Toward coherent neutrino detection using low-background micropattern gas detectors

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***Abstract*—The detection of low energy neutrinos ($<$ few tens of MeV) via coherent nuclear scattering remains a holy grail of sorts in neutrino physics. This uncontroversial mode of interaction is expected to profit from a sizeable increase in cross section proportional to neutron number squared in the target nucleus, an advantageous feature in view of the small probability of interaction via all other channels in this energy region. A coherent neutrino detector would open the door to many new applications, ranging from the study of fundamental neutrino properties to true "neutrino technology." Unfortunately, present-day radiation detectors of sufficiently large mass ($>$1 kg) are not sensitive to sub keV nuclear recoils like those expected from this channel. The advent of micropattern gas detectors (MPGDs), new technologies originally intended for use in high energy physics, may soon put an end to this impasse. We present first tests of MPGDs fabricated with radioclean materials and discuss the approach to assessing their sensitivity to these faint signals. Applications are reviewed, in particular their use as a safeguard against illegitimate operation of nuclear reactors. A first industrial mass production of gas electron multipliers (GEMs) is succinctly described.**

***Index Terms*—Coherent scattering, gas electron multipliers (GEMs), micromegas, micropattern gas detectors, neutrinos.**

I. Coherent Neutrino Detection: A Technological Challenge

A NEW family of radiation detector designs, generally referred to as micropattern gas detectors (MPGDs) [1] has emerged during the last 15 years in response to the demanding needs (fast counting rate, radiation resistance, high spatial resolution) of next-generation high energy physics experiments. While the specific design varies, their common principle is a sizeable voltage drop across microstructures immersed in a suitable gas mixture: electrons originating from particle ionization in a conversion volume are multiplied in the microstructures, where amplification gains of up to 10^7 are obtained. A popular example of a MPGD is the micromesh gaseous structure (MICROMEGAS) design, a concept recently put forward by Giomataris *et al.* [2]. This two-stage parallel-plate avalanche chamber consists of a 100 μm narrow amplification gap and a large conversion region—TPC volumes are possible—separated by a gauze-like electroformed conducting micromesh. Electrons released by ionizing particles in the gas-filled conversion region are drifted toward the amplification gap where they multiply in an avalanche process. Detectable signals are then induced on anode elements. A second example of MPGDs are gas electron multipliers (GEMs) [3], developed at CERN by Sauli *et al.*: small holes (diameter $\sim$80 μm) are photolithographically etched on a $\sim$50 μm-thick Kapton film copper-clad on both sides and a voltage difference of $\sim$400 V is generated across the GEM. The high density of electric field lines within the perforations induces the sought avalanche. An advantage of GEMs is the possibility of building multistage amplification layers (e.g., [4]), allowing for very large gains. The high-efficiency detection of single electrons at gas pressures of up to 20 atm has been achieved in a variety of MPGDs [5]. The effective energy threshold in these devices is the ionization energy of the gas mixture, i.e., a few tens of electron-volts.

The possibility of exploiting some of the features specific to MPGDs in a new realm, that of searches for rare events in neutrino and astroparticle physics has been recently examined [6]. The properties of these devices (background rejection capabilities, demonstrated ability for single-electron detection, versatility and simplicity) suggest a means to tackle a long-standing experimental challenge, the measurement of *coherent* neutral-current neutrino-nucleus scattering. An uncontroversial Standard Model process, the scattering off nuclei of low-energy neutrinos ($<$ few tens of mega electronvolts, e.g., reactor $\bar{\nu}s$) via the neutral current [7] remains undetected. The long neutrino wavelength probes the entire nucleus, giving rise to a large coherent enhancement in the cross section, roughly proportional to neutron number squared . Using this mode of interaction, it would be possible to speak of *portable* neutrino detectors: in some experimental conditions the expected rates can be as high as several hundred recoils/kg/day, by no means a "rare-event" situation. However, the recoil energy transferred to the target is a few keV at most even for the lightest nuclei, with only a few percent going into ionization (Figs. 1 and 2).

The interest in observing this process is not merely academic: a neutral-current detector responds the same way to all known neutrino types. Therefore, the observation of neutrino oscillations in such a device would be *direct* evidence for a fourth sterile neutrino. These have been invoked when all recently observed neutrino anomalies are accepted at face value [9] and may play an important role as dark matter [10]. Separately, the cross section for this process is critically dependent on neutrino magnetic moment. Agreement with the standard model prediction would *per se* largely improve on the present experimental sensitivity to μ_ν [11]. In addition to this, a measurement of the cross section would constitute a sensitive probe of the weak nuclear charge, testing radiative corrections due to new physics above the weak scale with a sensitivity comparable to atomic parity violation and accelerator experiments.

