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ARAPUCA a new device for liquid argon scintillation light detection

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Abstract: We present a totally innovative device for the detection of liquid argon scintillation light, that has been named ARAPUCA (Argon R&D Advanced Program at UniCAmp). It is composed of a passive light collector and of active devices. The latters are standard SiPMs that operate at liquid argon temperature, while the passive collector is based on a new technology, never explored in this field before. It is a photon trap, that allows to collect light with extremely high efficiency. The total detection efficiency of the device can be tuned by modifying the ratio between the area of the active devices (SiPM) and the area of the optical window. For example, it will allow to reach a detection efficiency at the level of 1% on a surface of $50 \times 50\,\text{cm}^2$ with an active coverage of $2 \times 2\,\text{cm}^2$ (two/three large area SiPM). It is also a cheap device, since the major part of its cost is represented by the active devices. For these reason this appears to be the ideal device for scintillation light detection in large Time Projection Chambers. With appropriate modifications it can be used also in next generation Dark Matter detectors.

Keywords: Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); Noble liquid detectors (scintillation, ionization, double-phase); Neutrino detectors; Dark Matter detectors (WIMPs, axions, etc.)

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1 The ARAPUCA concept

The idea at the basis of the ARAPUCA is to trap photons inside a box with highly reflective internal surfaces, so that the detection efficiency of trapped photons is high even with a limited active coverage of its internal surface. Photons' trapping is achieved by using a smart wave-shifting technique and the technology of the dichroic short-pass optical filters. The latter are multilayer acrylic films with the property of being highly transparent to photons with a wavelength below a tunable cut-off while being almost perfectly reflective to photons with wavelength above the cut-off. A dichroic short-pass filter deposited with two different wavelength shifters (one on each side) will be the core of the device. In particular, it will be the acceptance window of the ARAPUCA. The rest of the device will be a flattened box with internal surfaces covered by highly reflective acrylic foils (3M-VIKUITI ESR or VM2000, for example), closed on the top by the dichroic filter deposited with the two shifters. In principle the box can be filled with any kind of transparent material, since it is inessential to its operation. A fraction of the box internal surface is occupied by the active photo-sensors (Silicon Photomultipliers – SiPM) that detect trapped photons. A pictorial representation of the device is shown in figure 1, left.

1.1 Operating principle

The shifters deposited on the two faces of the dichroic filter, S_1 and S_2 respectively, must have their emission wavelengths, L_1 and L_2, such that: $L_1 < L_{\text{cut-off}} < L_2$, where $L_{\text{cut-off}}$ is the cut-off wavelength of the filter, that is the limit between the region of full transparency (typically$> 95\%$) and that of full reflectivity (typically $> 98\%$). The side of the filter deposited with S_2 faces the internal part of the box. Assuming that the ARAPUCA observes a LAr volume, scintillation Vacuum Ultra Violet (VUV) photons ($\lambda \simeq 127$ nm) produced by the passage of an ionizing radiation, hit the window of the device and are shifted to a wavelength of L_1 nm by the shifter deposited on the external face of the filter and enter the ARAPUCA. Once trespassed the filter, the photons

