CERN-LAA/94-19
College de France LPC/94-28
4/7/94

E

HELLAZ: A HIGH RATE SOLAR NEUTRINO DETECTOR WITH NEUTRINO ENERGY DETERMINATION

F. Arzarello, F. Ciralli and F. Frasconi
I. N. F. N., Bologna, Italy

G. Bonvicini, G. Laurenti and A. Zichichi
CERN, Geneva, Switzerland

J. Seguinot and T. Ypsilantis
College de France, Paris, France

S. Tzamarias
University of Liverpool, Liverpool, U.K.

Abstract:

A large solar neutrino detector capable of measuring neutrino energy is studied. Neutrino energy resolution (3 to 7% at 300 keV and 3 to 18% at 862 keV) may be attained throughout the large uniform volume (2000 m^3) of Helium gas using the long drift TPC method, detecting recoil electrons down to 100 keV. High rates of solar neutrino events (≈2500/yr) are obtained by pressurizing to 5 bars and cooling to 77^0K to increase the gas density. Shielding blocks of solid CO_2 will be used because of their radiopurity, high density, cheapness and coldness (e.g. radon is immobilized). Radiopurity of the TPC field cage is a critical item. A Prototype 40 m^3 detector can be used for a sensitive dark matter search (≈1 ton target) by adding 20-30% of Xe (or Ne) gas to the basic $He+CH_4$ gas mixture.

1. INTRODUCTION

A real time experiment to detect low energy solar neutrinos and measure their energy is of enormous theoretical interest and a great experimental challenge. A method to measure the energy of neutrinos, mostly from the $p+p \rightarrow e^{+}+d+\nu_e$ and $e^{-}+{}^{7}Be \rightarrow {}^{7}Li+\nu_e$ reactions but also from p-e-p, ^{15}O and ^{13}N reactions, has been described by Seguinot, Ypsilantis and Zichichi [1].

The experiment (HELLAZ for HELium at Liquid AZote temperature) consists of a Helium gas volume of 2000 m^3 at (5 bar, 77^0K) weighing 6 tons which acts both as target and detector of νe elastic scatters. The recoil electron from a νe scatter is stopped in the He gas leaving a trail of ionization electrons which define a track. These electrons then drift in an applied axial electric field until they reach a two-dimensional (x, y) detector located at the end of the drift volume. The third (z) coordinate of a point on the track locus is defined by the arrival time of the electron. This track imaging technique is known as the TPC [2]. These data determine the electron energy and direction and, given the sun's position, the neutrino energy.

The νe event rate for the pp and ^{7}Be fluxes, calculated with the Bahcall solar model [3] is 10^3/ton-yr hence, for a 6 ton He gas target, 6000/yr (16/d) if all recoil electrons ($T \geq 0$) detected. For the more realistic detection limit ($T \geq 100$ keV), the event rate is reduced to 2500/yr (7/d), still enormous compared to the existing (radiochemical, inverse β, threshold E_ν) detectors:

HOMESTAKE (127 tons ^{37}Cl in 615 tons C_2Cl_6, $E_\nu > 814$ keV, rate 0.07/d);

GALLEX (12 tons ^{71}Ga in 77 tons $GaCl_3$, $E_\nu > 233$ keV, 0.2/d);

SAGE (26 tons ^{71}Ga in 57 tons Ga metal, $E_\nu > 233$ keV, 0.1/d)

The only existing (real time, νe) detector

KAMIOKANDE III (680 tons H_2O, $T > 7.5$ MeV, 0.3/day)

has a low rate because of its high T threshold. Comparing to the recently approved (real time, νe) detectors:

SNO (1 kton D_2O, $T > 5$ MeV, 2/d)

SUPER KAMIOKANDE (22 ktons of H_2O, T > 5 MeV, 49/d) and the proposed (real time, νe) detectors:

ICARUS (5 ktons of liquid Argon, T > 5 MeV, 9/d)

BOREXINO (100 tons liquid scintillator, T>250 keV, 30/d).

We note that the HELLAZ rate, with only 6 tons of He mass, is competitive because it detects the high flux pp and ^{7}Be neutrinos. However, GALLEX with the same threshold but double the mass (12 tons) also detects the high flux neutrinos however at a much reduced rate because the ^{71}Ga density ($3.4 \cdot 10^{27}$/ton) is 1/88 of the He electron density ($3 \cdot 10^{29}$/ton), the ^{71}Ga cross section ($\sigma_\beta = 6.4 \cdot 10^{-45}$ cm^2) is 4.5 times the elastic νe cross section ($\sigma_{\nu e} = 1.4 \cdot 10^{-45}$ cm^2 at E_ν=300 keV) but its (collection/counting) efficiency is only 1/4, thus the HELLAZ rate (per ton) will be about 80 times larger. This difference is further accentuated if we note that the full GALLEX target mass is 77 tons of which only 12 tons is active ^{71}Ga.

Because the TPC is filled with low Z, low density gas ($He+CH_4$, 3.16 mg/cm^3) low energy recoil electrons (T ≥ 100 keV, range ≥ 50 mm) can be detected and electron energy and direction determined ($\sigma_T/T \approx 3\%$, $\sigma_\theta \approx 35$ mrad). These parameters then determine the neutrino energy with error $2\% < \sigma_{E\nu}/E_\nu < 4\%$ (at E_ν=300 keV). None of the existant or proposed νe detectors has any significant neutrino energy resolution. BOREXINO will detect electrons with T ≥ 250 keV but cannot determine the electron direction and so E_ν.

A great advantage of HELLAZ lies in its capability to identify spectral components of the neutrino flux thus highly constrain the solar models. In particular, the pp spectral shape and intensity is determined by the visible light luminosity hence any observed differences can be uniquely attributed to the neutrino oscillation parameters [4]. This is because the νe elastic cross section is known from the standard model electro-weak theory [5] and doesn't rely on the poorly known nuclear wave-function overlap integrals, needed to determine the inverse β decay cross sections.

The fluxes of the monoenergetic neutrino lines ^{7}Be (862 keV) and p-e-p (1422 keV) can also be measured and their ratio determines the core temperature of the sun [3]. Possibly the shape and width of these lines can be measured thus further constraining the solar models. Because HELLAZ measures neutrino energy, the MSW phase angle is determined hence matter dependent oscillations are observable. Other experiments average over this angle thus are insensitive to these oscillations. The excellent energy resolution and high counting rate of HELLAZ will permit detection of neutrino oscillations via day-night or longer time modulations of the neutrino flux [4, 6]. Also, if neutrinos have mass and magnetic moment and are transversely polarized by the suns magnetic field, this polarization will manifest itself in HELLAZ as an azimuthal modulation of the νe scattered intensity. Finally, measurement of νe scattering from a radiosource (^{7}Be, EC, $t_{1/2}$=53 days), required to calibrate the detector, will also give limits on the neutrino magnetic moment.

The cylindrical TPC drift region, ± 10 m long in the axial direction, is terminated at each end by ionization detectors which measure the projected electron track locus. The detectors will be Multi-Wire Chambers (MWCs) operating in a gas mixture of He+CH_4 with sufficient gain to attain significant single electron efficiency (>90%). Extremely pure He gas can be obtained from liquid boil-off because all impurities are frozen out at 4^0K. Electron lifetimes ≥ 200 ms are attainable as compared to the maximum drift time of 15 ms. We choose to use MWCs because the intrinsically high gain allows good single electron sensitivity (SES) thus giving the detector a calorimetric capability. This will permit determination of T by single electron counting (as well a by range) and identify the track start and the track end.

A critical feature of HELLAZ is the shield needed to absorb γ's and n's coming from the cavern walls. We propose a shield of solid CO_2 because it is radiopure, cheap, high density (1.6 g/cm^3),

strong and cold (recall that the TPC gas is at 77 ^{0}K). The low shield temperature is important because it condenses difficult impurities such as Radon, which would otherwise diffuse as a gas into the TPC volume. In general, HELLAZ will require very high purity in all its component materiels.