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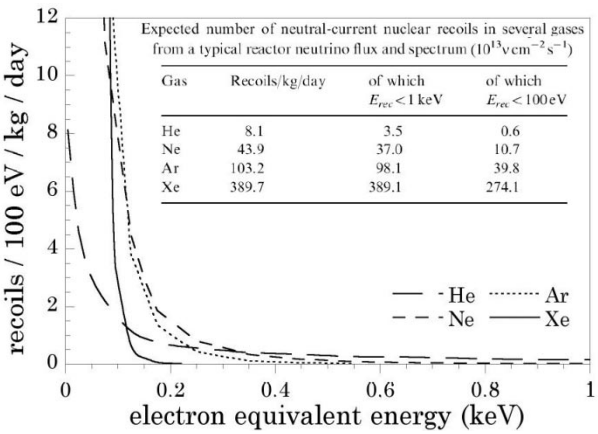

Fig. 1. Detectable signal in different gases from neutral-current nuclear scattering of reactor antineutrinos (10^{13} $\bar{\nu}$ cm^{-2} s^{-1}), obtained by folding of the differential cross section in [8] with the reactor spectrum in [24] and applying quenching factors derived from SRIM [25]. The tradeoff between endpoint energy and rate with increasing atomic mass is evident. *Table*: total coherent recoil rate in different gases under the same conditions.

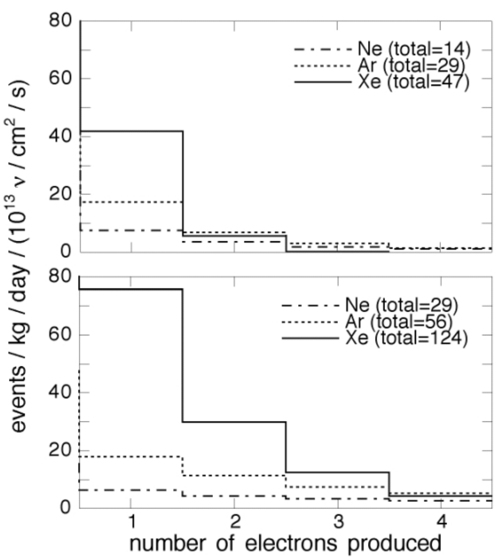

Fig. 2. Distribution in the number of free electrons produced by coherent nuclear scattering in a gaseous detector exposed to a typical reactor antineutrino flux. This estimate includes the reactor emission spectrum [24], differential cross section [8], a theoretical quenching factor derived from Lindhard's theory [25] and the mean ionization energy of the gas mixtures. "Total" denotes here the expected number of recoils/kg/d producing at least one free electron. *Top:* for pure noble gases, *Bottom:* after addition of a small fraction of TMAE vapor which may in principle reduce the ionization threshold to ~ 6 eV. The effect of gas additives such as TMAE or TEA on energy threshold is to be investigated as part of this work [26].

Statistically speaking, this can be accomplished in a nuclear reactor already with a modest detector mass and a short exposure [12]. Finally, this coherent mechanism plays a most important role in neutrino dynamics in supernovae and neutron stars [7], adding to the attraction of a laboratory measurement of this cross section. In particular, a measurement of the *total* (flavor-independent) neutrino flux from a nearby supernova using a large enough coherent detector would be of capital importance to help clarify the exact oscillation pattern followed by the neutrinos in their way to the Earth [13].

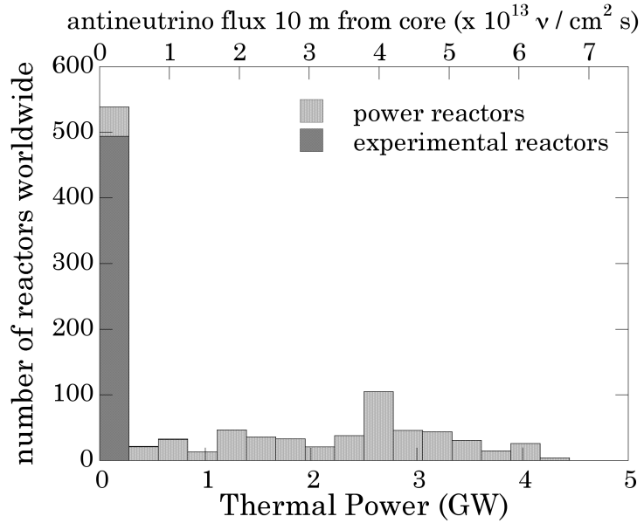

Fig. 3. Power and approximate antineutrino flux distribution of worldwide nuclear reactors, extracted from the databases in [27]. Proposals to monitor illicit reactor activity using conventional neutrino detectors (large liquid scintillator tanks) seem insufficient for this purpose: their sensitivity under realistic conditions would be adequate only for reactor powers larger than ~ 3 GWt and require the construction of underground infrastructure (~ 6 m.w.e.) close to reactor cores [16]. Detectors based on coherent scattering may be able to improve this situation in the near future.

