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Simulations and background estimate for the DAMIC-M experiment

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Summary. — DAMIC-M (Dark Matter in CCDs at Modane) is a near-future experiment aiming to search for low-mass dark matter particles through their interactions with the silicon nucleus or electrons in the bulk of charge-coupled devices (CCDs). With respect to its predecessor DAMIC at SNOLAB, DAMIC-M will have a 25 times larger detector mass and will achieve sub-electron readout noise thanks to the use of the so-called skipper CCDs. With these novelties, DAMIC-M will be sensitive to WIMPS with masses below 10 GeV and it will be leading the search of MeV-scale hidden sector candidates and eV-scale hidden photons. To achieve these results, DAMIC-M requires a radiogenic background rate of a fraction of decays/keV/kg/day. Thus, an extensive campaign of innovation of the detector technology and design is ongoing. Simulations are being exploited to optimize the detector design and drive the material selection and handling. This proceedings provides a comprehensive overview of the explored detector designs, the corresponding estimated backgrounds, and the strategies for its mitigation.

1. – Introduction

Nowadays we know that 27% of the Universe is made of Dark Matter (DM) [1], the nature of which is still unknown. Many DM models and candidates have been proposed. In one of the most popular models, the dark matter is in form of weakly interacting massive particles (WIMPs), which scatter off nuclei producing a detectable signal. However, alternative candidates are becoming more popular, *e.g.* the so-called hidden sector particles [2].

The DAMIC-M (Dark Matter In CCD at Modane) experiment searches for DM particle interactions in the silicon bulk of charge-coupled devices (CCDs). With its sub-electron resolution and low background, it will be leading the search of MeV-scale DM candidates in the hidden sector and eV-scale hidden photon. The CCDs are light sensors commonly used in digital cameras and telescopes for astronomical applications. Their applicability in the search for DM was successfully demonstrated by DAMIC, the predecessor of DAMIC-M located at SNOLAB [3]. DAMIC-M will be installed at the Laboratoire Souterrain de Modane (LSM) in France and it will deploy a kg-size detector. It will employ the so-called skipper CCDs to achieve sub-electron resolution on the charge measurements [4]. Due to these features and to a low level of dark current, DAMIC-M will be extremely sensitive to very feeble ionization signals down to a few eV, which are expected from DM interaction with nuclei or electrons in the silicon bulk. In particular the silicon low nucleus mass ensures a good sensitivity to WIMPs with masses in the range 1-10 GeV, while its small band gap (~ 1.1 eV) provides sensitivity to hidden sector DM-electron interactions [5]. To reach these results, DAMIC-M will require a radiogenic background rate of a fraction of d.r.u(1), 100 times lower than DAMIC's one. Therefore Geant4 based simulations have been exploited to optimize the detector design, drive the material selection and handling and test background rejection techniques. In the following, the different investigated designs and the corresponding background levels will be described along with the background mitigation strategies which DAMIC-M is going to adopt.

2. – Experimental setup and background simulations

In the current design, DAMIC-M will employ 200 CCDs. Each of them will feature 6k x 1.5k pixels over a 9 cm x 2.25 cm area and a thickness of at least 0.675 mm. CCDs are fabricated from n-type, high-resistivity silicon wafers and they are fully depleted [3].

The operation of a CCD applied to the DM search is based on the creation of electron-hole pairs due to nuclear/electron recoils in the silicon bulk. The produced ionization charges are collected by the applied electric field. The new DAMIC-M CCDs will be equipped with "skipper" amplifiers which will perform repeated and non-destructive measurements of the charge in each pixel, in order to damp the readout noise to a sub-electron level. The CCD output node signal will travel on low background kapton cables or pico-coaxial cables.

The detector design is ongoing. The baseline scheme is shown in fig. 1 (left). A cryostat vessel will house the CCDs, packed in a box surrounded by infrared (IR) shields. Cooling will be provided by the use of liquid nitrogen. Most of the components will be made of electro-formed (EF) copper, especially those nearest the CCDs, given their very low content of radioactive isotopes. The farther volumes will instead be made of oxygen-free high thermal conductivity (OFHC) copper. In the simple configuration similar to DAMIC's one, CCDs are disposed horizontally, on the top of each other (fig. 1, right (a)). Each CCD is held in a EF copper frame which ensures mechanical support for the CCD, cables and thermal contact. The background estimations presented in this proceedings are based on this option. Other configurations are under study as the one in fig. 1 (right (b)) with CCDs disposed vertically, hung on a copper support. A sandwich of electro-formed copper and ancient lead disks is placed on top of the CCD stack to shield from the background events from the above detector components. Simulations were used to optimize the thickness of the disks. A polyethylene and ancient lead shields with a thickness of about 40 cm and 20 cm respectively will surround the detector to screen it from external neutrons and γ-rays. The whole detector design is still under development and not finalized.