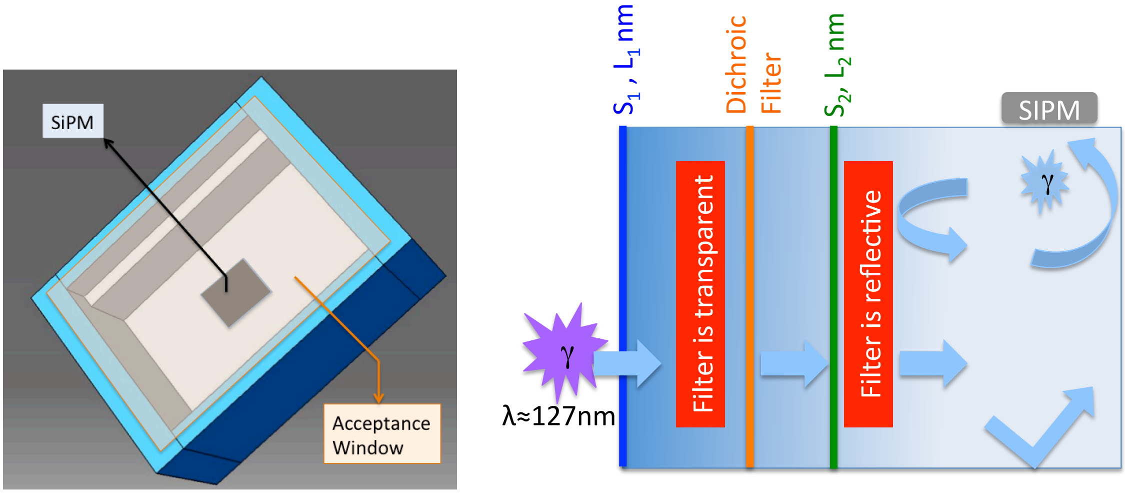

Figure 1. Left: pictorial representation of the ARAPUCA. Here are represented the box with internal reflective surfaces (in blue), the dichroic window and the photo-sensor (SiPM). Right: operating principle of ARAPUCA.

are converted to the wavelength L_2 and are forced to remain trapped inside the box: its internal surface is covered with an almost perfect reflector to L_2 nm and the filter that closes the box is itself reflective to L_2 nm photons. Photons are trapped inside the box. After few reflections the photons are detected by the active photo-sensor installed on the internal surface of the ARAPUCA (see figure 1, Right). If the reflectivity of the surface is high enough, it is easy to reach detection efficiencies at the level of percent even with an active coverage of the internal surface of the device below 10^{-3}.

2 Expected efficiency of the ARAPUCA

A rough estimation of the efficiency and of the potentialities of the ARAPUCA device can be done on the basis of simple hypotheses and calculations. It is more convenient to consider separately the cases of large TPCs for neutrino physics and of Dark Matter detectors based on liquefied noble gases.

2.1 ARAPUCA for large LAr TPC

This kind of application requires the coverage of large areas and a photon detection efficiency at the level of percent. If one considers, for example, an ARAPUCA with a macroscopic acceptance window of $50 \times 50\,\text{cm}^2$, it is easy to show that to reach a photon detection efficiency at the level of one percent an SiPM active surface of only $2 \times 2\,\text{cm}^2$ is enough.

Consider a very basic geometry for the ARAPUCA: a flat box with dimensions of $50{\times}50{\times}1\,\text{cm}^3$. One of the wide faces is constituted by the window of the device while all other faces are blind. The internal surface (except the window) is covered with acrylic foils with high reflectivity (3M VIKUITI ESR – reflectivity $\sim 98\%$ for $\lambda > 400$ nm). The acceptance window is made by a short-pass dichroic filter with cut-off wavelength of 400 nm (typical transmittance below 400 nm – Tw $\sim 95\%$ – typical reflectance above 400 nm – Rw $> 98\%$); the shifter deposited on the external side of the window is p-terphenyl (PTP) [1] – emission wavelength = 350 nm; the shifter deposited on the internal side of the window is Tetraphenyl-butadiene (TPB) – emission wavelength = 430 nm [2]. The shifting efficiency of PTP for 127 nm photons has been measured and is $\epsilon_{\rm PTP} \sim 100\%$ [3, 4], while the shifting efficiency of TPB for 350 nm photons is $\epsilon_{TPB} \sim 80\%$ [5, 6]. The efficiency of the acceptance window in transmitting photons through it can be easily calculated and results to be: $\epsilon_{\rm W} = T_{\rm w} \times \epsilon_{\rm PTP}/2 \times \epsilon_{\rm TPB} \simeq 1/3$. The factor 2 is due to the fact that half of the photons shifted by the PTP on the external side of the window are lost since the emission process is isotropic.[1] The fraction of photons collected on the SiPM can be estimated analytically. As shown in [7] the collection efficiency can be estimated as:

$$\epsilon_{\rm coll} = \frac{f}{1 - R_{\rm w}(1 - f)} \tag{2.1}$$

where f is the photo-cathodic coverage of the internal surface, that is the fraction of the internal surface covered by the SiPM. For $f = 0.001$ it results that $\epsilon_{\rm coll} = 0.048$. Considering the dimensions of the box a 0.001 coverage corresponds to a SiPM area of $\sim 2.2 \times 2.2\,{\rm cm}^2$. The total efficiency in collecting photons on the SiPM surface is given by the product: $\epsilon_{\rm W} \times \epsilon_{\rm coll} = 1.6\%$. Considering that next generation SiPM will have photon detection efficiency higher than 50% [8, 9], a total efficiency of this hypothesis of ARAPUCA at the level of 1% is realistic.

2.2 ARAPUCA for Dark Matter detectors

Dark Matter detectors need to have a high sensitivity to extremely low level of illumination, because the deposited energy that is expected by an interaction of a hypothetic dark matter particle is extremely low, below 100 keV. A typical Dark Matter detector using liquefied noble gases as active medium has an extremely high efficiency in detecting photons and light yields of 5 phel/keV or more are common [10, 11]. This is typically obtained with a high photo cathodic coverage of the detector (at the level of $20 \rightarrow 30\%$). Covering large areas with active photo devices is extremely expensive because high efficiency cryogenic photomultipliers have a unit cost of several thousands of euros. Next generation detectors will have active masses of the order of few tons and will need to cover areas of the order of square meters with active photo-devices in order to reach their target sensitivity. The economic effort can hardly be afforded.

The use of the ARAPUCA could be extremely interesting in this case. In fact, with its capability of trapping photons, it could allow to maintain high detection efficiencies while sensibly reducing the number of photo-sensors. It can be shown, with the same procedure discussed for large TPC, that it could allow to reduce the number of required photo-sensors by a factor of four, while keeping the 80% of the light detection efficiency of the detector. Consider first the case in which the active surface is fully instrumented with active devices (being photomultipliers or silicon sensors). The detection efficiency for shifted photons hitting the active surface, is given by the quantum efficiency of the sensor, $\epsilon_{\rm Tot} = \epsilon_{\rm sens}$. In the case of the ARAPUCA one has to consider the transparency of the window, the efficiency of TPB and the collection efficiency of the device:

$$\epsilon_{\rm Tot}^{A} = \epsilon_{\rm sens} \times T_{\rm W} \times \epsilon_{\rm TPB} \times \epsilon_{\rm coll}. \tag{2.2}$$

[1]The same effect holds for any kind of photo detection system since the 127 nm photons need to be wave-shifted in any case before being detected.

Hence:

$$\frac{\epsilon^A_{\text{Tot}}}{\epsilon_{\text{sens}}} = T_{\text{W}} \times \epsilon_{\text{TPB}} \times \epsilon_{\text{coll}}. \tag{2.3}$$

Considering that $T_{\text{W}} \times \epsilon_{\text{TPB}} \sim 0.9$, one can obtain an ϵ_{coll} of about 0.9 for f $\sim$ 0.13. This combination gives a relative efficiency of 0.8. Since the internal surface of the ARAPUCA is given essentially by two times the surface of the window, a coverage of 0.13 corresponds to covering the equivalent of 26% of the surface of the window with active devices. A solution of this type would give a detection efficiency that is 80% of what can be obtained with a pure active coverage, but using only one fourth of the sensors.

3 The first prototype

The first prototype of the ARAPUCA has been recently realized at UNICAMP. It is a small box with a window of 3.5 cm × 2.3 cm. The box is made of teflon and has an internal height of 1 cm. A dichroic filter with a cutoff of 400 nm has been used, and the shifters are P-Terphenyl (350 nm) for the external side and TPB (430 nm) for the internal one (see figure 2). Photons are detected by means of a $3 \times 3\,\text{mm}^2$ Hamamatsu SiPM (1 pixel of the SiPM array Hamamatsu S11828-3344M [12]) The expected detection efficiency to 127 nm photons for this first prototype has been estimated to be around 2%. The estimation is based on analytical calculations, similar to those presented in section 2.1 and 2.2.