2. THE EXPERIMENT

A transverse section of HELLAZ (see Fig. 1) shows the TPC field cage from radii 5.5 to 5.7 m, the CO_2 shield from 6 m to 8.8 m, a paraffin n converter to 8.95 m and a gas layer out to 9.1 m. The 180^{0}K steel pressure vessel between 9.1 and 9.2 m is followed by thermal insulation to 10.0 m and a paraffin n converter out to 10.25 m. This (early) version of the HELLAZ geometry was used to simulate the efficiency of the CO_2 shield to attenuate γ's and n's from the rock and steel sources [7].

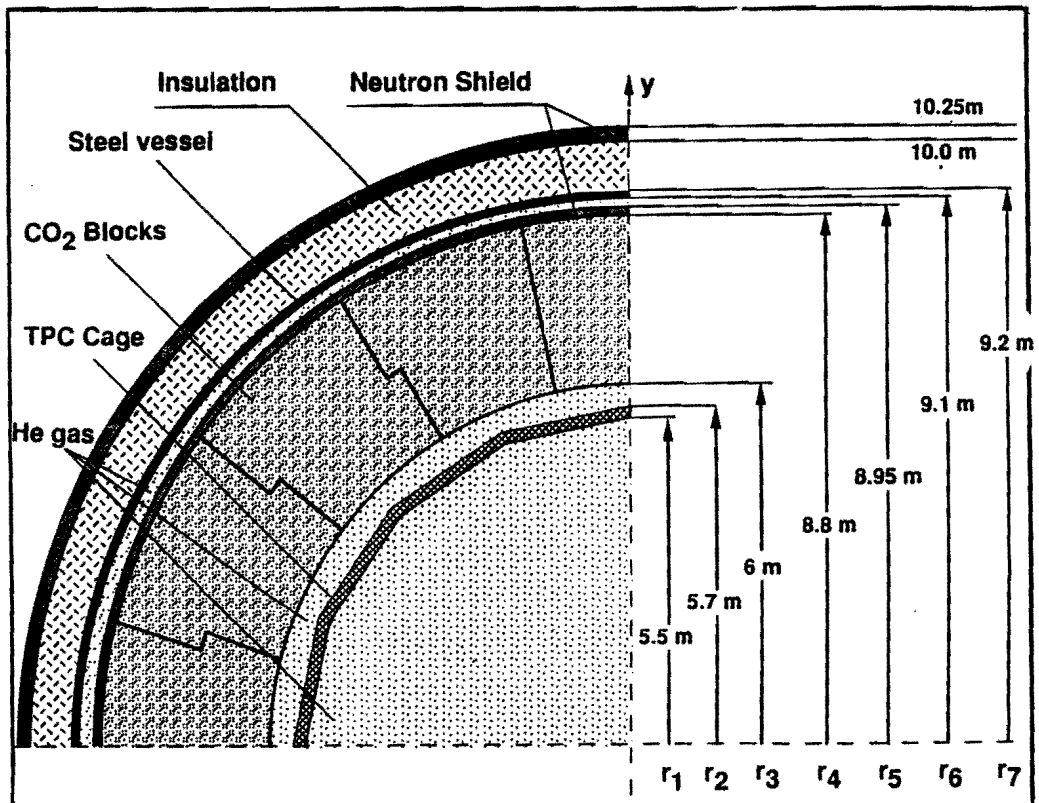

Fig. 1. A transverse view of Hellaz with the indicated elements.

Transverse and longitudinal views of HELLAZ are shown in Fig's 2, 3. Washer-like segments of the dry ice shield composed of 16-1 meter thick blocks weighing 15 tons each (a total of 240 tons) are assembled on a hemi-cylindrical steel base plate outside the pressure vessel as a self supporting Roman Arch and then rolled into the cylindrical steel pressure vessel. Twenty-two of these washers comprise the full barrel shield.

Next the preassembled-gas tight-TPC field cage with MWPC endcaps will be inserted into the shield cavity and then each endcap section with its shielding blocks will be rolled into place and the endcap pressure vessel sealed to the barrel (see Fig. 4). To minimize CO_2 sublimation during assembly, with consequent loss of shield mass, the pressure vessel will be kept at 180^0K by circulation of cold N_2 gas. This part of the Gran Sasso tunnel will be climatized to remove water vapor which would otherwise condense onto the CO_2 blocks.

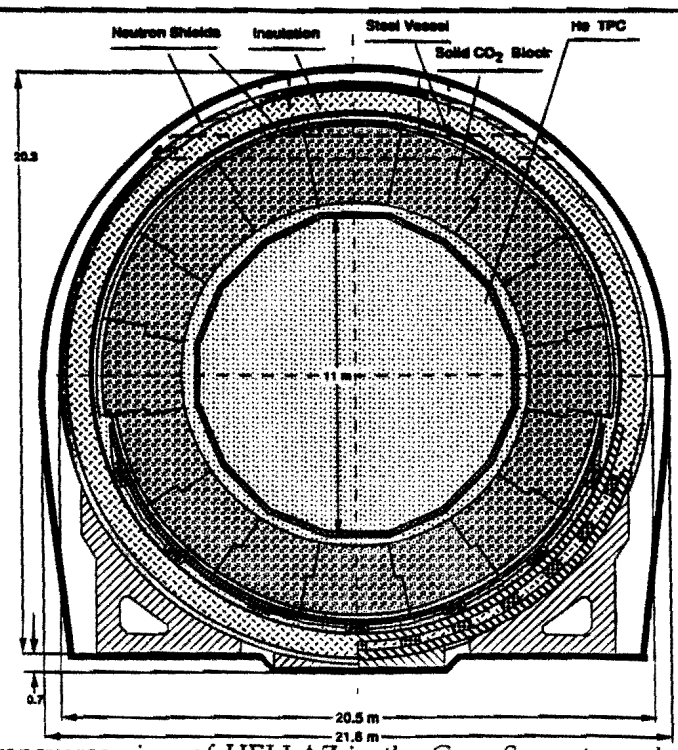

Fig. 2. A transverse view of HELLAZ in the Gran Sasso tunnel. The dotted line shows the top crane position. Assembly of last 25% of the steel vessel is by hand.

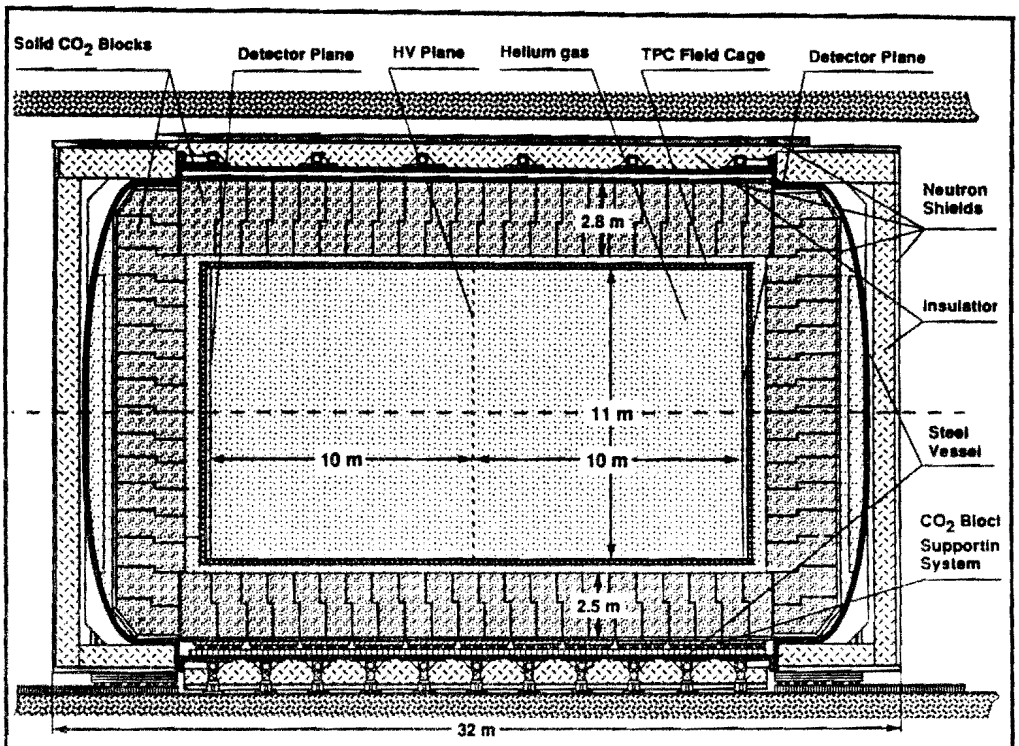

Fig. 3. A longitudinal view of the experiment in a cavern of the Gran Sasso Lab.