Until now, no existing device had met the mass and energy threshold requirements involved in this measurement, even though unrealized cryogenic proposals abound [8], [14]. A considerable fraction of the neutrino signal in a reactor experiment is nevertheless expected above MPGD energy thresholds (Fig. 2). Structurally simple MPGD-based coherent neutrino detectors would open the door to more mundane but no less important applications than those listed above ("neutrino technology"? [15]): for instance, nonintrusive monitoring of nuclear reactors against illegitimate uses (e.g., fuel rod diversion, unauthorized production of weapon-grade material) with a compact device, potentially improving on existing proposals that rely on standard neutrino detectors and processes [16], (Fig. 3).

II. Present Status and Immediate Plans

We have recently commenced fabrication and characterization of radioclean MPGDs with a first goal of coherent neutrino detection while keeping in mind other possible applications of the same devices, e.g., weakly interacting massive particle (WIMP) searches. Three techniques are currently being pursued in parallel: use of a micromegas backpanel as a proportional-scintillation reflector, multistage GEMs and large electron multipliers (LEMs). The last are similar to GEMs but with all dimensions increased by a factor of ten. The use of LEMs may be advantageous in applications like the present one where no spatial information is required and only modest energy resolution is needed. As a tradeoff they offer a larger resistance against discharge-induced damage than GEMs, due to their reduced capacitance, and the simplicity that comes with their being self-supporting (no careful mounting

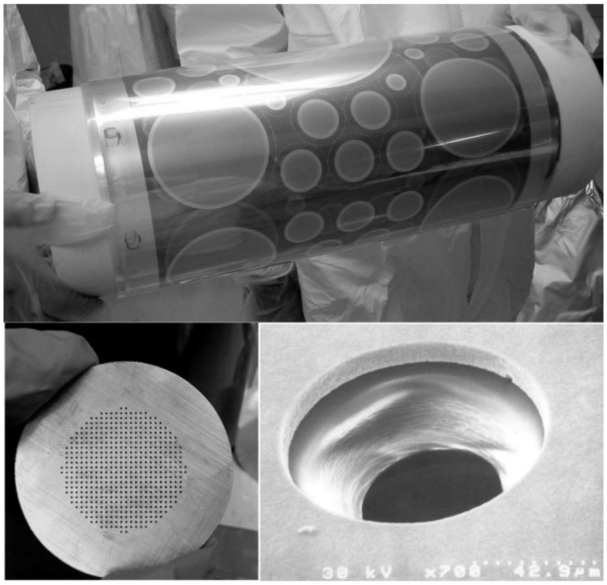

Fig. 4. *Top*: A first mass-production of GEMs using 3M's Microflex adhesiveless reel-to-reel process. The roll in the figure contains 35 panels of 33 GEM elements each. Any GEM pattern up to $12'' \times 12''$ can be produced. Perforations to facilitate detachment are visible around each element. *Bottom right*: SEM photograph of one of these GEMs (hole diameter 80 μm, pitch 140 μm). *Bottom left*: LEMs produced at EFI using automated micromachining on low background laminates (oxygen-free high conductivity (OFHC) copper plated directly onto virgin teflon).

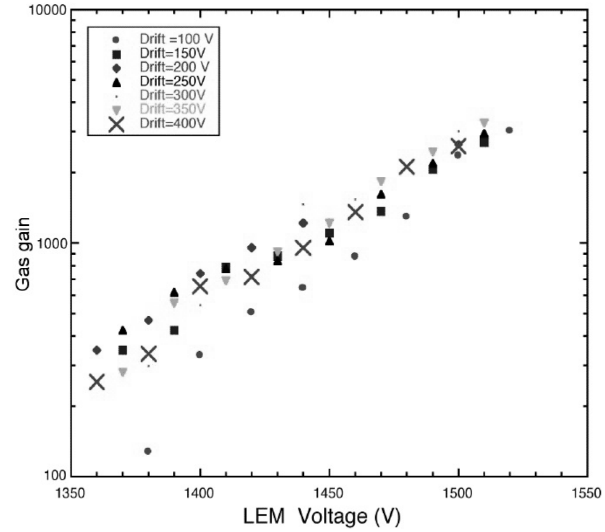

Fig. 5. Preliminary tests of gas gain in a single LEM (Ar:DME(9:1) at 1 atm) using a ^{55}Fe uncollimated source. The drift cathode was grounded and the LEM held at a positive potential ($\mathrm{drift\ distance} = 0.5$ cm). A multilayer LEM structure should provide enough amplification to detect single electrons at moderate gas overpressures. We plan to investigate the dependence of the proportional-scintillation light yield on operating pressure as a possible mechanism to increase gas density while maintaining single-electron sensitivity.

