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PICO-500: A tonne scale bubble chamber for the search of dark matter

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Summary. — The PICO-500 experiment will search for dark matter by first operating a 260 liters bubble chamber filled with C_3F_8, with a target sensitive to the spin-independent and spin-dependent WIMP-nucleon cross-sections of approximately $10^{-44}\,\mathrm{cm}^2$ and $10^{-42}\,\mathrm{cm}^2$, respectively. To guarantee a low background rate and therefore find a WIMP signal or set strong exclusion limits, the geometry and radio-purity of the materials to be used must be optimized. A detailed model of the detector has been developed in GEANT4 to perform the Monte Carlo simulations. The main sources of background signals in this detector are from (α, n) reactions and spontaneous fission. Contributions from internal components, exposure to radon present in SNOLAB's Cube Hall as well as photonuclear reactions have been considered in this work. Preliminary results show a very low estimated rate of background events, less than one single bubble event per year.

1. – Introduction

The search for weakly interacting massive particles (WIMP) is challenging due to the small predicted WIMP-nucleon scattering cross sections [6], which require very small nuclear recoil energies (1-100 keV) deposited by WIMPs through elastic scattering in detector target nuclei. To achieve sufficient sensitivity at this low threshold, experiments require a large detection volume located in an environment with sufficient background suppression, such as the SNOLAB [13] underground laboratory. In recent years, bubble chambers have been used as nuclear recoil detectors searching for dark matter in the form of WIMPs. The use of superheated liquids makes the bubble chambers insensitive to the undesired β and γ background radiation that normally plagues the WIMP search region. In superheated liquid, the bubble nucleation process can be described using the "hot spike" model [12]. In this model the phase transition is allowed if the energy deposited

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in a distance less than the critical radius is greater than a certain threshold. This type of technique has been shown to allow excellent rejection of the alpha background using the acoustic signal recorded by the piezoelectric sensors. The PICO collaboration was formed in 2013 from the merger of the PICASSO [5] and COUPP [14] groups to use the best of both experiments and together build the next generation of the superheated liquid detectors, which are operated underground in SNOLAB. PICO uses C_3F_8 [2] as an active target in their bubble chambers, this liquid has a better spin-dependent sensitivity due to a higher concentration of fluorine; and these detectors have a higher efficiency in detecting fluorine recoils at low thresholds without background of electron recoils ($\sim 10^{-10}$ suppression). After the success of the PICO-2L [4] and PICO-60 [3] detectors in the direct search for dark matter in the spin-dependent and spin-independent sectors, the collaboration proposed the construction of detectors with a higher target mass.

The collaboration is currently completing the commissioning of PICO-40L, a bubble chamber filled with approximately 40 liters of C_3F_8 which is expected to improve by a factor of 5 the PICO-60 limits. Additionally, a scaled-up detector with an active volume of approximately 260 liters (PICO-500) is fully funded and currently in the design and procurement phase (fig. 1). In this work the results of preliminary neutron background simulations for PICO-500 made in GEANT4 [1] are presented, which have allowed the collaboration to develop a correct model of the detector as well as to establish the necessary radiopurity limits in the different materials.

2. – Materials and methods

In experiments for the direct detection of Dark Matter (DM), a crucial factor for their success is to achieve a background level low enough to exclude the WIMP search region with high confidence, or to clearly establish a discovery in case of an excess of events.

The model of the PICO-500 detector was performed with GEANT4 version 10.03 patch-03 and the compilation was done with gcc 9.3.0 and GNU Make 4.2.1, including the physics lists provided by the advanced underground_physics and neutron_hp example libraries. The covered physics are suitable for a low-background experiment.

In the search for DM with bubble chambers it is imperative to understand the neutron backgrounds as these mimic the same type of interaction in detectors as expected by DM particles. Neutron sources identified in PICO-500 include (α,n) reactions, fission neutrons, direct neutron decay of the ^{238}U chain and neutrons produced in (γ,n) reactions. To determine the production of neutrons in the materials of the detector the code SOURCES4C [15] has been used. The SOURCES4C code is a software that determines neutron production rates and energy spectra for (α,n) reactions, spontaneous fission, and delayed neutron emission (β,n) due to decay of radionuclides.

Monte Carlo simulations are used to model the neutron backgrounds in the PICO-500 detector to propagate them through the components considered and thus determine the background rate of the detector. The results are analyzed using Python and C++ programming languages, as well as the ROOT [7] software. To calculate the number of single bubble events per year (R) due to the neutrons emitted from the different components of the detector, eq. 1 is used:

$$R = m \cdot Y \cdot A \cdot P_{leak} \cdot f, \tag{1}$$

where m is the mass of the component in grams, Y is the yield factor in units of neutrons per second per grams per parts per billion ($[n/s/g/ppb]$), A is the activity of each

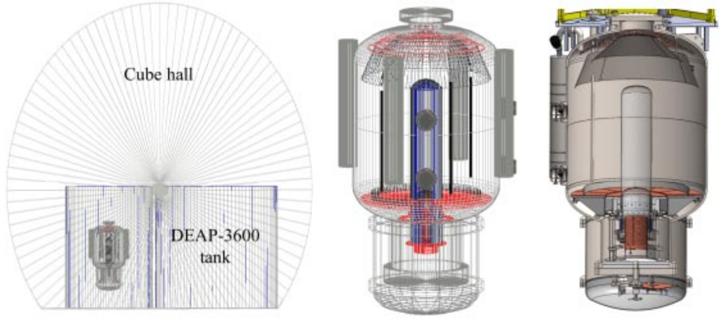

Fig. 1. – Left: PICO-500 detector inside the water shield located in the SNOLAB Cube hall. Center: Current GEANT4 model of the PICO-500 detector with the main components. Right: PICO-500 detector CAD model.

component for the different decay chains (^{232}Th, ^{238}U and ^{210}Pb) in units of parts per billion and taken from [9], P_{leak} is the Monte Carlo interaction probability, and f is a conversion factor between year and seconds.