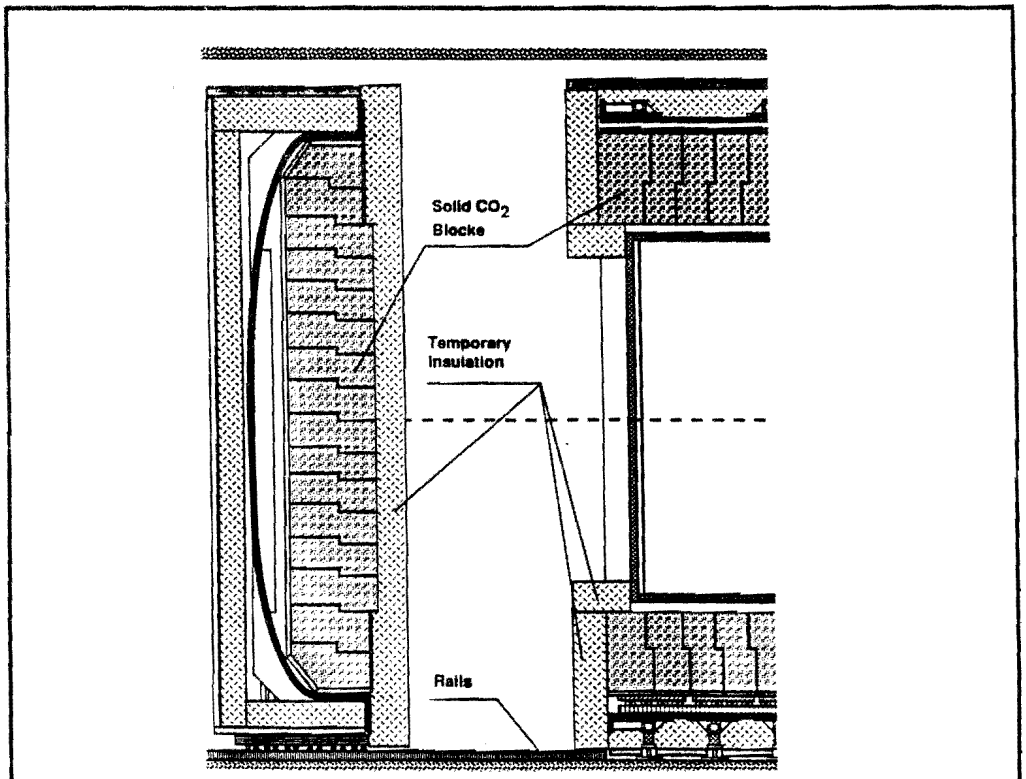

Fig. 4. The endcap shield and pressure vessel with access to the TPC electronics.

When the shield is complete and closed, cold He gas will be injected into-and recirculated through-the TPC while the entrapped air is removed by external cold traps. When the recirculating He gas is stable at 77 ^{0}K, then initial 1 bar tests of the TPC can start. Later, the pressure of the TPC will be slowly increased to its nominal value of 5 bar, but it will be able to operate at any pressure ≤ 10 bar thus allowing considerable flexibility in the choice of the experimental conditions. If necessary, one or the other endcap can be retracted in order to access the electronics, as shown in Fig. 4.

2.1 THE TPC AND MWC DETECTORS

The TPC barrel field cage is constructed of Kevlar honeycomb panels joined to form a decahexahedron as shown in Fig. 5. The 200 mm thick panels are composed of two slabs of 10 mm thick Kevlar honeycomb separated by 180 mm thick I-bars. The slabs and I-bars are each covered with a 100 μm thick skin of Kevlar-Epoxy, as shown in Fig. 6. The panel surfaces are lined with 100 μm thick Kapton on which 1 mm wide metallic field shaping strips with 20 mm pitch have been deposited. A radiopure metal mesh is built into the middle of the cylindrical field cage to provide the 200 kV equipotential plane needed to produce the drift electric field. A resistive chain, outside the TPC cage, feeds the strips the required linearly decreasing potential. The Kevlar, the Kapton, the resistors and the strip mesh metals will be controlled to ensure acceptable radiopurity. The 20 m long field cage has a total mass of ≈2.5 tons. Since we aim to reduce the γ rate from the TPC cage to ≤ 300/d and since an easily detectable signal is ≈15/d thus about 5% of the field cage mass must be sampled. This defines a scale of ≈40 m^3 for the Prototype TPC (see § 3.2.1).

Each 100 m^2 endcap is composed of 1 m^2 modular detectors made of 10 mm thick Kevlar honeycomb planes with 100 μm thick Kevlar-Epoxy skins. The inner surface of each section is covered by a 100 μm thick Kapton layer on which 0.95 mm wide metallic

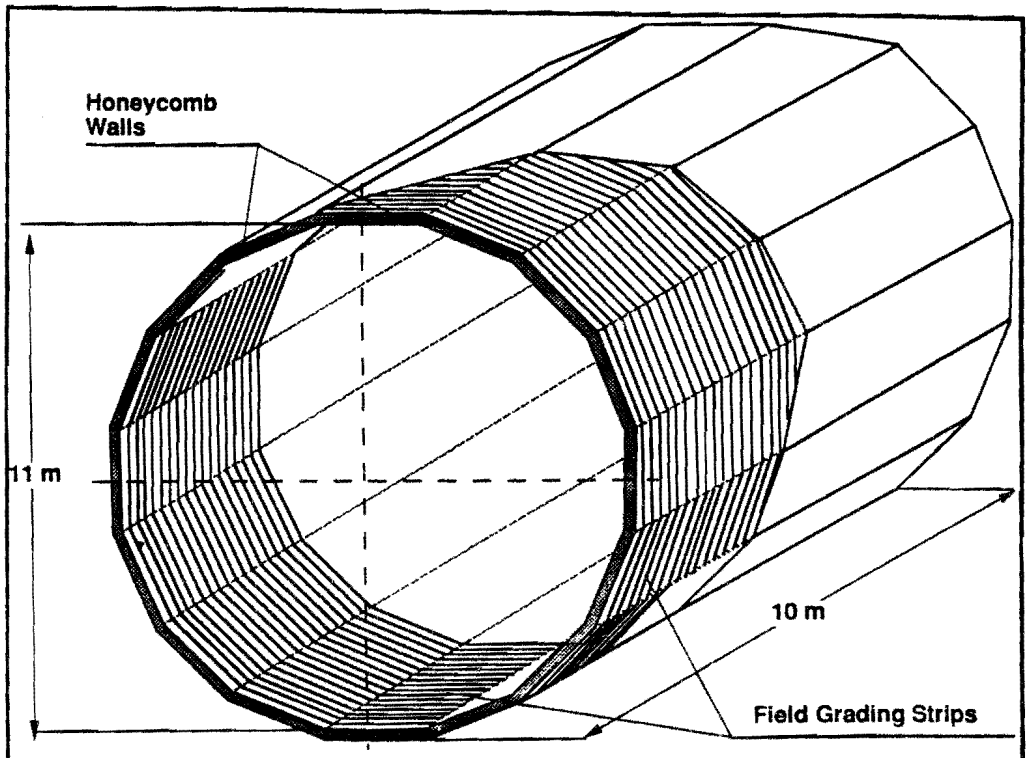

Fig. 5. A view of half the TPC field cage made of Kevlar honeycomb slabs (Fig. 6)

