rays of 1.17 and 1.33 MeV. These gammas can interact with the copper itself through Compton and create a gamma background inside the gas. This effect has been simulated using the FLUKA MC as follows: - the geometry of the SPC is implemented with its actual dimension as a spherical copper vessel that surrounds a gas of Ar-CH$_4$ (2%) at pressure 50 mb. - two monochromatic photons of 1.33 and 1.17 MeV originating in a random position in the copper vessel are emitted according to an isotropic angular distribution (R sampling proportional to $R^2$). – two independent runs of 3M events for each photon energy are produced. – the results are combined and the energy deposition inside the gas is calculated on event-by-event basis. To separate electron and photon contributions, since no automatic distinction is possible at scoring time (because all energy deposition is done by electrons, even when the primary is photon), we could selectively kill electrons (or photons) at the boundary between copper and gas. Figure 2 shows the energy deposition inside the gas from photons (the electrons are killed in the boundary) originating from cobalt-60. The two peaks in the left plot indicate the two single gamma lines around 8 keV from the induced fluorescence at the copper vessel. Adjusting a detector resolution 10% at FWHM we obtain the right plot.

Figure 2. The energy deposition obtained by FLUKA simulation inside the gas of the SPC when only photons, originating from cobalt-60, are entering from the Cu vessel inside the gas.

The Monte Carlo gives ~ 190 hits in copper out of 3M decays of cobalt. Thus, there is 1 photon in copper per ~ 16000 decays of cobalt-60. The measured data at LSM give a rate in copper ~ 1 Hz. Provided that the measured rate is fully attributed to the cobalt-60, the expected radioactivity should be ~ 16000 kBq. But the measured radioactivity at the LSM on the SPC copper gives an upper limit for the cobalt-60 < 1.3 mBq/kg [14] or $A = 1.3 mBq * 200 kg = 0.26 Bq \Rightarrow f_{Cu}(data) \sim 1.6E-5 \text{ Hz}$. As a result, the contribution from cobalt-60 at the measured rate in copper is negligible. So the environmental gammas should induce the main signal on copper at LSM as it is indicated at the next session.

3.3. Estimation of the photon background at LSM
After showing that cobalt-60 cannot explain the measured ~ 1 Hz rate in copper, the next step is to see what the effect of the environmental gammas is. Figure 3 shows a table with photon fluxes of the most prominent lines at LSM at various locations. There are uncertainties on these fluxes roughly a factor 2, depending on the location of measurement. With a simulation it could be possible to predict the energy spectrum observed in the SPC installed at LSM (Modane) and to provide a first hint to simulate real background spectra.

**Figure 3.** The photon flux at LSM at various locations

Extract of report (2004) by R. Gurriaran about measurement of photon flux in LSM at various locations (xxl, nemo, ...) for most prominent lines.

Unit = $10^{-3}$ photon/cm$^2$/s

| Radionuclide  | $^4$He | $^{210}$Po | $^{212}$Bi | $^{214}$Po | $^{212}$Po | $^{214}$Ti | $^{208}$Tl | $^{208}$Tl | $^{40}$K | $^{60}$Co | $^{60}$Co |
|---------------|-------|------------|------------|------------|------------|------------|------------|------------|-------|---------|---------|
| Energy (MeV)  | 1489.8| 351.9      | 608.6      | 238.6      | 585.2      | 2614.5     | 861.7      | 1173.2     | 1332.5|
| xxl (bindage)| 75    | 255        | 405        | 8.18       | 8.5        | 25.1       | 1.44       | 6.9        |
| nemo (bindage)| 85.5 | 221.2      | 353.9      | 5.32       | 10.77      | 27.1       | 7.14       | 6.01       |
| radon         | 25    | 42.6       | 88.6       | 13.7       | 143.1      | 42.1       | 6.6        |
| jaon          | 127   | 333        | 643        | 11.6       | 126        | 40.7       | 2.25       |
| tg/ver        | 141   | 29.5       | 414.4      | 7.36       | 9.23       | 29.1       | 5.62       |
| Bureau (caged)| 207   | 31.1       | 722.2      | 17.3       | 18.1       | 511        | 1.07       |