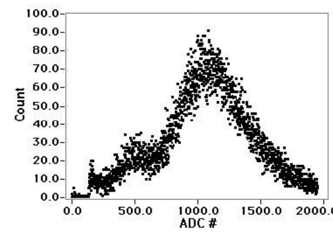

Fig. 6. Observed resolution in a single LEM under horizontal irradiation using an uncollimated ^{55}Fe source (10 cm^2 active area, 0.5 cm drift distance, 1 atm Ar:DME(9:1), $\mathrm{gain} = 1000$). The Ar escape peak is visible.

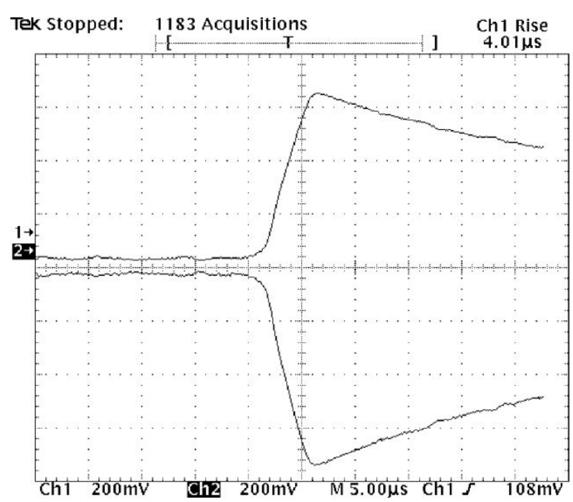

Fig. 7. Signal development in a single LEM under ^{55}Fe irradiation. The top (bottom) trace corresponds to the anode (cathode) signal. Timing and amplitude are identical. A slow ~ 4 μs rise time is observed (some 60 times slower than in a typical GEM), as expected from the large (800 μm) avalanche regions.

and stretching on a frame is needed as in the case of GEMs). LEMs or capillary plates have been previously considered in the context of large TPCs and WIMP detectors [17]. Several LEM prototypes ranging in thickness from 0.25 to 0.75 mm (Fig. 4) have been micromachined at the Enrico Fermi Institute (EFI) from low-activity materials (10 μm OFHC copper plated directly onto virgin teflon) and have undergone satisfactory preliminary tests at Purdue. First measurements on single LEMs are encouraging: only a modest increase in voltage is needed to produce gains similar to GEMs (Fig. 5), most probably due to the longer avalanche regions. They nevertheless exhibit a diminished energy resolution in comparison to GEMs (Fig. 6). While more detailed studies are underway, we can hypothesize that this effect is due to a large fraction of primary ionizations taking place within the LEM holes (in these calibrations the conversion volume was small, a 0.5 cm drift distance). If this is the case, the resolution is expected to improve for larger TPC volumes. As expected, the rise time of the signal is also slower than in GEMs, an effect unimportant for most low-counting rate applications (Fig. 7). It is also observed that the leakage current across these LEMs is of only a few pA @ 2000 V, whereas typical GEMs exhibit values in the few nA @ $\sim$500 V (the volume resistivity of teflon is $\sim 10^{18}$ ohm·cm while this is $\sim 2.3 \times 10^{16}$ ohm·cm in Kapton). A second production of LEMs using a polyetheretherketone substrate is underway (polyetheretherketone exhibits a much lower outgassing than teflon).