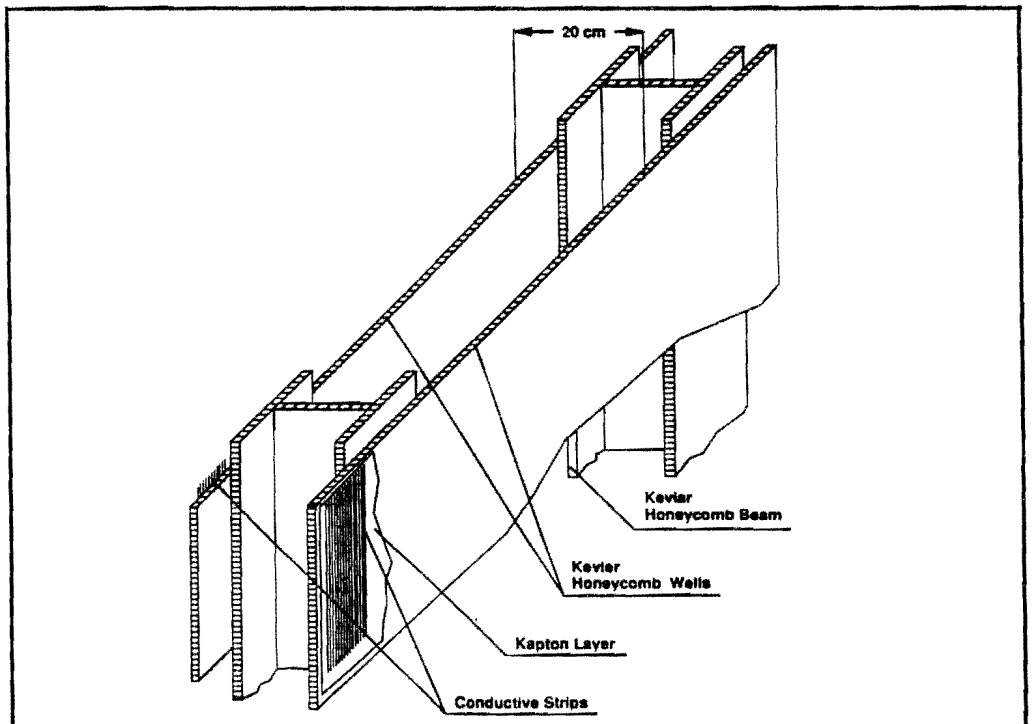

Fig. 6. The Kevlar panels of the TPC field cage are covered with a thin Kapton skin with deposited metalic field shaping strips (1 mm wide, 20 mm pitch).

cathode strips are deposited along x (1 mm pitch in y). The 1 m long MWC wires are strung along y (1 mm pitch in x). The anode wire-cathode strip distance is fixed by 0.5 mm thick quartz spacers placed at 10 cm intervals along x. The small anode-cathode distance was found essential to obtain high (≥97%) single electron cathode strip efficiency in CH_4 gas [8]. The density of CH_4 necessary for single electron sensitivity (SES) is $67 g/m^3$, i.e. a partial pressure of 26 mbar at 77^0K. This is very close to the solid-vapor equilibrium pressure thus, to be safe, we must probably work at the slightly higher temperature of $90\text{-}100^0$K.

The energy resolution of a MWC is usually dominated by fluctuations in amplification however, if the MWC has good SES then only ionization fluctuations are important. However, energy loss in He gas is a special case because the dominant energy loss processes are ionization and scintillation with very little energy lost to excitons. For example, a T=100 keV electron in He produces about 2500 electrons and 2000 UV photons ($\tau \leq 2$ ns, $\lambda_{ph} \approx 60$ nm, E_{ph}=21.2 eV) thus accounting for almost all the 100 keV energy. The CH_4 total absorption cross section (30 Mb at 21.2 eV) is about 50% photoionizing thus the He photons will photoionize CH_4 resulting in (photo)electrons being injected into the TPC gas at a point very near the emission point ($l_{abs} \approx 35$ μm), thus an important fraction of the scintillation energy will be recovered. Simple counting of electrons could then give energy resolution $\sigma_T/T = 1/\sqrt{N} \approx 1/\sqrt{3500} = 1.7\%$. The remaining photabsorption cross section gives rise to a H_2^- ion which, by thermal agitation in the applied electric field, may lose its extra electron and add further to the ionization signal. SES-MWCs have already been developed for Cherenkov ring imaging [8] and primary ionization counting [9].

Silicon front-end electronics working at 87^0K has already been developed for ICARUS [10] but is probably too slow for our needs. Studies of Germanium and GaAs front-ends are now started.

A 16 bit time-to-digital-converter (TDC) with 20 ns time bins observes 1.3 ms of drift time (i.e. a track length of ≈1 m or 10% of

the total). This type of electronics is commercially available but perhaps a VLSI version must be developed for HELLAZ.

A trigger to start data acquisition will be obtained from a coincidence between neighboring wires and/or strips of the MWC. This occurs when the first electrons of the track arrive at the detector plane therefore, the absolute z position of the track cannot be determined however this coordinate is not needed to find the electrons initial direction and energy.

2.2 THE SHIELDING

This experiment is immune to many kinds of low energy backgrounds because of its excellent pattern recognition properties and the extreme purity of the detection medium. Solar neutrinos are not energetic enough to interact inelastically with ^{4}He nuclei so the only process available is νe elastic scattering. The dominant background source will be γe Compton scattering with the same kinematics as the νe signal but a cross section 10^{20} times larger.

Backgrounds from the cavern walls and the steel pressure vessel were simulated in [7] using the FLUKA program for particle transport. The sources, mainly from ^{238}U, ^{232}Th and ^{40}K in the Gran Sasso rock, produce on the pressure vessel surface a γ flux of $4 \cdot 10^{11}$/d ($\langle E_\gamma \rangle \approx$ 1.1 MeV) and a neutron flux of $4 \cdot 10^6$/d (0 to 10 MeV) [10]. The (n,γ) reaction in CO_2 produces a distribution with $\langle E_\gamma \rangle \approx 8$ MeV, whereas in H_2 a 2.22 MeV line is emitted.

Absorption of the (γ, n) background radiation by the solid CO_2 shield of Fig. 1 was simulated in [7] and listed in Table 1. We give rates into the TPC gas from the five background sources. Thus if the CO_2 shield is made and assembled hermitically, it will suppress the external (γ, n) radiations.

The TPC cage of 5.5 m radius and 20 m length will weigh 2.6 tons Since the field cage cannot be shielded it must made of intrinsically low activity material. Assuming that the presently attained level of purity $\approx$0.1pg (^{232}Th/^{238}U)/g Acrylic [11] can be attained also in Kevlar (else we use Acrylic), hence the 2.6 ton TPC

TABLE 1: BACKGROUND RATES FROM EXTERNAL SOURCES

Source	Rock	Rock	Vessel	Vessel	All
Shield					
solid CO_2	0.2 γ/d	<.01n,γ/d	0.3 γ/d	<.01n,γ/d	≈1 n/d

cage would produce about 200 decays/d. Since these decay chain produces 1.5γ's above 217 keV (minimum energy to produce a T>100 keV electron) we expect a total of 300 γ/d from the TPC cage. The tracking and energy measurement capability of the TPC allows to reject rates even 30 times larger. This is done by identifying a large sample of Compton electron recoils in the TPC which cannot be due to solar neutrinos because either the reconstructed energy is negative or because the event exhibits two or three scatters in the TPC. We use this sample in delayed (or random) coincidence with the sun to find the "background" under the pp continuum (or the ^{7}B line). The [(νe signal+background)-("backround")] is shown in Fig. 7 for a γ rate of 10^4/d (33 times expected rate). This excellent result follows because the background is so well measured (126/d are contained under the pp continuum) [12].

We expect to screen the radiopurity of all the materials by neutron activation analysis. To confirm this result for Kevlar and to measure directly the background as well as the signal, we plan a 40 m^3 SES-TPC for placement inside the Gran Sasso tunnel with full CO_2 shielding. When filled with (He+CH_4 at 5 bar, 77 ^{0}K) it should see 2 % of the signal (0.14/d) and about 5% of the background (0.4/d). If the shielding is efficient, this background will come only from the ^{238}U or ^{232}Th radioctive impurities of the TPC cage. Monoenergetic low energy γ lines, from U and Th decay chains, can be identified by adding 10% of Xe gas to the TPC (at 10 bar and 160^{0}K to avoid Xe condensation) because below 250 keV in Xe, the photoelectric effect dominates over the Compton effect.