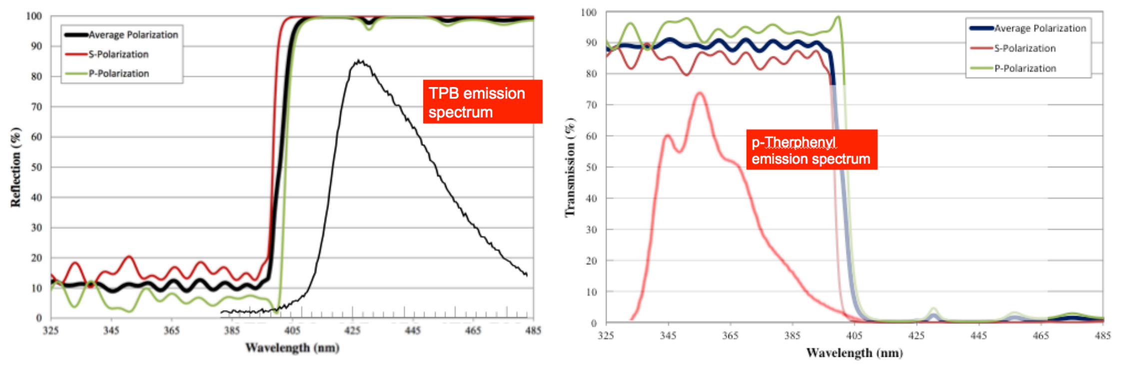

Figure 2. Left: TPB emission spectrum overlapped to the reflectivity of the short-pass dichroic filter (Edmund optics [13]). Right: p-Therphenyl emission spectrum overlapped to the transmissivity of the short-pass dichroic filter (Edmund optics [13]).

3.1 Ongoing tests

The entire prototype is being tested in gaseous argon (GAr) at room temperature at the CTI *Centro Tecnologico da Informação Renato Archer* [14] of Campinas where a sealed chamber that can be flushed with GAr is available. An alpha source made of an alloy of aluminum and uranium, with a continuos spectrum up to an end point of ~ 5.3 MeV, has been installed in the chamber. Alpha particles excite GAr that emits VUV photons, mainly with a wavelength around 127 nm (the same of LAr). The outcomes of these tests will give a clear indication of the performances of the ARAPUCA. The tests in a Liquid Argon chamber will be carried on at UNICAMP cryogenic laboratory, when it will be ready (hopefully in the first half of the next year).

4 Conclusions

This idea of the ARAPUCA is expected to set a new status of the art in scintillation light detection for noble liquids, mainly in applications that foresee the realization of multi-kton TPC. But it will not be restricted to it. In general low background and low illumination applications could find this new experimental technique useful. For example, next and ultimate generation of Dark Matter detectors could strongly profit of it. It could allow to drastically reduce the number of active photo-sensors, without significant loss of efficiency. This is a relevant point for detectors that foresee the installation of several square meters of active photo-devices: it improves the radio-purity of the system, makes easier the design of the read-out electronics and reduces the costs.

It can have a great impact also in the field of neutrino-less double beta decay. For example GERDA [15], that is actually one of the leading experiments in this filed, uses LAr as an active veto, exploiting its scintillation light. The radio-purity requirements are even more stringent in this case than for dark matter detectors and the use of ultra-pure silicon sensors in place of standard photomultipliers coupled to passive light traps, would significantly increase the background rejection capability of the detector. Furthermore, the interest for silicon sensors coupled to noble liquids is growing also outside the field of fundamental physics. In particular SiPMs, in combination with LAr or LXe, are being considered for the gamma detectors of Positron Emission Tomography (PET).

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