As an input for the simulation, the values of the fluxes at the edelweiss location (next to where the SPC was placed) are used. Seven FLUKA analogue runs took place (one for each of the seven photon lines) and then the results were merged. The methodology is similar with the one in the previous subsection with the difference that each of these gammas is coming from an extended source.
shaped as a spherical shell with radius the external one of the SPC copper vessel and \(4\pi\) isotropic direction. In all cases a mixture of Ar–CH\(_4\) (2\%) is used at pressures of 50 mb, 250 mb, 1 atm and 5 atm. The energy deposition spectra, obtained by FLUKA simulation, inside the gas of the SPC for various pressures, originating from the seven most prominent gamma lines at the edelweiss location are shown in Figure 4. At 50 mb a wide distribution mostly from electrons is shown and is peaked around 8 keV. By increasing the pressure this distribution is moving towards higher energies. By killing the electrons at the boundary between copper and gas we end up in the energy deposition spectra in Figure 5 (this can be done with the real data thanks to the analysis method by applying fiducial cuts using the rise time measure). At higher pressures, the rather steady background hit rate which is actually due to Compton electrons inside the gas, becomes more dominant.

**Figure 5.** The energy deposition obtained by FLUKA simulation inside the gas of the SPC for various pressures, originating from the seven most prominent gamma lines at the edelweiss location when only photons are entering from the Cu vessel inside the gas.

![Energy Deposition Spectra](image)

In LSM, at pressure 50 mb, the measured rate on copper is \(\sim 1\) Hz. FLUKA MC gives \(\sim 200\) hits in copper out of 8.3M photons (=Nevents). The measured total flux at the edelweiss location is: \(413.9\times 10^{-3}\) g/cm\(^2\)/s, the surface of the SPC: \(4\pi R^2=53093\) cm\(^2\), 1 sec \(\Rightarrow 53093\times 413.9\times 10^{-3}=21974\) gammas. Thus, the rate in copper is: \(f_{\text{Cu}} = 200\times 21974/8.3\times 10^6 = 0.53\) Hz at \(4\pi\) direction. Adding a factor 2 due to the preferential direction of the gammas towards the sphere according to the definition of the flux, we conclude that the simulated rate in copper is \(\sim 1\) Hz which comes into agreement with the data.

The scatter plot of the energy deposition at gas pressure of 1 atm, versus the radius of the SPC is shown in Figure 6. A photon with energy of 1461 keV hits the SPC copper vessel having a \(4\pi\) isotropic direction and only short tracks are kept requiring 1 hit inside a cell of 1 cm side (the long tracks have large rise time and can be excluded with the data analysis method). It is obvious that most of the local energy depositions are at the periphery of the SPC gaseous volume and by performing fiducial cuts we could decrease the background.
The use of SPC as an optical photon detector

In the WIMP’s search, the XENON project is one of several direct detection experiments worldwide, using a noble liquid as target and detector medium. The XENON100 detector is a double-phase (liquid-gas) time projection chamber (TPC). The ratio S2/S1 (where S1 is the primary scintillation light and S2 the secondary) allows event discrimination between nuclear recoils (WIMPs, neutrons) and electron recoils ($\gamma$, $\beta$) [15].

A spherical proportional counter (SPC) made by Al (served as UV light reflector) and filled with high pressure noble gas, can be applied for the detection of optical photons. Simulations are performed using the FLUKA MC for the estimation of the light collection efficiency (LCE) of the S1 on the installed photomultipliers (PMTs).

Optical photons can be generated and propagated in FLUKA [13] and can be treated according the laws of geometrical optics. Therefore, they can be reflected and refracted at boundaries between different materials, absorbed in flight or elastically scattered (Rayleigh scattering).