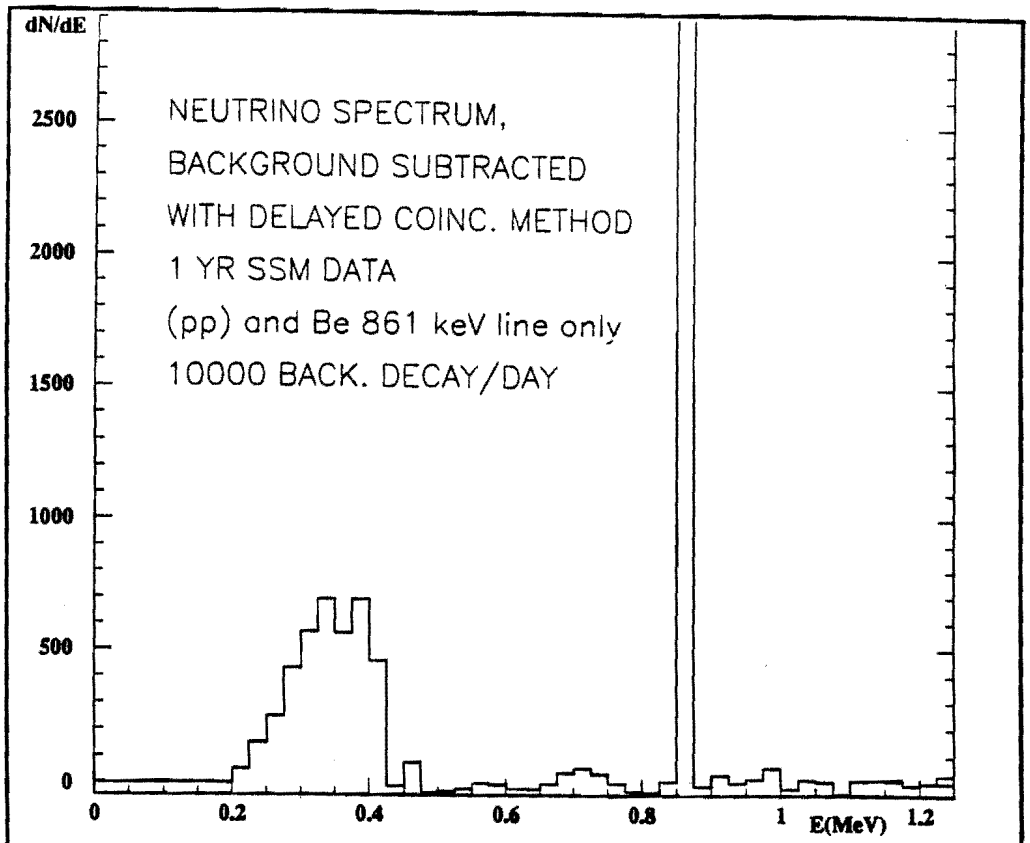

Fig.7. Neutrino spectrum background subtacted with 10^4 γs/d from the TPC cage.

Thus, low energy γ rays from U/Th cage impurities will appear as identifiable monoenergetic lines. Observation of γ's at rates in excess of the 0.4/d expected from the kevlar U/Th impurities, will indicate insufficient or inefficient shielding of the rock and steel.

An additional background source is the β decay of ^{14}C from C in the TPC gas. This is minimized by using old CH_4 (>1My) but cannot be completely eliminated. After 1My the only remaining ^{14}C activity is due to the $^{13}C(n, \gamma)^{14}C$ reaction with n's coming from (α, n) reactions in rock. We estimate that old CH_4 has a ratio $^{14}C/C<10^{-18}$. The HELLAZ volume of ≈2000 m^3 with a CH_4 density of 67 g/m^3 (the minimum for efficient SES) will contain $5 \cdot 10^{27}$ C nuclei hence $N_{14C} < 5 \cdot 10^9$. Its decay constant $\lambda=3.3 \cdot 10^{-7}/d$ (i.e. $t_{1/2}$=5730 y) hence its activity $A=N_{14C}\lambda<1650/d$. Since the β decay end point of ^{14}C is 156.5 keV and 80% of the decays have T>100 keV thus <1300e/d will be seen with T between 100 and 156

keV. This background is ≈4.3 times that of the TPC cage and can be subtracted in the same way. The actual amount of ^{14}C in old CH_4 must to be measured. If $He+H_2$ is used in the TPC the problem vanishes (since H_2 is stable) but, so far, we have not been able to obtain SES in a $He+H_2$ mixture.

2.3 TRACK SIMULATION

We use the general Monte Carlo package GEANT to describe the detector geometry and to generate the recoil electron tracks. The two major physical processes which occur when an electron traverses a gas, ionization and multiple scattering, are simulated by GEANT. Ionization energy loss is described by Vavilov theory (below 1 MeV) or Landau theory (above 1 MeV) whereas Moliere theory is used for multiple scattering [13].

2.3.1 THE DETECTOR AND TRACK DEFINITION

The active TPC volume is defined by a cylindrically symmetric decahexahedron of radius 5.5 m and length 20 m filled with ($He+CH_4$) gas at 77^0 K and 5 bar with the horizontal (X), and vertical (Y) axes shown in Fig. 1 with the cylinder axis (Z) normal.

The MWC detectors (1 m^2 modules) are located at the Z=±10 m endcaps. They measure the position and arrival time of incoming electrons via wires and cathode strips running along X and Y, respectively. The timing data is obtained from a 16-bit TDC (20 ns time bins) servicing each wire and strip. A uniform electric field, parallel to the Z axis (outward from Z=0), causes the ionization (and photo) electrons to drift to the detectors.

Nine tracks of 100 keV electrons, shown in Fig. 8, were generated along the Z axis [14]. The variances in track direction are from multiple scattering in He gas. Drift diffusion is not included but would cause a 3D Gaussian smearing of each point by an amount $\sigma_x=\sigma_y=\sigma_t\sqrt{z}$ and $\sigma_z=\sigma_l\sqrt{z}$ where (σ_t, σ_l) are the (transverse, longitudinal) diffusion coefficients in He gas (5 bar, 77^0K, E=20 kV

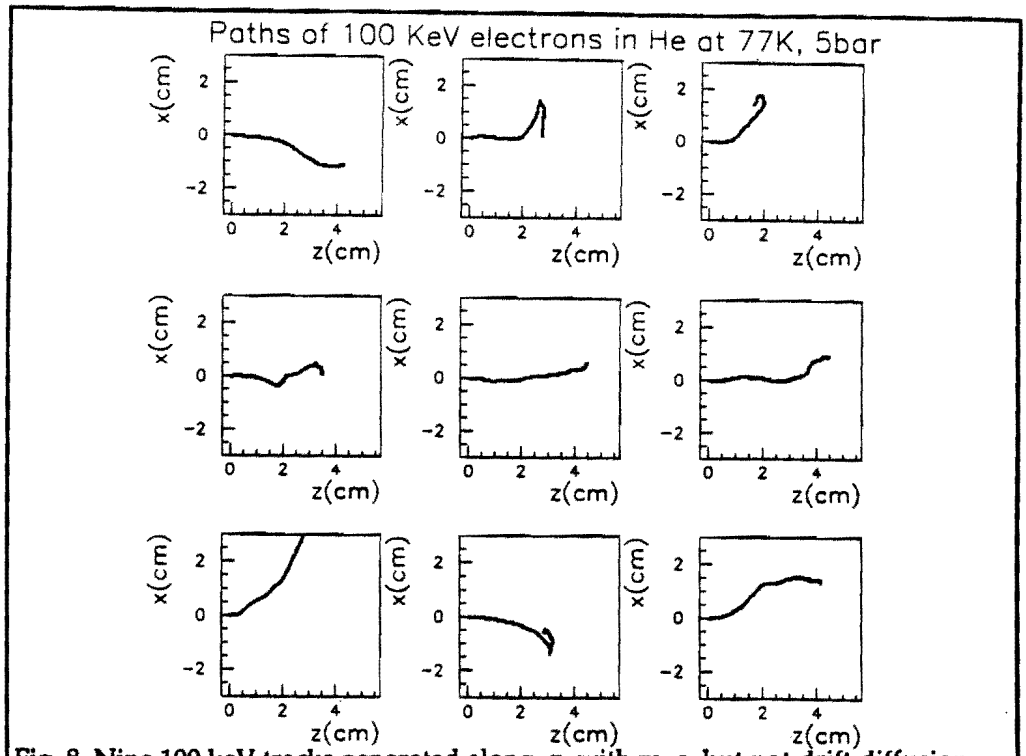

Fig. 8. Nine 100 keV tracks generated along z with m. s. but not drift diffusion.

