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New particle detectors (and possible R&D's) of interest in NON-accelerator physics

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Summary. — This paper shortly summarizes some of the many R&D activities in the field of NON-accelerator physics. New conceptual detectors, read-outs and associated electronics are presented for a wide scenarios of applications in physics, such as rare events (dark matter, double beta decay, ...) investigations, neutrino physics, cosmic rays experiments (either at ground level and in the space), gravitational waves and general physics studies.

PACS 29.40.-n – Radiation detectors.

1. – Introduction

This paper aims to gather and to shortly summarize some of the many R&D activities funded by INFN in the field of NON-accelerator Physics. Actually, these activities are shared between the experimental activities within the Scientific Committees of INFN for NON-accelerator Physics (CSN2) and for technological and interdisciplinary research (CSN5). In such respect, the arguments here reported have also been discussed more extensively in the presentations by P. Belli in CSN2 [1] and by R. Battiston in CSN5 [2]; more arguments can also be found in the slides of P. Belli at this Conference [3].

2. – Themes of interest in NON-accelerator physics

The community of NON-accelerator physicists is engaged in frontier researches, which often require new technologies and/or enhancements on the detection technologies. Some of these developments take place within the CSN2 of INFN, others —at more preliminary stage— within the CSN5. Most of them will be shortly summarized in the following and concern a wide scenario of applications, such as rare events (dark matter, double beta decay, ...) investigations, neutrino physics, cosmic rays experiments (either at ground level and in the space), gravitational waves and general physics studies. The R&D's in this field imply continuous interactions with industries and research centers. In particular, new instruments are available, such as for electromechanical systems MEMS ("Micro-ElectroMechanical Systems") project [4] with FBK ("Fondazione Bruno Kessler") [5]. Moreover, there are new opportunities, as the birth of TIFPA ("Trent Institute for Fundamental Physics and Applications") [6] in collaboration with FBK CMM ("Center for Materials and Microsystems") [7].

The themes of interest and the R&D's on the techniques of detection in the field of NON-accelerator physics can be summarized as:

– *Light measurements.* In particular, the hot keys are the devices and the related electronics, their sensitivities depending on their specific use, the necessity to read-out a large number of channels (may RFID help?), a suitable radiopurity when required, the possible detection of fluorescence light of the atmosphere in the NIR ("Near Infra-Red"), etc. Moreover, when cryogenics are needed, as in case of LAr TPC, a crucial role is preliminarly covered by all the problems and possible solutions for low temperature devices; as PMTs, SiPM, APD, ASIC, ...

– *Detectors.* A particular care must be dedicated to the definition of the detector for the needed purposes. In NON-accelerator physics a very important role is played by the (ultra/very)-low background detectors for experiments on rare events, as Dark Matter and double beta decay investigations, neutrino physics, ... In addition, detectors for single photon counting with low counting rate at level of 1 eV–1 keV for WISPs ("Weakly Interacting Slim Particles"), axions and axion-like particles are under study and development. Some ideas that must be encouraged are the polarized active targets for the neutrino Physics [8] and silicon-carbon nanotubes junctions (see for example [9] and possible far future applications).

– *(Micro)Mechanics.* A large set of developments exists in the field of the search for gravitational waves through interferometers and in the field of fundamental physics.

– *(Micro)Bolometers and low energy thresholds.* These devices can be used in the Dark Matter and double beta decay investigations, in general physics, in the study of CMB and, possibly, in application in space.

– *New technologies for Dark Matter investigations.* The field of the direct detection of Dark Matter particles is interested in looking for new detectors with peculiar features mainly in the application of the directionality [10]. In this respect, anisotropic scintillators can play a role, as well as (nano)technologies, nanotubes and (nano)emulsions. Other applications regard the use of bubble chambers.

– *Radio detection of EECR.* The developments of possible new methods to detect very high energy cosmic rays (CR) through their possible microwave emission when crossing the atmosphere [11] is in progress (see *e.g.* ref. [12]).

– *Others.* In this category we can include all the R&D's for neutrino factories, and the arguments of interdisciplinarity as the study of environmental radioactivity [13], possible correlations between geophysics and cosmic rays [14], radio-protection from CR in space through a magnetostatic device [15], etc.

