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WLS System for the Pressurized Helium Calorimeter "PHeSCAMI"(*)

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Summary. — The possible presence of low-energy anti-deuterons in cosmic rays is a golden channel to test the antimatter asymmetry in the Universe or to identify annihilating Dark Matter particles in the galactic halo. The PHeSCAMI (Pressurized Helium Scintillating Calorimeter for AntiMatter Identification) project aims to study a new signature for the identification of anti-deuteron and anti-protons in cosmic rays. In particular, when a Z=-1 heavy antiparticle is stopping in Helium, it can produce an exotic atom having lifetime of microseconds. Helium gas is a fast scintillator, thus a relatively simple calorimetric measurement of the stopping particle kinetic energy is possible. A two-stage Wavelength Shifter (WLS) system is necessary to convert the VUV (80 nm) scintillation light into visible. The performances of the FB118 WLS, manufactured by "Glass to Power", are investigated. A promising usage of FB118 as a high-efficiency Cherenkov radiator is also inferred.

1. – The PHeSCAMI detector

Investigation of Low-energy antideuterons in cosmic rays (CRs) is a promising tool for detecting dark matter annihilation and primordial antimatter in our galaxy. Research from the PHENIX [1] and ALICE [2] collaborations indicates that low-energy $\bar{d}$ are unlikely to be produced as secondary particles during CR propagation. Therefore a negligible astrophysical background is expected in the search for complex antinuclei in CRs. The PHeSCAMI project intends to identify low-energy $\bar{d}$ by utilizing the expected delayed annihilations within a helium target. In particular, when Z=-1 antinuclei stop in helium, they can form exotic atoms in a meta-stable state. Approximately 3.3% of these atoms have a long lifetime ($\sim \mu$s), leading to a detectable delayed annihilation [3].

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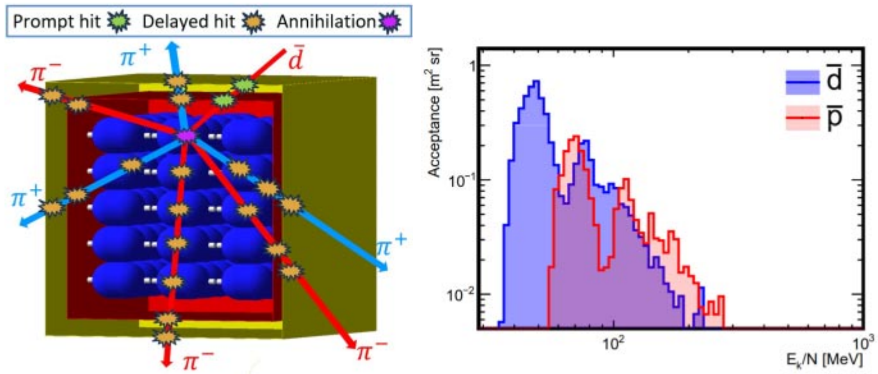

Fig. 1. – On the left, the proposed design of the PHeSCAMI detector. The TOF is made up by the two layers of segmented plastic scintillators, shown in red and yellow. The HeCal, blue, is made of 75 space qualified helium tanks. In the figure a representation of a $\bar{d}$ annihilation is shown. The prompt hits, in green, indicate the energy depositions occurring within few ns produced by a $\bar{d}$ entering in the detector. The delayed hits, in yellow, show the energy depositions result of a $\simeq \mu$s delayed annihilation. On the right plot, the expected acceptances of this design of the PHeSCSAMI detector for $\bar{d}$ and $\bar{p}$ are shown [4].

Figure 1 (left) illustrates a proposed design for the PHeSCAMI detector, which consists of two main components: a Time of Flight (TOF) system and a segmented helium calorimeter (HeCal). The TOF is constructed from two cubic layers of segmented plastic scintillators, each face of the cube is made up of 64 squared slabs, 0.4 cm thick. The distance between the external and the internal TOF layers is 20 cm. The HeCal features 75 carbon-fiber tanks [5], each one is filled with 50 L of helium pressurized at 310 bar which act as a fast scintillator. The external size of the detector is $3\times3\times3$ m^3. The left part of fig. 1 also depicts an example of an $\bar{d}$ undergoing delayed annihilation within the HeCal. The prompt hits, in green, indicate the energy depositions occurring within few ns produced by the $\bar{d}$ slowing down in the TOF and stopping in the helium. The delayed hits, in yellow, show the energy depositions of several $\pi^{\pm}$ emitted in the $\simeq \mu$s delayed annihilation. On the right of fig. 1 the expected acceptances of this design of the PHeSCAMI detector are shown. The sensitivity to $\bar{d}$ is in the range 40-200 MeV/n while the sensitivity for $\bar{p}$ is in the range 60-250 MeV/n [4].