/m) and z the drift length [15]. Note that the mean trackdeflection in the first cm is about 1 mm thus a directional error ≤ 100 mrad may be expected if the sampling is sufficient. The ionization signal from a 100 keV electron track is about 2500 electrons distributed over the R≈5 cm range (with perhaps 1000 more from the photoionization). Good sampling statistics are feasible with a SES-MWC because 400 single e's are expected in the first cm of the track corresponding to a statistical error ≈50 mrad. A precise estimate for the directional error is $\sigma_\theta=(\sigma/s)\sqrt{(12/N)}$ where σ is the space-point error (≈3 mm for diffusion averaged over 10 m drift), s is the track length sampled (≈12 mm) and N the number of electrons detected (≈400) hence σ_θ=43 mrad. The sampled track length s cannot be chosen much larger because the multiple scattering deflection builds up. Now it can be understood why we require 20 ns time binning (i.e Δz=.014 mm) even thougth the position error is much larger (σ≈3 mm); it assures good sampling because each electron arrives alone and is efficiently detected by

the SES-MWC. In addition, SES avoids the ambiguities inherent in wire and strip projective readout and, as a bonus, endows the detector with a calorimetric capability.

Before fitting a straight line to a track (i.e. to the cloud or cigar of single electron points) we calculate the principle axes of the cloud by diagonalizing its moment of inertia tensor [14]. We see in Fig. 9 distributions for three 100 keV tracks (5 bar, 77^0K with R=5 cm) projected onto three principle axes (drift diffusion of σ=3 mm is included). The distributions along the principle y and z axes are symmetric with $\sigma \approx 3$ mm, as expected, whereas the x distribution shows the increased ionization at the track end. The first track is normal while the second and third track show the effects of large angle deflections (range is too small for the ionization). Clearly, the track energy, range and direction are more easily calculable in this coordinate system.

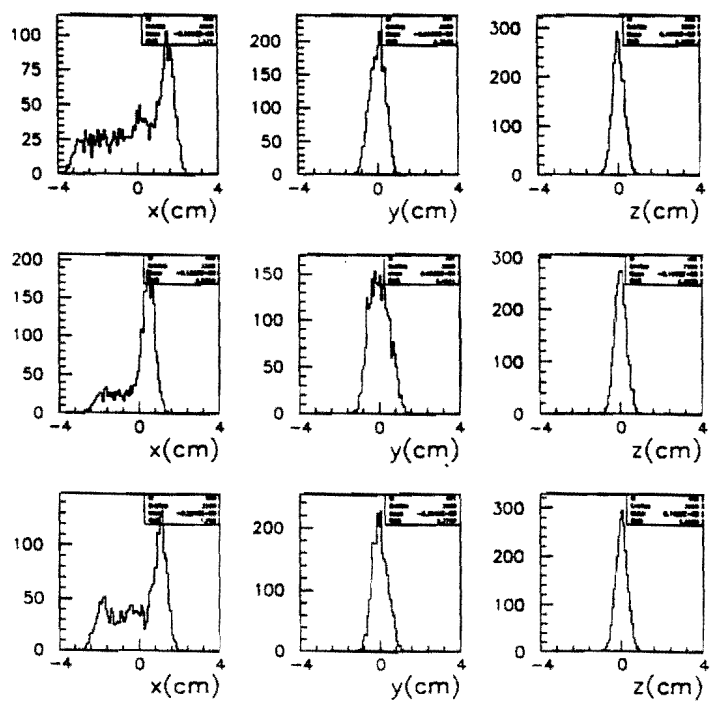

Fig. 9. Distribution of hit points along the principle axes for the first three tracks of Fig. 8 including multiple scattering and diffusion .

2.3.2 TRACK DIRECTION AND ENERGY DETERMINATION

We show in Fig. 10 the direction error σ_θ obtained fitting a straight line (x=bz) to track segments vs the drift error $\sigma_d=\sigma_{dz}=\sigma_{dx}$ for 100 keV electrons, s=12 mm, $\Delta x=\Delta y=1$ mm, $\Delta z=.014$ mm=20 ns and N=428. The space-point position errors are $\sigma_x=\sqrt{(\sigma_d^2+\Delta x^2/12)}$ and $\sigma_z=\sqrt{(\sigma_d^2+\Delta z^2/12)}$. As is seen, σ_θ varies from (15 to 90 mrad) for σ_d from (0 to 4.5 mm) with an average $<\sigma_\theta>\approx 60$ mrad. If, however, we fit the track with a curved line ($x=bz^{3/2}$) with the same parameters we obtain σ_θ from (13 to 50 mrad) for σ_d from (0 to 4 mm) with an average $<\sigma_\theta>\approx 30$ mrad. This may be improved even further by using a track length s=22 mm and N=785 with the other parameters as before. We then obtain for the ($x=bz^{3/2}$) curved line fit a constant $\sigma_\theta\approx 25$ mrad for σ_d from (0 to 4.5 mm). All fits assume the starting point of the track has been found from the principal axis distributions (Fig. 9). Each fit is for a 2-D projection (x, z) or (y, z) thus the space angle error is larger by $\sqrt{2}$ i.e. $\sigma_\theta\approx 35$ mrad.

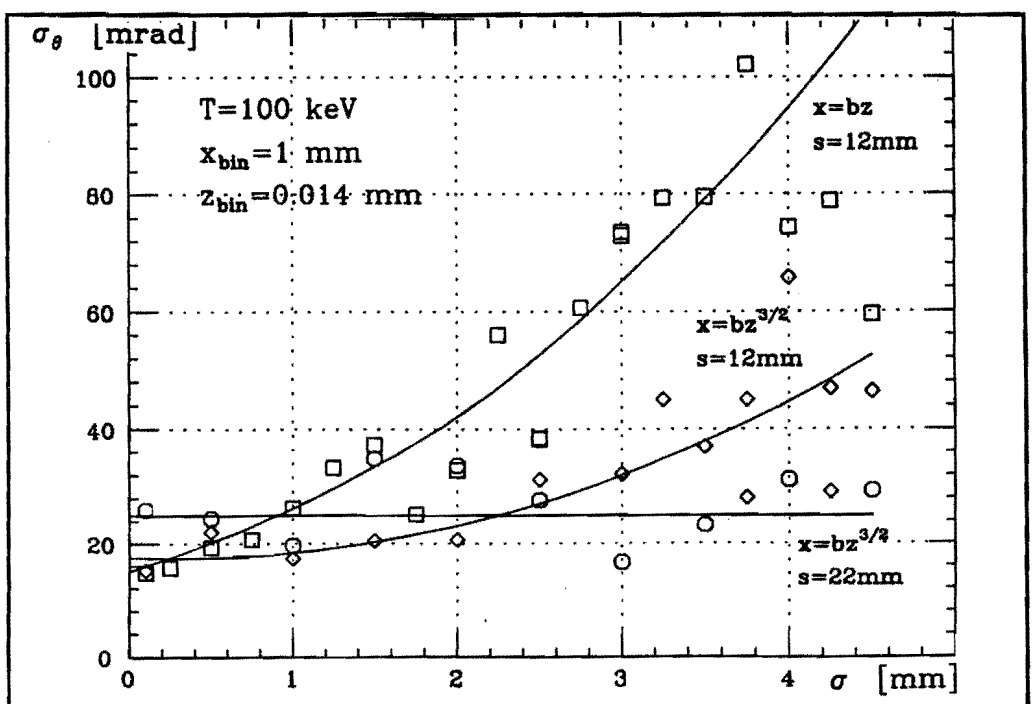

Fig. 10. Direction error σ_θ for N samples of a 100 keV track vs drift error σ. The indicated fits are either to a straight line (x=bz) or to a curved line ($x=bz^{3/2}$).

