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PERSPECTIVES OF RESEARCH IN FUNDAMENTAL PHYSICS AND ASTROPHYSICS IN THE GRAN SASSO UNDERGROUND LABORATORY

Dedicated to the memory of
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Abstract

The huge underground laboratory, GSL, being excavated under the Gran Sasso d'Italia at a depth of ~4.200 m e.w., will offer a unique opportunity to develope a wide experimental program of "Science Underground", presumably expanding into the years 2000. For the validity of such a long-range program it appears essential to install in the GSL a sophisticated detector of mass in the 10 Kt region. A possible solution for such a "Giant Underground Detector" (GUD) is outlined. GUD has a modular structure, consisting of several massive fine-grained track calorimeters capable to provide accurate space-time information, energy measurements, often direction of particle motion and sometimes particle identification. Some of the main possible applications of GUD to fundamental problems of Physics and Astrophysics (matter instablity, neutrino osccilations, extra-terrestrial neutrinos, monopoles, etc.) are briefly discussed.

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1. Introduction

The opinion is by now widespread that the installation of very massive and sophisticated particle detectors deep underground will provide a new way to attack frontier problems of subnuclear Physics, Astrophysics and Cosmology, opening up a new field of fundamental research probably destined to expand into the years 2000. Matter instability, neutrino oscillations, extra-terrestrial neutrino sources, extremely high-energy cosmic ray events, heavy monopoles, neutrino bursts from stellar collapse,... are examples of such problems; all beyond the frontier of our present knowledge and mostly impregnable by other existing tools such as particle accelerators, reactors and the largest present-day astronomical installations.

These considerations fully justify in my opinion the efforts being made in different parts of the world to open up the new field of "Underground Science". But perhaps some effort should also be made to coordinate the many initiatives on a world scale in order to avoid a dispersion of the available forces (in manpower and economics) which are necessary for these new big enterprises to become a reality.

Let me briefly recall here the present situation of Underground Science in Western Europe, where right now the only existing underground laboratory, already in operation since several years, is located under the Mont Blanc, at a depth of about 5000 m of water equivalent (w.e.). This laboratory has unfortunately a limited capacity which does not appear realistic to increase. A proton decay "calorimetric detector" of mass ~160 t, developed and installed there by the "Nusex Collaboration"$^{1)}$, entered recently into operation and has recorded already one possible nucleon decay candidate$^{2)}$.

Another underground laboratory, of useful volume about 10 times larger than that of the Mont Blanc laboratory, is now being excavated near the Fréjus tunnel, at a depth of about 4500 m w.e. A detector of mass 1.5 Kt, being constructed by a French-German Collaboration$^{3)}$ using again a track calorimeter but of improved granularity and lower cost per ton with respect to "Nusex", will be installed there starting next year.

Finally, a much larger laboratory will be constructed under the Gran Sasso d'Italia (see next Section) at a depth similar to that of the Fréjus laboratory. The lines of a project for a modular Giant Underground Detector ("GUD") of mass expandable into the 10 Kt region, to be installed in this last laboratory, were presented at the "GUD Workshop" held in Rome last year$^{4)}$ following a letter of intent sent in June 1980 by a Frascati-Milan-Rome-Turin Collaboration to the Italian authorities.

The conclusions of the GUD Workshop confirmed the validity of the wide-range experimental program made possible by the construction under the Gran Sasso Laboratory of a modular track detector of high space-time resolution and of mass expandable beyond the 10 Kt limit.

