Progress on a spherical TPC for low energy neutrino detection

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Abstract. The new concept of the spherical TPC aims at relatively large target masses with low threshold and background, keeping an extremely simple and robust operation. Such a device would open the way to detect the neutrino-nucleus interaction, which, although a standard process, remains undetected due to the low energy of the neutrino-induced nuclear recoils. The progress in the development of the first 1 m$^3$ prototype at Saclay is presented. Other physics goals of such a device could include supernova detection, low energy neutrino oscillations and study of non-standard properties of the neutrino, among others.

1. The spherical TPC concept and first prototype

The spherical TPC is a novel concept \cite{1} with very promising features, among which is the possibility of easily instrumenting large target masses with very low energy threshold. This could open the way of detecting the tiny (few hundreds of eV) nuclear recoils produced by neutrino-nucleus coherent interaction, which, although a standard process, has never been within reach of current detectors sensitivities.

The spherical TPC consists of 2 concentric spheres, the external one usually connected at ground and the inner one at high potential. The external sphere plays also the role of the vessel that tightly encloses the target gas inside the drift volume. The ionization charges produced in the interaction drift towards the center are collected by an adequate gaseous readout, which covers the surface of the inner sphere. In the simplest design, such amplification structure is just a small spherical electrode, around which the avalanche is produced, and which is read by a single channel electronic chain. More sophisticated options are envisaged for future prototypes readouts, the preferred choice being Micromesh Gaseous Structures (Micromegas \cite{2}) due to

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the high precision, fast response and excellent energy resolution. High efficiency for detecting single electrons have been proved with Micromegas \cite{3} even at high pressures \cite{4}. In addition, Micromegas readout is currently being used for solar axion detection in the CAST experiment \cite{5,6} where a great stability and ability to reject background events has been achieved.

A first prototype has been built in Saclay to demonstrate the concept. The external sphere is a 1.3 m diameter, 6 mm thick copper vessel, and the central amplification electrode is a sphere of 14 mm. First tests with Ar/CO$_2$ and Ar/Isobutane mixtures have proven issues like robustness, gain and stability of operation \cite{7,8}.

In spite of the simplicity of the readout, some spatial resolution is achieved in the radial coordinate by inspecting the time pattern of the charge pulse detected at the center of the sphere. Its temporal extension is determined by the longitudinal diffusion of the ionization cloud and therefore by the distance drifted. The $1/r^2$ dependence of the electric field enhances this effect with respect to plane or cylindrical TPCs. Preliminary, a resolution of at least 10 cm has been achieved in the estimation of the radial coordinate, and better values will be achieved when a faster readout structure, like Micromegas, will be implemented. This will also allow to have transversal dispersion information, by means of an appropriate pixelization of the Micromegas readout. Nevertheless, the result already achieved by the current prototype is enough to perform rough fiducial cuts and to achieve some degree of event identification and background rejection.

Other important advantages of the spherical TPC are:

- The spherical geometry naturally focuses a large drift volume into a small amplifying detector with only a few (or even just one) read-out channels. It is the most cost-effective way of instrumenting a large detector volume with a minimum of front-end electronics. Such approach simplifies the construction and reduces the cost of the project.
- Spherical symmetry minimizes the external surfaces per unit of detector volume, as well as the thickness of material needed to hold the gas, therefore allowing a lower background per unit volume due to external surface or material contaminations. In principle, the simplicity of its design should allow an easy optimization from the point of view of radiopurity. Work is in progress to evaluate expected sources of backgrounds as well as to design a radiopure version of the present prototype.
- Large drift volumes can be built without the use of a field cage, unlike cylindrical TPCs. The spherical symmetry means that the detector capacity is very low, allowing for extremely low levels of electronic noise (in fact, the outer sphere acts as a perfect Faraday cage to the inner electrode). The first preliminary tests with the prototype have easily achieved estimated thresholds of about 200 eV. Keeping in mind that no special measure has been taken for reducing electronic noise, using special quiet electronics or pushing to very high detector gains, the prospects to achieve thresholds well below 100 eV are realistic.
Current efforts focus on the design of an electrostatic structure that allows to bring the high voltage to the internal sphere with minimal distortion of the spherical field, both for purposes of drift and homogeneous amplification all around the small sphere. In the absence of such structure, the central stick bringing the high voltage to the small sphere (and mechanically supporting it) distorts the field away from the ideal spherical field. Numerical calculations, like the ones shown in Fig. 1, show that approximately only one third of the detector volume has an electric field reasonably close to the ideal one. To correct for this effect several basic ideas are pursued, both by doing numerical calculations of the electric field and by performing experimental tests with the prototype. Some options under test consist in the use of rings or cylinders (see Fig. 1) placed at fixed positions around the central stick and at certain intermediate voltages. Another option being used in combination with the previous structures is a resistive conic layer placed at the end of the metallic rod in contact with the small sphere. For appropriate dimensions of the cone, it provides automatically in its surface the correct voltage gradient along the first millimeters away from the sphere, the critical region where the avalanche occurs. More sophisticated ideas are envisaged for the future, an example being charging systems like the one used in electrostatic accelerators, using a series of small metallic balls on an insulator chain.

2. Supernova detection and other physics goals
The detection of neutrino-nucleus interaction opens the way to other very interesting physics goals. In particular, due to the coherence of the interaction, modest detection rates can be achieved by relatively small amount of target material. Neutrinos coming from a supernova could produce between 600 and 1900 events in a spherical TPC of 4 m of radius filled with Xe at 10 bar, by no means a rare event search[9]. A network of smaller spherical TPCs, distributed around the world has been proposed[9] as a very efficient supernova detector, with very simple operation and low cost. It has been also noted that the neutrino-nucleus interaction may give information about particular properties of this particle, like the neutrino charge radius[12] and other non-standard properties of the neutrinos[13]. On the other hand, more conventional neutrino-electron interaction in the gas can also be considered[10], and very low energy neutrino oscillations could be measured[11] using a tritium source, which could have sensitivity to $\theta_{13}$. This type of setup would have a high sensitivity to the neutrino magnetic moment[11]. Another by-product of the spherical TPC is to use it as a neutron detector by partially (or totally) filling it with He-3. That set-up would be able to do neutron spectrometry in very low neutron fluxes, being extremely interesting to characterize neutron backgrounds in underground laboratories.

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