Separately, sixty $16'' \times 16''$ GEM panels (for a total of 1980 GEM elements) have been produced in collaboration with 3M [18] using their proprietary reel-to-reel FLEX technology [19], (Fig. 4). This is the first instance of GEM industrial mass production: until now GEMs have been available exclusively from

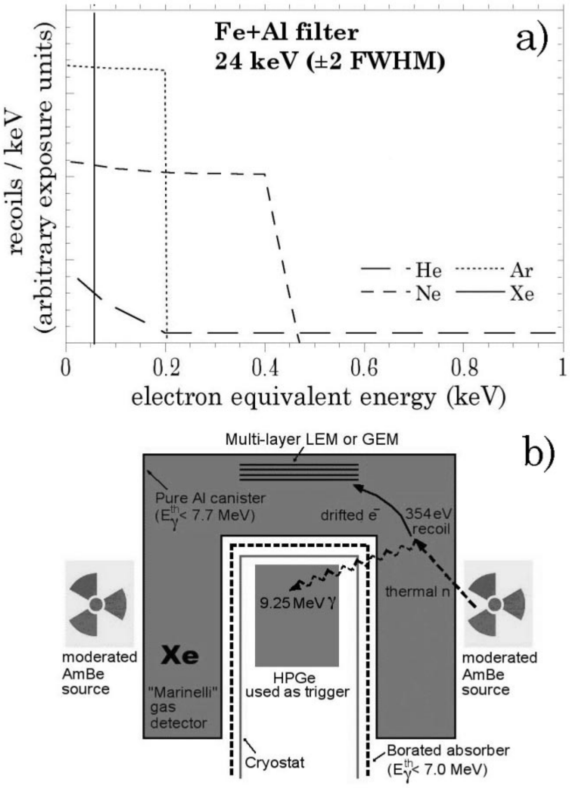

Fig. 8. (a) Recoil signals (energy lost to ionization) expected in different target gases from a filtered (Fe + Al) neutron beam of 24 keV (2 keV FWHM) using the IPNS facility at Argonne National Laboratory. The energy distribution mimics that expected from reactor antineutrinos (Fig. 1). Other neutron energies to be used in these calibrations are 55 keV (Si + S) and 144 keV (Si + Ti) [20]. The distribution of recoils in the figure is obtained from SPECTER [28]. (b) A table-top setup able to produce low-energy monochromatic recoils in the range 140–350 eV in Xe (see text).

CERN, generally in small surface areas most suitable for research and development. Two different techniques (additive and subtractive copper cladding) have been tested, with a third one under production. A large variety of finishings and treatments is possible from 3M's production line: for instance, the periphery of each GEM element within a panel can be perforated for easy detachment. Any GEM pattern is possible, up to a $12'' \times 12''$ size. At the time of this writing the first batch was undergoing testing. Their characterization has been treated since elsewhere [18].

The short-term physics objectives are as follows.

- A calibration facility to provide monochromatic (filtered) neutron [20] beams able to produce recoils almost identical to those expected from reactor antineutrinos (Fig. 8) is to be built at the Intense Pulsed Neutron Source (Argonne National Laboratory). These measurements will provide not only a convincing proof of the ability of MPGDs to detect these low-energy signals, but also a chance to characterize the low-energy quenching factors and thresholds for different gas mixtures as well as the attainable gain as a function of gas pressure. This information is of the utmost importance for the interpretation of a subsequent neutrino experiment. The same facility can be later employed to characterize WIMP detectors. A second calibration setup presently under construction uses well-defined monochromatic daughter recoils from the $\mathrm{Xe}(\mathrm{n}_{\mathrm{thermal}}, \gamma)$ reaction, ranging in energy from 140 eV to 350 eV (Fig. 8). Monte Carlo simulations show that a careful selection of materials can ensure a high signal-to-noise ratio. Thermal neutron absorption has been used before to study quenching factors in Ge for recoil energies down to 250 eV [21].
- An interesting intermediate physics result is expected from measurements of intrinsic detector backgrounds, to take place at a depth of 60 m.w.e. in the low-background laboratory at EFI. A four-liter OFHC Cu prototype is under construction for this purpose. This unique combination of shielding against cosmic rays, sizeable target mass (~ 40 g) and ultra-low energy threshold should return an improvement of several orders of magnitude on the present experimental sensitivity to a slow solar-bound WIMP population [22] and to recently proposed non-pointlike dark matter particle candidates [23]. While the nature of radioactive backgrounds below ~ 1 keV is a true *terra incognita* for large devices, experience in WIMP detector development indicates that no sudden rise is expected in this energy region from known natural sources. Low-energy neutron recoils and recoiling daughters from $(\mathrm{n}_{\mathrm{thermal}}, \gamma)$ can be controlled with layers of moderating and absorbing shielding. Degraded α and β radiations from surfaces can be kept to a minimum using radioclean materials in the detector construction. Similarly, if the need ever arises, it should be possible to reduce spurious single-electron emission from Malter and field effects down to a negligible level via surface treatment (as in accelerating RF-gun cavities) and rigorous control of gas composition and purity.

The progressive achievement of these goals will allow a first measurement of this exciting mode of neutrino interaction by means of a gaseous or two-phase detector near a nuclear reactor.

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