Detector simulations are performed to estimate the background level and drive the detector conception.

A Geant4 [6] based code has been developed to simulate the physics processes under-

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(1) 1 d.r.u (differential day units) corresponds to 1 event/day/kg/keV.

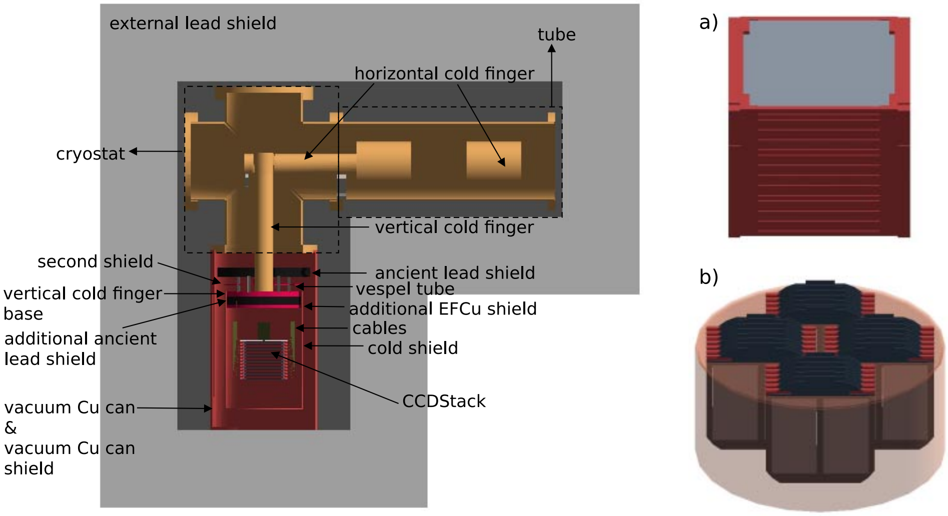

Fig. 1. – Left: latest simulated detector design. The electro-formed copper components are shown in red, while the OFHC copper ones in yellow. Right: zoom on two possible solutions for the CCD stack. a) Horizontal CCD stack. b) Vertical CCD stack. The gray parts are the CCDs, the red parts the copper holders.

gone by a particle passing through the experimental setup. The code uses the Livermore physics list [7] (between 20 eV and 100 GeV) and includes neutron processes and radioactive decays. The DAMIC-M detector design and the relative materials are implemented through a GDML (Geometry Description Markup Language) file [6]. Production cuts are defined for electrons, positrons, γ and protons to optimize the computing time without introducing energy spectrum deformations. The sensitive region and all the components close to the CCD have the lowest production cuts to ensure the maximum precision and minimum energy thresholds. The results reported here are obtained with Geant4 v.10.04 and by applying the following production cuts: 10^{-4} mm for the CCD, 3×10^{-4} mm for the cables and copper components nearest to the CCD, 10^{-3} mm for the farthest copper components and 10^{-1} mm for ancient lead.

A code written in python (WADERS) is used to reproduce the detector response and provides the cluster reconstruction. In the reconstruction all the contiguous charged pixels above the electronic noise threshold are collected in a cluster. Its total energy, 3D position and additional pattern parameters are calculated. For the purpose of the current studies the detector effects as diffusion, saturation, clustering threshold, dark current and readout noise are not included, being their effect negligible.

The DAMIC-M detector design is under continuous development. Each of the proposed designs has been implemented in the simulation to evaluate the corresponding background level and possibly propose further improvements. The included components of the two examples are shown in fig. 1.

The radioactive isotopes in the simulation were uniformly distributed in the bulk of the detector components, choosing only the proper ones depending on the volume material. The following isotopes from the ^{238}U and ^{232}Th chains were considered: ^{210}Pb, ^{210}Bi,

^{212}Pb, ^{212}Bi, ^{214}Pb, ^{214}Bi, ^{234}Th, ^{234}Pa, ^{228}Ac, ^{208}Tl. The cosmogenic isotopes from copper activation were included: ^{60}Co, ^{56}Co, ^{57}Co, ^{58}Co, ^{54}Mn, ^{59}Fe. The ^{40}K and the ^{87}Rb isotopes were also considered because traces of them can be found in epoxy and copper. The components of a radioactive chain were simulated separately. The background rate is obtained for each isotope scaling the cluster energy spectrum by a proper scale factor f:

$$\text{f} = \frac{\text{n}_{\text{bins}} \cdot \text{A}_{\text{iso}} \cdot \text{m}_{\text{vol}}}{\Delta\text{E} \cdot \text{N}_{\text{decays}} \cdot \text{M}_{\text{detector}}} \tag{1}$$

where $\text{n}_{\text{bins}}/\Delta\text{E}$ is the bin width, A_{iso} is the activity of the isotope in decays/kg/day, m_{vol} is the mass in kg of the volume of the detector in which the radioactive element is simulated, $\text{M}_{\text{detector}}$ is the mass of the whole sensitive detector in kg and N_{decays} the number of simulated events. The used isotope activities were measured at SNOLAB for the DAMIC experiment or provided by the material suppliers. An assay program is planned for all the detector materials.