3. – Results

Preliminary results obtained for the simulation of the internal components of the detector as well as the photonuclear reactions are presented in table I. Figure 1 shows the GEANT4 model of the detector and its location in the Cube Hall at SNOLAB. The

Table I. – *Estimated contribution of the main simulated components to the number of background events per year (preliminary).*

Component	Mass [kg]	Single bubble events per year
PV	5880	1.63×10^{-3}
Top and Bottom flanges	1256	6.18×10^{-6}
Retroreflector	65	1.42×10^{-6}
Mineral Oil	6800	< 0.1
Cameras	0.4	3.62×10^{-7}
Lenses	0.22	4.52×10^{-7}
Outer vessel	56	2.4×10^{-3}
Inner vessel	23	8.81×10^{-5}
C_3F_8	270	< 0.1
Inner and Outer Copper Plates	327	0.197
Piezo (12)	0.6	0.05
Photonuclear reactions		
Water shielding	174×10^6	0.02
Pressure vessel	5880	1.2×10^{-8}
Mineral Oil	6800	0.017
C_3F_8	358	1.25×10^{-3}
Total		< 0.489

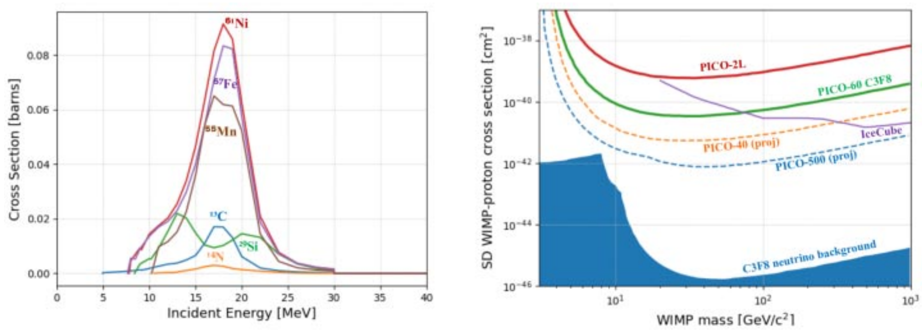

Fig. 2. – Left: Cross sections values as a function of the incident energy of the gamma particle in the nucleus forming the stainless steel [8]. Right: Exclusion curves for spin-dependent coupling obtained with the PICO-2L, PICO-60 data and projections (proj) for the PICO-40L and PICO-500 detectors.

simulated components are: Pressure Vessel (PV), top and bottom flanges, retroreflector, mineral Oil, 4 cameras, outer Vessel (OV), inner Vessel (IV), target volume (C_3F_8) and 12 piezoelectric sensors. The PV has a maximum radius of 121.92 cm, a height of 426.72 cm, and a wall thickness of 1.905 cm. The C_3F_8 target is held within the two concentric quartz vessels. The OV has a maximum radius of 23 cm and a height of 200 cm, while the IV has a radius of 21.4 cm and a height of 76 cm. The two jars are coupled together by a stainless steel bellow and flange system. Filling the space inside the PV and outside the vessels, there are approximately 8 tons of mineral oil. Four cameras are mounted outside the PV; they have been simulated considering the lens, the printed circuit board (PCB) and a ring of LED lights. Different numbers of neutrons have been simulated due to the path that have to travel to reach C_3F_8 from the different components and to have sufficient statistics. It is important to note that from the results of the simulations it was possible to guide the final design of the detector.

For the (γ,n) reactions, the production of neutrons in the water shield (H_2O), PV, Mineral Oil and C_3F_8 have been considered. A gamma flux of 2 to 100 MeV [10, 11] was emitted from outside the detector and the energy deposited by the gammas in each considered volume was recorded. Using the photonuclear cross-sections for the atoms in the materials [8] (fig. 2, left) the number of neutrons produced in each component was calculated and from those that reach the C_3F_8, the number of single bubble events per year due to photonuclear reactions was obtained. Background contributions induced by radon (emanation, deposition) were also estimated. A maximum exposure time of 1.36 years has been estimated to prevent backgrounds from radon exposure.

4. – Conclusions

A complete model in GEANT4 of the PICO-500 detector has been developed, which allows to simulate and determine background sources of contamination. Preliminary results for the single bubble events per year produced by neutrons emitted from the main components and photonuclear reactions from external gamma-rays are summarized in table I. Radiopurity limits necessary in some components such as mineral oil, top and bottom flanges and C_3F_8 have also been determined. With these results it can be assured that the PICO-500 experiment will reach the goal to achieve $<$ 1 single bubble event per year, which will greatly expand the search region for dark matter, achieving low exclusion limits or reach a DM discovery. Other backgrounds are currently being studied.

In fig. 2 (right), the exclusion curves for the data from the PICO-2L and PICO-60 detectors are shown, which culminated the data collection in 2015 and 2017, respectively. In the same figure, the projections of the exclusion limits for the PICO-500 detector are shown, a notable improvement in the exclusion limits can be seen.

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