In the following some of these arguments will be shortly discussed.

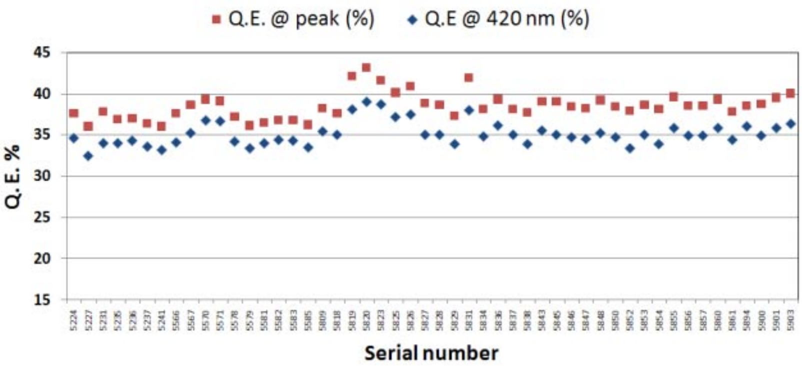

Fig. 1. – Quantum efficiency at peak and at 420 nm of each one of the 50 high Q.E. PMTs, installed in DAMA/LIBRA-phase2 [16].

2˙1. *Light measurements*. – A large set of experiments is based on the detection of scintillation/Cherenkov light produced either in organic liquid or inorganic crystal scintillators or in water or in air.

The items of improvement for the traditional photomultiplier (PMT) and its related electronics concern the increase of the quantum efficiency (Q.E.), the reduction of the noise due to single photoelectrons and to afterpulses, the necessity to get transit time as uniform as possible, to improve the charge response, and whenever required to reduce the residual radioactive background below 10-100 mBq per PMT.

As an example, this line guide has been followed by DAMA: after the DAMA/LIBRA-phase1 all the PMTs have been replaced by new PMTs having higher quantum efficiency (see fig. 1) than those previously used [16]; the DAMA/LIBRA-phase2 is now continuously running in this new configuration with a lower energy threshold. The light response typically increases from 5.5–7.5 photoelectrons/keV (ph.el./keV) to 6 up to 10 ph.el./keV in DAMA/LIBRA-phase2, and improvements in the energy resolutions of the ultra low background NaI(Tl) detectors have been consequently obtained [16].

As regards scintillation light collection in Liquid Noble gases, as LAr, the new conceptual design of the QUPIDs in fig. 2 has been somewhat proposed within the activities of Dark Matter investigation [17]. A R&D is in progress at LNGS [18]; this activity has produced a low noise prototype that will be installed in Darkside. Moreover, applications as read-out for the veto system made of LAr in GERDA experiment for the double beta decay search is under evaluation [19].

When low energy thresholds are not required, alternative solutions to PMTs can be considered; large R&D's are in progress for the use of SiPM (Silicon photomultiplier) of sufficient area around few squared cm. They may be particularly useful for the NUV (near ultraviolet) detection and when a very large number of channels is required, as in underwater experiments (KM3), in the focal plane of CTA, in experiments in the space (JEM-EUSO, Gamma400, HERD, ...) and, possibly, in future neutrino experiments (for example upgrades in Daya Bay).

Of course, for an effective use of either PMTs and other alternatives an effective electronics is mandatory; projects to develop front-end electronics, cryogenic and miniaturized devices, with the necessity of high radiopurity, when required, are in progress. For example, the amplification in loco is considered either in order to decrease the gain

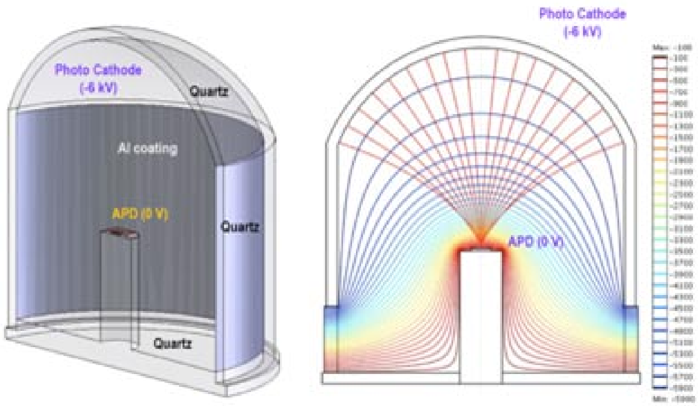

Fig. 2. – Schematic views of the QUPIDs, implemented for light read-out in Liquid Noble gases detectors.