2. – The PHeSCAMI WLS system

Helium gas scintillators, which will make up the HeCal, produce both a slow ($\sim 1.3\mu$s) and a fast component ($\sim$ 5ns), which allows reaching a time resolution within 300 ps [3]. However, the emission spectrum of the scintillation light is in the vacuum UV range, peaking at 80 nm [6]. To extract the scintillation light from the pressurized vessel we plan to use a design similar to X-Arapuca developed for LAr in the context of the DUNE experiment [7]. In particular, the scintillation photons will be downshifted in two stages. First, a para-Terpheny (PTP) layer will shift the VUV photons to 350 nm, then a PMMA fiber doped with 5-Bis(5-tert-butyl-benzoxazol-2-yl)thiophene (FB118 manufactured by "Glass to Power" [8]) further shifts the light to 425 nm (fig. 2(b)). As shown in fig. 2 a PTP coating will be deposited on the internal walls of the tank, while a FB118 cylindrical fiber will act as an optical window guiding the light toward an external Photo Multiplier

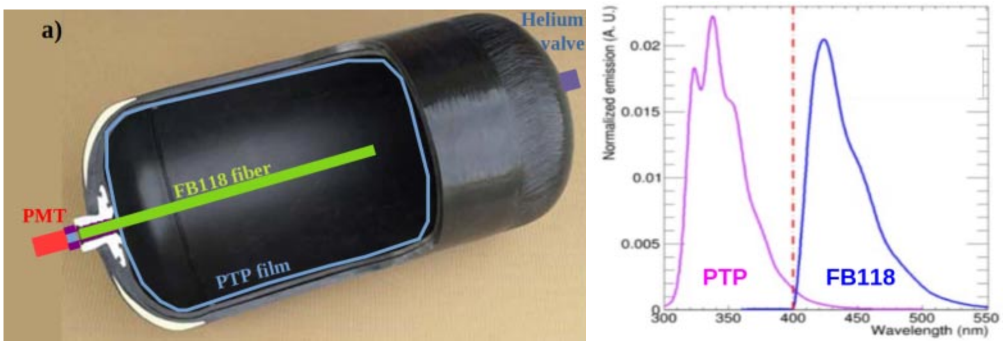

Fig. 2. – Left: the design of the two-stage WLS system considered for the PHeSCAMI detector. In the inner part of the vessel a PTP film is deposited. A central fiber made by FB118 will shift into visible the 350 nm light emitted by PTP and guide the light to a PMT placed outside the vessel. Right: the emission spectrum of PTP and FB118.

Tube (PMT). In the following some test measurements aimed at verifying the absence of residual scintillation in FB118 are shown. This is necessary to avoid an undesired signal when charged particles incidentally cross the central fibers of the HeCal.

3. – Test of scintillation in FB118

We compared the light yield produced by a ($9\times4\times1$ cm^3) FB118 sample against the signal collected by a sample of EJ-200 plastic scintillator of the same size. Two experimental setups were developed: one dedicated to the detection of charged particles and the other for the detection of gamma rays. Both experiments are alternatively running with the FB118 sample and with the EJ-200 control sample, coupled to the same Hamamatsu R5946 PhotoMultiplier Tube (PMT).

The charged particle setup (fig. 3(A)) consists of a muon telescope made up of two additional EJ-200 scintillators (Trigger1 and Trigger2) tagging atmospheric muons

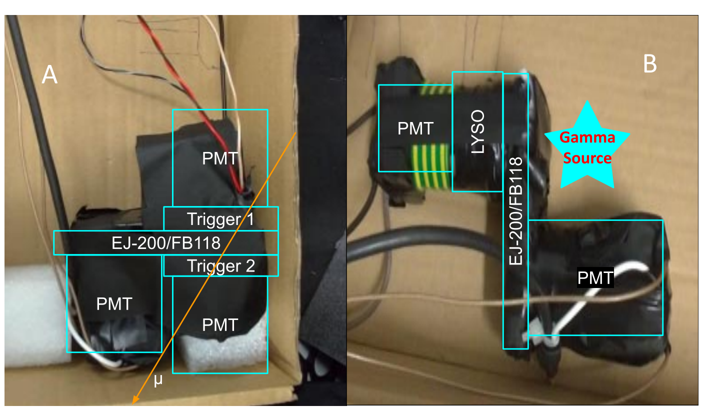

Fig. 3. – Pictures of the two setups: (A) the charged particle setup, and (B) the gamma ray setup. In both pictures, the single components are labeled with an overlay.