The activity of the cosmogenic isotopes is calculated based on the time of exposure to cosmic rays (T_{exp}), the time spent underground before data collection (T_{cool}) and the running time of the experiment (T_{run}):

$$\text{A} = \text{S} \cdot (1 - \exp(-\lambda \text{T}_{\text{exp}})) \cdot \exp(-\lambda \text{T}_{\text{cool}}) \cdot (1 - \exp(-\lambda \text{T}_{\text{run}}))/(\lambda \text{T}_{\text{run}}) \tag{2}$$

where $\lambda = \ln(2)/\text{t}_{1/2}$, $\text{t}_{1/2}$ is the half life of the isotope and S is the cosmogenic production rate [8]. The exposure time, cooling time and run time of the copper components were fixed to 3, 6 and 12 months respectively. The rate of background events was estimated by a fit to a constant in the energy interval between 2-7.5 keV. This energy range is chosen to exclude the silicon and copper fluorescence Kα emission peaks at 1.7 keV and 8 keV respectively. The total background estimation is shown in fig. 2 for the baseline design with CCDs stacked horizontally (fig. 1, left). The total background rate is less than 0.2 decays/day/keV/kg, where 75% of it is due to the external lead shield. It is worth noticing that the background levels of the ancient lead components are based on

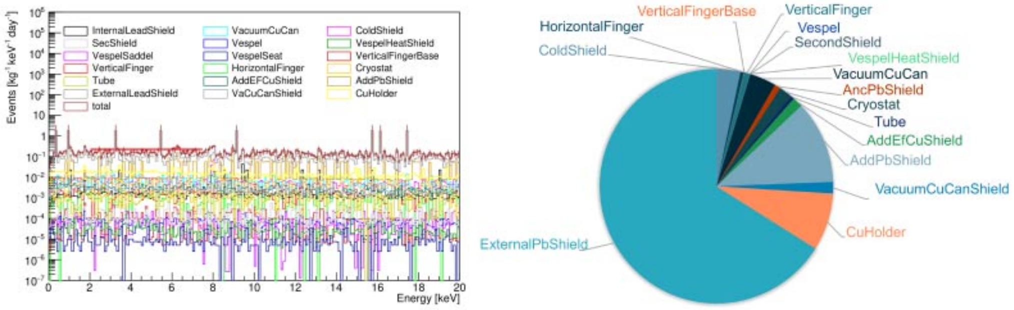

Fig. 2. – Left: total cluster energy spectrum expected and contribution from the individual components. The high peaks present in the total energy spectrum are due to ^{210}Bi from the external lead shield. The red line is the result of a linear fit to a constant. Right: contribution to the background rate of each detector component. The total background rate is 0.2 d.r.u. Note that the used lead activities are upper limits.

weak activity upper limits. A dedicated assay will help to reduce these contributions. The result shown here doesn't take into account the cables and the cosmogenic activation of the electro-formed copper components. A study of the background rate for varying values of T_{exp} and T_{cool} (with fixed T_{exp} = 1 y) has been performed helping to set the limits for the exposure to cosmic rays of the EF copper volumes. With T_{exp} = 10 days and T_{cool}= 6 months, these components would contribute with 0.1 d.r.u. This result decreases by a factor 10 if T_{exp}=1 day and increases by a factor 3 if T_{cool}=0. Finally, different options for the cables are under evaluation. The kapton cables (5-layers kapton cables) used by DAMIC at SNOLAB are discarded since they would produce a background of approximately 3 d.r.u, well beyond DAMIC-M's goal. Therefore two lower background options are being considered: 2-layers kapton cables and ultra low background pico-coaxial cables. In both cases, preliminary results show a reduction of the background rate of about a factor 10 with respect to the standard kapton cables. Precise background evaluations depend on the specific packaging and the CCD holder design.

3. – Conclusions

A major objective of the DAMIC-M experiment is to lower the radiogenic background to a fraction of d.r.u. To this end, simulations are being performed to drive the detector design and the material selection and handling. The design is not yet finalized but current results show that the background level goal is within reach. The major contributors are the cables and the copper holder. The design with vertical CCDs reduces further the background by decreasing the amount of copper around the sensitive CCDs as well as the number of cables. In the background budget shown in fig. 2, the external lead shield looks as the dominant contributor. This result is however obtained with activity upper limits. Pivotal to better background evaluations are precise measurements of radiogenic isotope activities. Further studies are ongoing to perform fiducial cuts to reject part of the cable background events. The validity of simulations, especially at low energies, will be tested with the Low Background Chamber, the DAMIC-M prototype which is going to be installed this year.

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