of the PMTs, and consequently to reduce their ageing problems, or in order to sum together many channels of solid state detectors (APD, SiPM, ...) to produce sensitive areas competing with those of PMTs.

2·2. *Detectors*. – The choice of the detectors is a fundamental item for the goodness of an experiment. Several works are performed in order to produce, to develop and to optimize (very-)high purity detectors for rare events searches; particular care is also adopted for enhancing their characteristics.

As concern GERDA experiment (see fig. 3), new detectors of phase 2, BEGe, are studied in order to have: i) greater capability to distinguish signal events (single-site events)

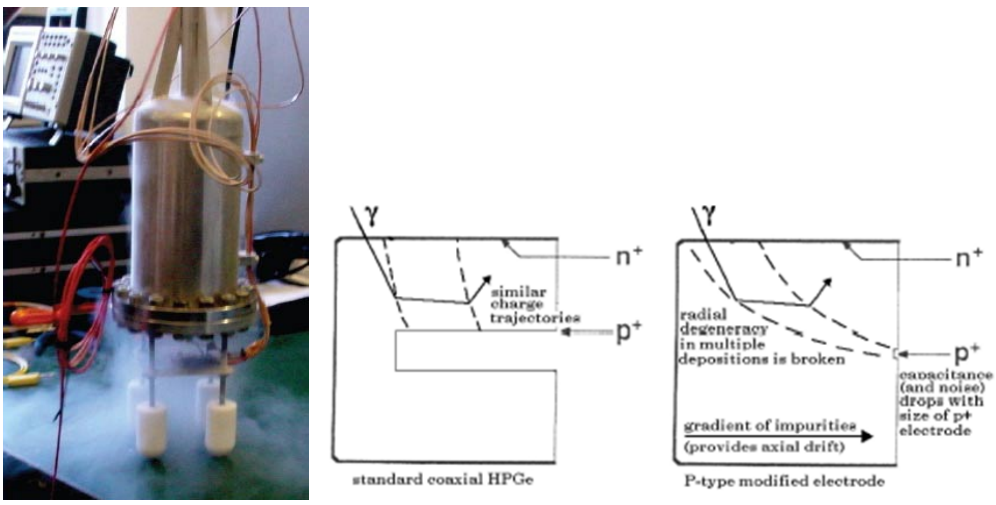

Fig. 3. – A photo of a HPGe detector of GERDA and the conceptual difference between HPGe and BEGe detectors.

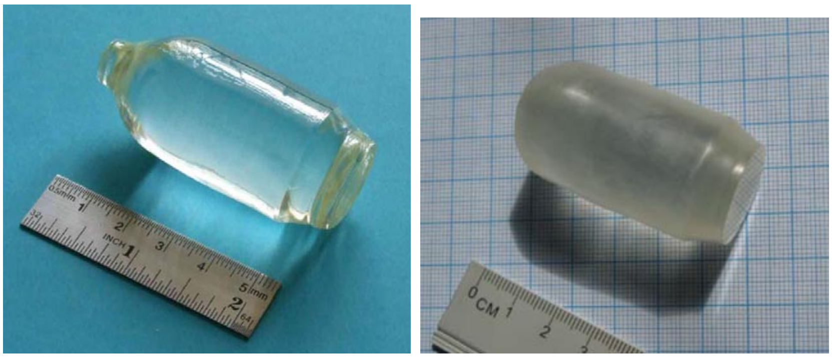

Fig. 4. – Boule (left) and scintillating element (right) of $^{106}CdWO_4$ crystal grown by the low-thermal-gradient Czochralski process used by the DAMA collaboration for the experiment on the double beta decay of ^{106}Cd isotope.

from background events (multi-site events); ii) better energy resolution. Moreover, the collaboration is evaluating the possibility to read-out the LAr scintillation through either APD or SiPM.