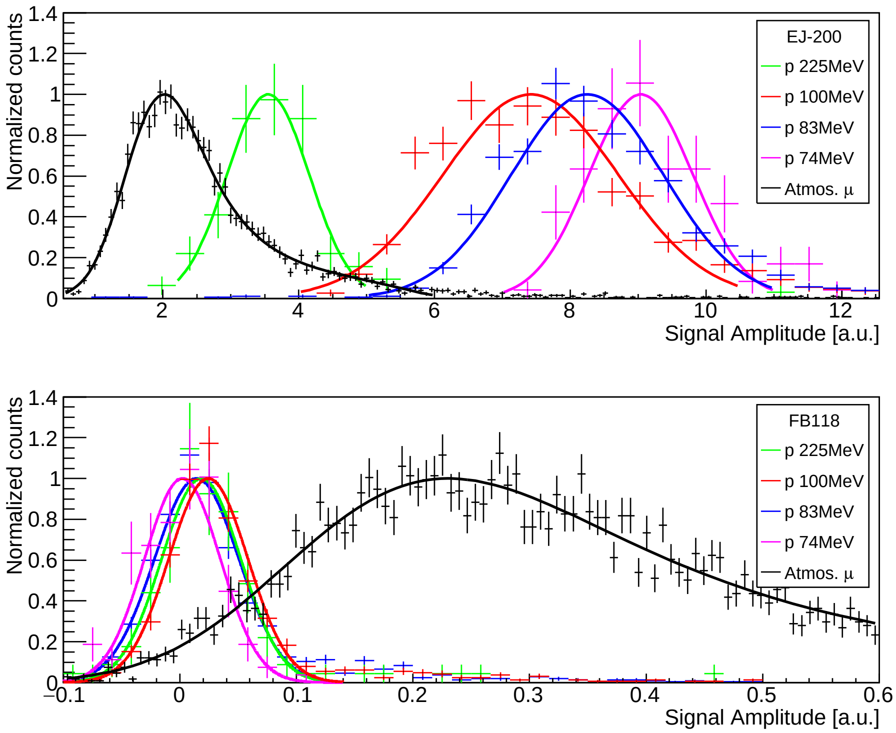

Fig. 4. – Normalized signal amplitude distributions measured with the EJ-200 scintillator (top panel) and FB118 sample (bottom panel) for protons (green, red, blue, pink) and μ (black).

crossing the FB118/EJ-200 sample outside the cathode of its PMT. Without changing configuration the same setup was tested at 74-225 MeV proton beam in the Trento Proton-therapy center. Being triggered by two external scintillators, in this configuration, there was not a minimum threshold for the amplitude of the signal collected by the FB118/EJ-200 detectors under comparison.

The top panel of fig. 4 shows the signal amplitude distributions measured with the EJ-200 plastic scintillator crossed by protons and muons. For the scintillator, the behavior is compatible with the one given by the Bethe-Bloch formula, where the energy deposition is larger for particles having lower velocity. The lower panel shows the signal amplitude distributions measured with the FB118 sample. In this case, there is no evidence of a light emission induced by protons. This suggests that the light signal measured with the FB118 is mostly given by Cherenkov radiation, since the expected Cherenkov threshold for protons in FB118 is 310 MeV. Table I summarizes the measured distribution Most Probable Value (MPV) for the different particle beam tests in the two samples.

By comparing the signal amplitude distribution measured for muons in EJ-200 and FB118, we can infer a light yield ratio of $9.1 \pm 0.6^{stat.} \pm 2.5^{syst.}$ where the cautious systematic uncertainty was inferred by repeating the measurements by changing the PMT, the bias voltage, and the PMT optical coupling.

The gamma ray setup (fig. 3(B)) consists of a coincidence system of an 8g slice of LYSO scintillator with the test detector (either the FB118 or the EJ-200).