The track energy can be determined from the track range R after the prinipal axis transformation (q.v. Fig. 9). Fluctuations of σ_R/R vary from 8 % at 100 keV to 4% at 1000 keV. Using this result with $<\sigma_\theta>$=35 mrad gives the neutrino energy resolution σ_{E_ν}/E_ν vs E_ν shown in Fig. 11 with fixed T contour lines. This shows that resolution σ_{E_ν}/E_ν between 3% to 7% may be obtained in the pp region 220 < E_ν < 420 keV. The resolution σ_T/T is improved to between 2% and 4% if T is measured by electron counting.

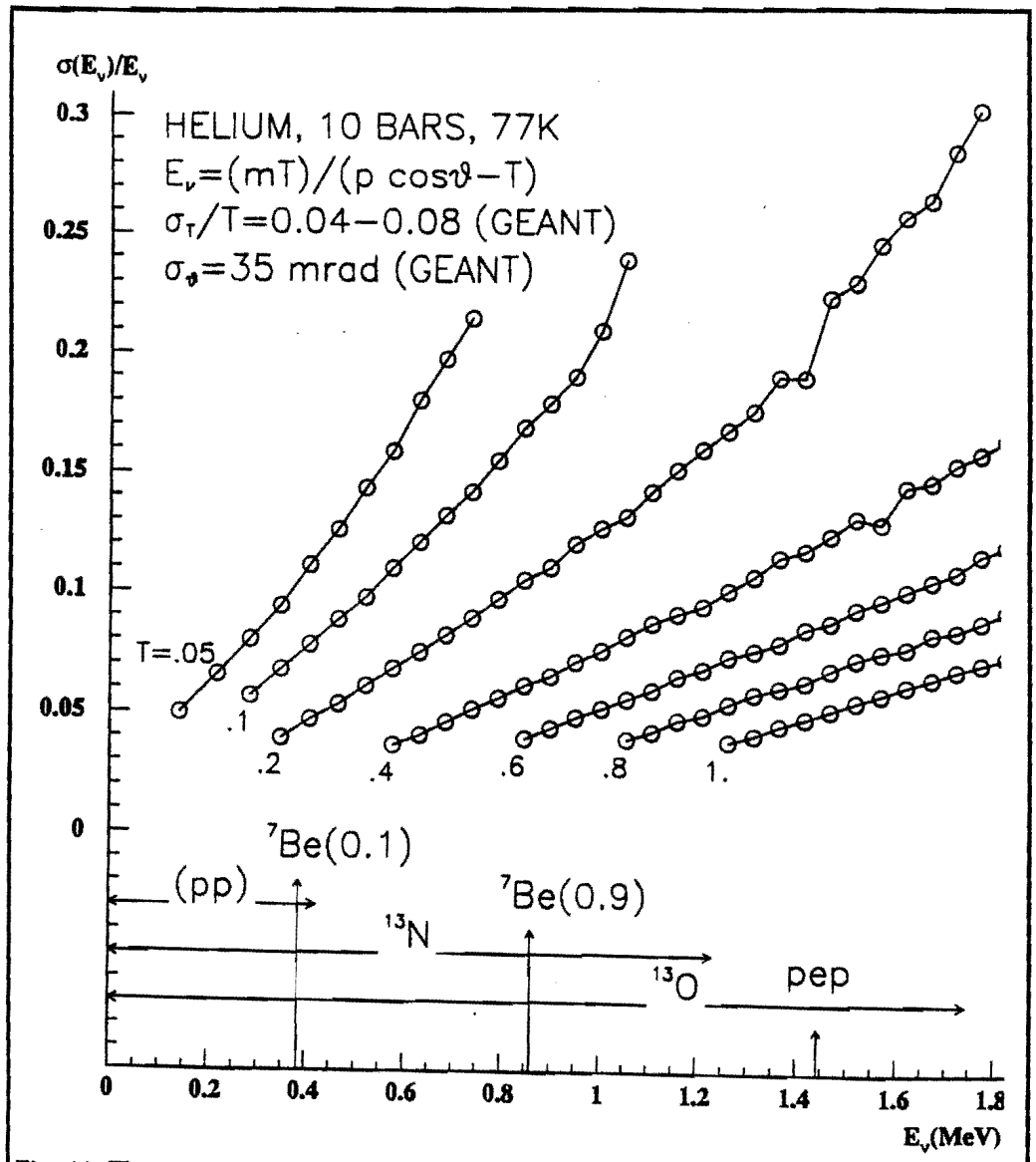

Fig. 11. The neutrino energy resolution vs neutrino energy E_ν for fixed T (MeV).

3. THE R & D PROGRAM

3.1 THE TEST TPC's

We have already attained single electron sensitivity in a test MWC with a gas mixture of (He+100 mbar CH_4) at STP, a CH_4 gas density of 67 g/m^3. We have built and assembled a 5 liter TPC (50 cm drift length, 10 x 10 cm^2 MWC detector) which can operate up to 10 bar at 77 ^{0}K, to test the SES-TPC concept at higher density. To assure that the expected neutrino energy resolution can be attained, we have designed and will build a 2.5 m^3 SES-TPC, with a 1 m^3 MWC to detect Compton recoil electrons from a radioactive γ source and measure the resolution function $\sigma_{E\gamma}/E_\gamma$.

3.2 THE SHIELDED HELLAZ PROTOTYPE IN GRAN SASSO

As described in § 2.2, we plan a 40 m^3 SES-TPC for placement inside a Gran Sasso tunnel with the full CO_2 shield, shown in Fig. 12. It should detect 2 % of the ve signal (0.14/day) and 5% of the background (0.4/day). If the shielding is efficient, this background will be from the U/Th impurities of the TPC cage. Observation of γ rates in excess of 0.4/d, will indicate insufficient or inefficient shielding of the external rock and steel radioctivity.

3.2.1 THE HELLAZ PROTOTYPE AS DARK MATTER DETECTOR

It appears that the 40 m^3 HELLAZ Prototype, once it has fulfilled its main function of measuring the ve signal and γe background for HELLAZ, will be ideal for a dark matter search. It is expected that the first function can be accomplished in about one year of running. While building full-scale HELLAZ ($\approx$2000 m^3) the Prototype could be operated as a dark matter detector. If, as expected, the SES-TPC has good energy sensitivity in the 10 to 100 keV energy region (i.e an ionization signal of 250 to 2500 single electrons) then the HELLAZ background measurement will also establish the background level in this energy region (i.e target "empty"). By adding 20-30% of Neon gas (clean, non-radioactive)

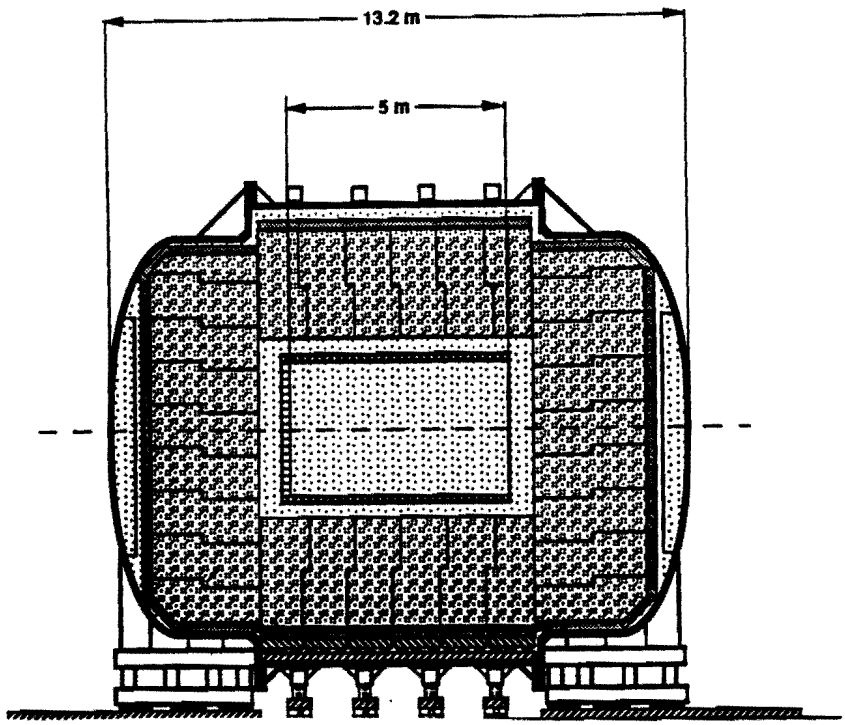

Fig. 12a.A longitudinal view of HELLAZ 40 m^3 Prototype with solid CO_2 shield.