A particular mention must be done to the developments of very low background scintillating crystals made by the DAMA collaboration [20] for rare events searches; in particular, continuous new efforts to improve their radiopurity and performances are adopted and many low-background crystals have been developed and measured, such as [21]: NaI(Tl) (towards very high radio-pure detectors for the possible DAMA/1ton set-up), CaF_2(Eu), LiI(Eu), LiF(W), SrI_2(Eu), BaF_2, $CeCl_3$, CeF_3, $LaCl_3$(Ce), $CdWO_4$ enriched either in ^{106}Cd (see fig. 4) or in ^{116}Cd, $ZnWO_4$, Gd and Nd loaded scintillators, Li_2MoO_4, $Li_6Eu(BO_3)_3$, ZnS(Ag), etc. and development of new scintillators containing interesting isotopes (for the investigation of Dark Matter, solar axions, double beta decay in several isotopes, and other rare processes).

The study of the most performable detectors is also of importance in the application of experiments in space; also for this purpose R&D's are performed on SiPM with reduced dark current and larger sensitivity in the UV and blue for the read-out either of crystal calorimetry (see fig. 5), or of scintillating fibers for time of flight systems and for anticoincidence at high timing response.

Many other studies are in progress; here we just mention the project NIRFE [22] to detect the NIR radiation produced by UHECR interaction in the atmosphere, as reported in fig. 6, and the R&D's for future Long Baseline neutrino experiments.

2·3. *(Micro)Mechanics*. – In this category we can include all the efforts towards very low losses mechanical devices, as sensors, actuators and test masses. The technical goals are: i) lower thermal noises to/below quantum noise limit; ii) increase of the coherence time; iii) cool by feedback. The application fields and the related experiments are: i) investigation of quantum-mechanical systems with macroscopic degrees of freedom (see fig. 7), as SQUALO in CSN5 [23]; ii) gravitational wave detectors and quantum gravity effects, as HUMOR [24] (studies of quantum effects on macroscopic resonators to test quantum gravity theories), LISA-PF [25] (interferometry in space, see fig. 8), VIRGO [26] (interferometry at ground, see fig. 8), etc.; iii) investigation of noise fluctuations in non equilibrium systems (RARENOISE [27]); iv) development of higher performance mechanical sensors and actuators.

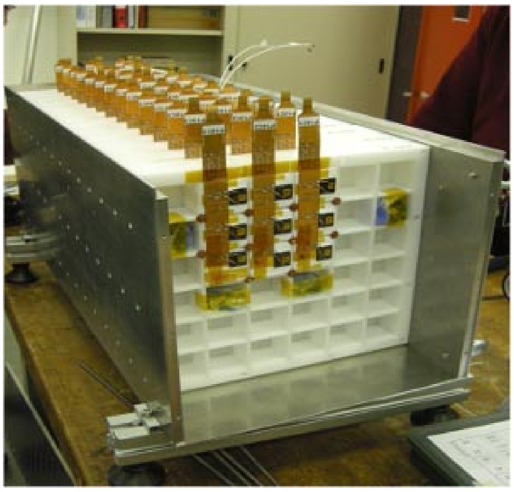

Fig. 5. – A photo of the GAMMA400 prototype tested on an ion beam at CERN.

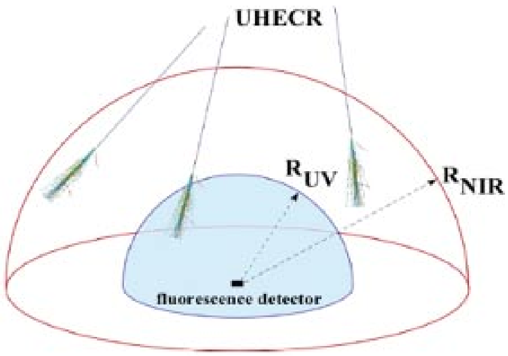

Fig. 6. – Conceptual idea of NIRFE: NIR fluorescence has much longer absorption length in air than UV. Hence an increase of the observable event rate is expected.