TABLE I. – *MPV of signal amplitudes measured by EJ-200 and FB118 for Protons and μ.*

Particle	$p\,74MeV$	$p\,83MeV$	$p\,100MeV$	$p\,225MeV$	μ
MPV EJ-200	9.04 ± 0.08	8.25 ± 0.04	7.42 ± 0.05	3.55 ± 0.06	2.0 ± 0.1
MPV FB118	0.001 ± 0.003	0.014 ± 0.001	0.024 ± 0.001	0.018 ± 0.003	0.22 ± 0.01

The trigger is provided by the internal radioactivity of ^{176}Lu contained in the LYSO (39 Bq/g) emitting gamma rays (mainly 307 keV and 202 keV and rarely 401 keV) possibly detected by the FB118 or EJ-200 detector in coincidence. The same setup was also tested with an external ^{60}Co radioactive source, by tagging the coincidences of the 1332 keV and 1173 keV gamma rays.

It is important to note that, due to the low Z composition of the FB118 and EJ-200, mainly Compton electron recoils are detected in these plastic detectors. This leads to a continuous energy distribution in the spectra rather than distinct peaks. For the case of the LYSO gamma rays most of the Compton electron energies are below the Cherenkov threshold ($\sim$ 170 keV for electrons). In contrast, for the ^{60}Co gamma rays, a larger fraction of Compton recoils are above the Cherenkov threshold. In fig. 5 is shown a comparison of the spectra collected with the EJ-200 and FB118. The much smaller count rate measured by FB118 for the LYSO gamma ray, as compared with ^{60}Co gamma rays suggests that Cherenkov emission is the dominant effect for FB118 luminescence, while the scintillation process appears to be suppressed.

By comparing the signal amplitude distributions measured with FB118 with the ones measured with EJ-200 we can estimate an upper limit for the light-yield of the scintillation in the FB118 sample. In particular, the ^{60}Co test constrains the FB118 light-yield to be lower than 10 times that of the EJ-200. The LYSO test suggests it is up to 30 times lower, and thests with proton beam indicate that id could be less than 0.3%.

Finally, from the comparison of the light yield of EJ-200 ($\sim$ 10000 ph/MeV) with that of the FB118 during the test with μ it is found that FB118 acts as a high-efficiency Cherenkov radiator ($\sim$200 ph/mm in the visible). A plausible explanation for this behav-

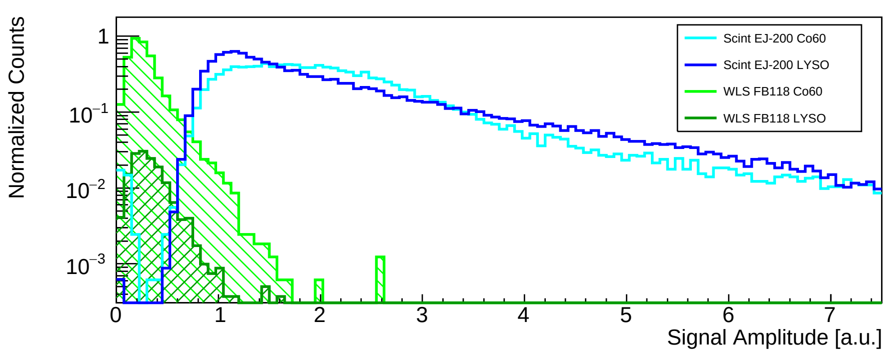

Fig. 5. – Signal amplitude distribution measured with different gamma sources, normalized to counts collected by EJ-200 scintillator (not filled area). The signal amplitudes measured by the FB118 sample (filled area) are much smaller as compared with EJ-200.

ior is related to the good efficiency of FB118 in internally converting the large fraction of the UV Cherenkov light into visible. Due to the loss of the original photon direction, the FB118 is not suitable as a radiator for Ring Imaging Cherenkov Detector but it could be a promising compact "threshold/photon-counting" Cherenkov detector able to replace the Time of Flight velocity measurement in small particle detectors in space (*e.g.*, [9]).

4. – Conclusions

The light yield of the FB118 WLS material manufactured by "Glass to Power" [8] was investigated. The material does not exhibit scintillation emission, this is a requirement for the use of FB118 as a WLS in the PHeSCAMI project. A high-efficiency Cherenkov emission is observed, this is related to the capability of FB118 to convert UV photons into visible. The impact of this effect should not affect the antideuteron identification capability of the PHeSCAMI project, since the region of interest of this detector is limited to $E_k < 300 MeV/n$ that is below the Cherenkov threshold of FB118 ($\beta_{threshold} \simeq 0.65$). Finally, it is suggested that FB118 could be considered as a Cherenkov layer for the velocity measurement in the range $v/c = [0.7 - 0.9]$ in compact space detectors where a complex Time of Flight system is typically unfeasible.

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