In the simulation below, 6 PMTs of 12.5 cm in diameter are placed on the SPC (top left plot in Figure 7) and the LCE on them is estimated considering that the surrounding vessel has a reflectivity of 92%. At first approach there is no absorption in flight and no Rayleigh scattering. 2k optical photon sources are generated randomly inside the SPC and each of them emits at $4\pi$ direction 1k optical photons.

Two types of reflection are used: the specular (mirror-like) and the diffuse reflection. Without reflection, the LCE of 6 PMTs is: $6*A_{PMT}/A_{SPH} \sim 1.4\%$. Thus, for a SPC with radius of 65 cm and 6 PMTs, a diffuse reflection of 92% and 99% improves the LCE by ~ 10 times ($LCE = 15\%$) and ~ 40 times ($LCE = 58\%$) respectively. In the case of 99% diffuse reflection, if there is an absorption length of 50 m and the Rayleigh scatter length is of 24 m, the LCE drops to ~ 38%.

Figure 7 summarises these results with the addition of the use of one single PMT placed on the centre of the SPC.

A spherical proportional counter with the present dimensions and with just 6 PMTs installed around, presents a S1 LCE large enough to provide event trigger for a 100 keV gamma, enough for DBD searches and good sensitivity for $O(keV)$ events in the field of DM searches. Such an event trigger can provide radial-position information for fiducial volume selection.
Figure 7. The light collection efficiency in the SPC, obtained by FLUKA simulation, for specular and diffuse reflection and the particle tracklength density spectra (fluence) expressed in particles/cm².

5. Conclusions

A new detector has been developed that combines large mass and low sub-keV energy threshold with the capability of sensing even single electrons. Detailed simulations are essential to evaluate the background level expected at the sub-keV energy range relevant for each project that this type of detector can be used. Its moderate cost, simplicity, robustness and versatility since it can be served as an optical photon detector, make this technology a promising approach opening a new window in dark matter searches.

REFERENCES

[1] E. Bougamond et al., arXiv: 1010.4132 [physics.ins-det], to be published at JMP (2010).
[2] K. Nakamura et al. (Particle Data Group), J. Phys. G 37: 075021 (2010).
[3] I. Giomataris and J.D. Vergados, Nucl. Instrum. Meth. A530: 330-358 (2004).
[4] J.I. Collar, Y. Giomataris, Nucl. Instrum. Meth. A471: 254-259 (2000).
[5] R. Bernabei et al., Eur. Phys. J. C67: 39-49 (2010).
[6] D.Z. Freedman et al., Ann. Rev. Nucl. Sci. 27: 167 (1977).
[7] A. Drukier and L. Stodolsky, Phys. Rev. D30: 2295 (1984).
[8] S. Aune et al., AIP Conf. Proc. 785: 110-118 (2005).
[9] I. Giomataris et al., Nucl. Phys. Proc. Suppl. 150: 208-213 (2006).
[10] I. Giomataris et al., JINST 3: P090007 (2008).
[11] E. Bougamond et al., J.Phys. Conf. Ser. 309 012023 (2011).
[12] E. Bougamond et al., Conf.Proc: www-library.desy.de/preparch/desy/proc/proc11-03.pdf (2012).
[13] "The FLUKA code: Description and benchmarking" G. Battistoni, S. Muraro, P.R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fasso’, J. Ranft, Proceedings of the Hadronic Shower Simulation Workshop 2006, Fermilab 6--8 September 2006, M.Albrow, R. Raja eds., AIP Conference Proceeding 896, 31-49, (2007) 
"FLUKA: a multi-particle transport code" A. Fasso’, A. Ferrari, J. Ranft, and P.R. Sala, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773, www.fluka.org
[14] Private communication with P. Loaiza from LSM laboratory
[15] E. Aprile (XENON coll.) Journal of Physics: Conference Series 203 (2010) 012005