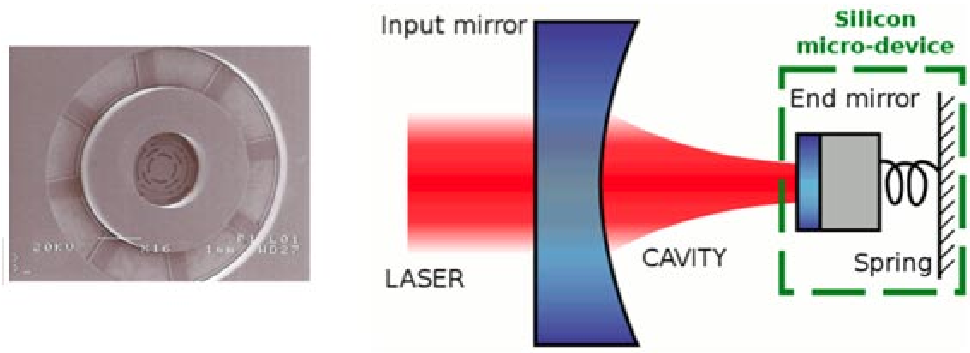

Fig. 7. – MEMS mirrors for quantum opto-mechanics. Radiation pressure couples a moving mirror and laser light in a Fabry-Perot cavity.

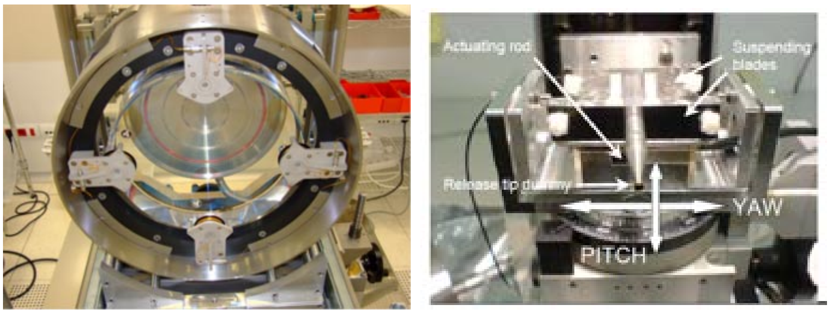

Fig. 8. – Pictures of VIRGO mirror and of the system of LISA-PF.

2·4. *(Micro)Bolometers and low energy thresholds.* – New techniques have been developed to identify the background of detectors used in the rare events searches. In particular, Lucifer [28] uses scintillating bolometers, as $Zn^{82}Se$ crystals, as shown in fig. 9; the α-induced background could be recognized through two independent measurements: 1) the decay time of the scintillating signal; 2) the different scintillation yield between α and γ/β particles (the "usual" light *vs.* heat scatter plot).

Some ideas have been proposed about experiments of classic and quantum gravitomagnetism in laboratory [29] and developments of amplifiers at quantum limit [30]. Their possible applications in general physics and detection of eV photons for the study of cosmological axions, coherent scattering of neutrinos and dark matter are straightforward.

Detection of WISPs is proposed through their possible interaction with a suitably cooled micro-membrane, whose motion within a resonant Fabry-Perot cavity can be detected by the cavity finesse [31].

Another example of new conceptual devices is the MKIDs [32]: micro-resonator detectors for neutrino physics. Possible applications are: i) athermal detector arrays with embedded ^{163}Ho for direct neutrino mass measurement; ii) athermal detector arrays for energy and/or position resolved particle detection (neutrinoless double beta decay); iii) arrays of large area for scintillation or Cherenkov light detection in double read-out bolometers; iv) thermal mode resonator sensors for large volume low temperature detectors for neutrinoless double beta decay, dark matter, coherent neutrino-nucleon scattering.