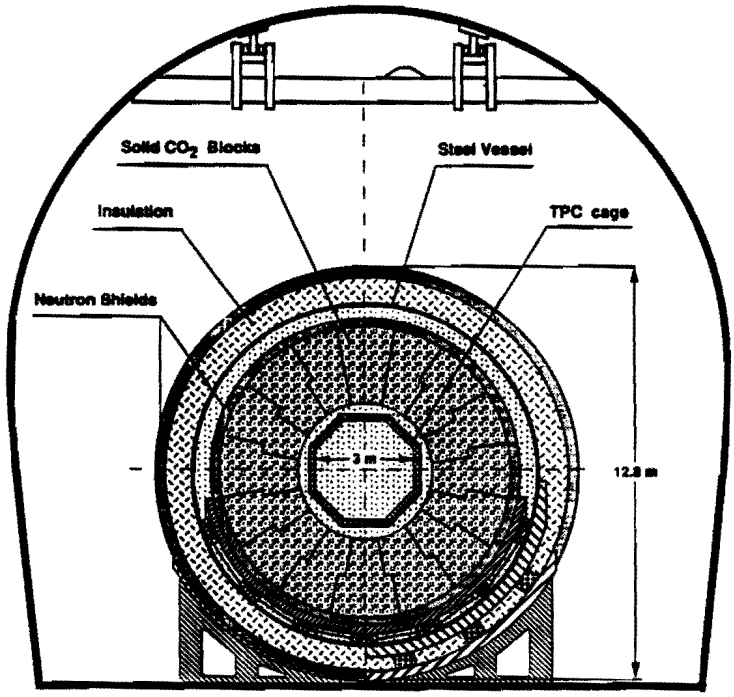

Fig. 12b. A transverse view of HELLAZ 40 m^3 Prototype with solid CO_2 shield.

to the basic TPC gas mixture ($He+CH_4$) we fill the TPC with 127-190 kg of Neon (target "full"). Detection of a recoil energy spectrum above the background level could thus represent a dark matter signal. Note that we are here considering 100-200 kg of instrumented target material with sensitivity below 10 keV but with the enormous added advantage of background subtraction. Recall that for heavy dark matter (100 GeV), the maximum Neon recoil energy is 27 keV. Establishment of a signal distribution and an end point would be the ultimate goal. A second target material such as Xenon may then be tried however, for Xenon with partial pressure ≈3 bar, the temperature must be raised to T≈190 K hence to get the same background target mass the total pressure must be raised to 12 bar. Then 30% of Xe gas can be then be added without condensation, i.e. 1.2 tons of instrumented Xe target. In this case the maximum recoil energy rises to 49 keV. We would again look for a signal distribution over background with an extrapolated end point. Of course, all this depends critically on the radioactivity level of old CH_4 (or finding a non-radioactive quencher which allows SES).

Note that the predicted dark matter rates vary between 10^{-3} to 1/kg-d [16] hence, a target of 1200 kg would have the needed sensitivity but the background subtaction capability of the detector is equally important. If two end points T_1 and T_2 can be measured for two different target masses m_1 and m_2 then kinematics gives the dark matter mass m_d and sun's velocity v_s (relative to the Galactic center) as

$$m_d=m_2(\tau_{21}-\mu_{12})/(\tau_{21}-\mu_{21}) \qquad (1)$$
$$v_s=(1+m_2/m_d)\sqrt{(T_2/2m_2)}$$

where $\tau_{21}=\sqrt{(T_2/T_1)}$ and $\mu_{21}=\sqrt{(m_2/m_1)}$. Measurement of two end points would then allow v_s to be determined. This quantity is well known to be ≈300 km/s so if the measured value agrees, this may

indicate that the signal is real and we are dealing with astrophysics (not artefacts) and therefore, the value of m_d is meaningful.

Experimentally, the single electron sensitivity of this mix of gases must be verified. Also, the energy deposit for recoiling He, Ne or Xe atoms must be studied to calibrate the energy scale. This is most easily done with monenergetic neutron beams e.g. a 44 keV neutron gives a maximum of 8 keV recoil energy to He, a 165 keV neutron gives a maximum of 30 keV to Ne and a 1.67 MeV neutron gives a maximum of 50 keV to Xe.

4. OTHER OPTIONS

A shield materiel which might possibly be used instead of solid CO_2 is reactor grade graphite. If its U/Th purity is sufficient, then its advantages are: i) higher density (2.1 vs 1.6 g/cm^2) and ii) room temperature solidity which facilitates construction. The higher density allows to increase the TPC gas diameter by 1.4 m thus increasing the volume from 2000^3 m^3 to 2500 m^3 (for constant ± 10 m drift length). Of more practical importantance, the shield can be built at room temperature by simply stacking brickets of graphite.

However, placing graphite (which is a conductor) near the TPC field cage would short out the electric field lines. This may be avoided by surrounding the field cage with a voltage degrader however, if made of 0.2 m thick Kevlar, then 0.4 m of gas diameter would be lost. More importantly, it would increase the field cage mass by a factor 2-3 and thus increase the background by the same factor. This option can only be evaluated when precise data on the TPC field cage (U/Th) impurities are measured.

5. CONCLUSIONS AND PERSPECTIVE

It appears that we have at hand an experimental tool which can provide a major advance in understanding of the sun and ascertain if new physics is needed to explain the existing data. It is

the only viable experimental method to measure neutrino energy and so fix the MSW phase angle, necessary if day-night matter dependent neutrino oscillations are to be demonstrated. The large volume of Hellaz is imposed by the need to observe sufficient events and not be dominated by statistics. Up to the present time, all solar neutrino experiments have suffered from this deficiency.

It is possible that the Protype HELLAZ TPC can be also used for a high sensitivity dark matter search with background subtraction capability and sufficient redundancy to prove that a signal is real and related to astrophysics.

REFERENCES

[1] J. Seguinot, T. Ypsilantis and A. Zichichi, LPC 92-31, College de France, 12/8/92 and T. Ypsilantis, Proc. 4th International Neutrino Telescope Workshop, Venice, 10/3/92.

[2] D. Fancher et al., Nucl. Instr. and Meth. 161 (1979) 383.

[3] J. H. Bahcall, Neutrino Astrophysics, Cambr. Univ. Press 1989.

[4] G. Bonvicini, Proc. 5th International Neutrino Telescope Workshop, Venice, 2-4/3/93.

[5] G. t'Hooft, Phys. Rev. Letters, B37 (1971) 95.

[6] S. Pakvasa and J. Pantaleone, Phys. Rev. Lett. 65 (1990) 2479.

[7] HELLAZ Notes 92-01, 92-02, 92-03, G. Bonvicini, Nov. 1992.

[8] R. Arnold et al., Nucl. Instr. and Meth. A314 (1992) 465.

[9] G. Malamud et al., Nucl. Instr. and Meth. A307 (1991) 83 aa well as A323 (1992) 294 and A330 (1993) 150.

[10] P. Cennini, Private communication.
S. Centro, Private communication.

[11] P. Jagam, J-X. Wang and J. J. Simpson, GWP^2-N-21, 10/2/92. Th and U Determinations in Acrylic by Neutron Activation Analysis.

[12] HELLAZ Note 93-05, G. Bonvicini, 29/7/93.

[13] GEANT Simulation Program, CERN-DD-E83-01.

[14] HELLAZ Note 7, F. Ciralli, 15/12/93.

[15] A.Peisert and F. Sauli, CERN 84-08.

[16] A. Bottino et al. Physics Letters B295 (1992) 330.