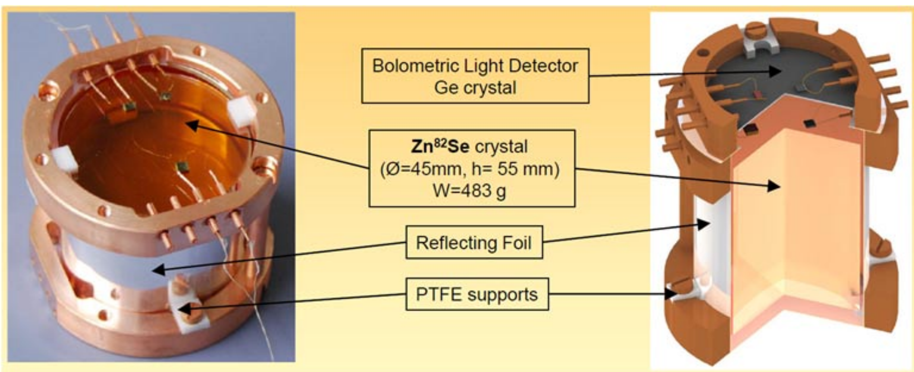

Fig. 9. – Photo and schema of a typical detector of Lucifer experiment.

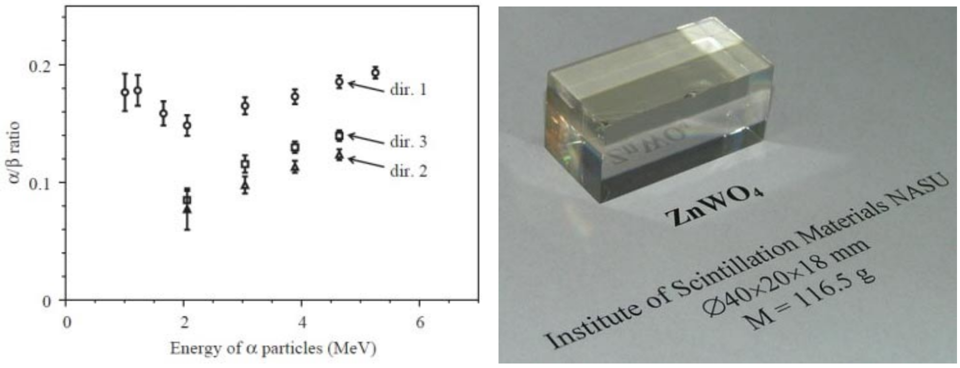

Fig. 10. – ADAMO project. Left: dependence of the α/β ratio on energy of α particles measured with $ZnWO_4$ scintillator for different α directions of irradiation. The anisotropic behaviour of the crystal is evident. Right: a picture of a $ZnWO_4$ scintillator.

2˙5. *New technologies for Dark Matter investigations.* – New detectors with peculiar features mainly in the application of the directionality have been proposed in the field of the direct detection of Dark Matter particles. The anisotropic scintillators can offer a unique way to study directionality for Dark Matter candidates that induce nuclear recoils [33]. Figure 10 shows the case of $ZnWO_4$ scintillator, suggested in ref. [10] as a suitable detector for such a purpose. Both light output and pulse shape have anisotropic behavior for highly ionizing particles (while these scintillators show an isotropic behaviour for e/γ) and can provide two independent ways to study directionality; these detectors can be produced at very high level of radio-purity and energy threshold at keV is feasible. Moreover, other ideas to develop Carbon Nano Tubes (CNT) detectors are in progress [34]: the detection principle is based on variation of the transport properties in CNT due to the particle irradiation. The intrinsic 1-D nature of CNTs makes them very promising for the study of directionality.

The exploitation of (nano)emulsions [35], similar but with higher spatial resolutions than those used in OPERA experiment, is ongoing; the application of bubble chamber [36] in the identification of recoils is another tools studied in this field. In both cases, technical limitations on the technique (reachable sensitivities, energy thresholds, stability, etc.) can arise, and validation of the performances at low energy is required.

3. – Conclusions

The activities of physics without the use of accelerators involve many different lines, from the neutrino physics to the study of the Dark Matter in the Universe, from the double beta decay searches to the gravitational waves, from the study of cosmic rays to the general Physics. These experiments are a wide source of technological developments for new detectors, new (technological and/or low background) materials and new experimental techniques; large efforts are in progress. Moreover, these activities also provide continuous interactions among industry and research institutes.

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