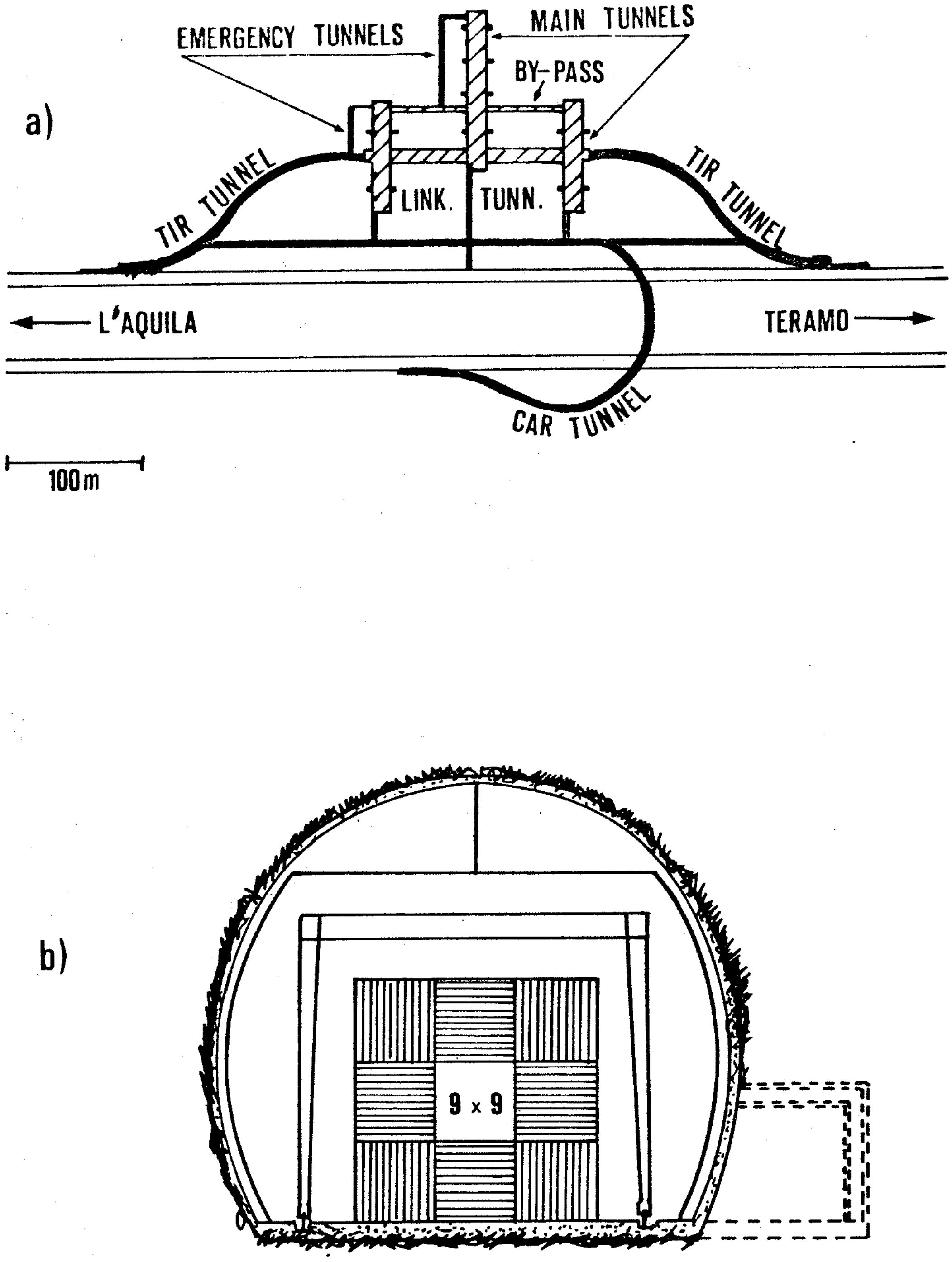

Fig. 1 - a) General plan of Laboratory (three "Main Tunnels" connected by a linking tunnel) and access to it.

b) Cross-sectional view of Main Tunnels.

(Drawings from A.Zichichi: "Scienza e Vita" <u>4</u>, n.12, 27 (1982))

2. The Gran Sasso Laboratory Project

The project of the Gran Sasso Laboratory (GLS) is going on under the direct responsibility of the present President of the Italian Institute for Nuclear Physics (INFN) who presented already its basic features at the GUD Workshop5) in October 1981. Since then the project underwent some relevant modification in the Laboratory shape, which will now consist of three main holes interconnected as shown in Fig. 1. Here I will merely recall the most relevant characteristics and the main "figures of merit" of this new large INFN facility.

The GSL will be located at about 100 miles from Rome, near the tunnel excavated under the Gran Sasso d'Italia on the high-way which links up l'Aquila with Teramo. The GSL will have a total volume of $\sim 5\ 10^4\ m^3$. It will be under an average thickness of matter corresponding to about 4200 m w.e. As mentioned above, in the present version of the project the Laboratory will essentially consist of three holes of $(9m)^2$ useful cross-sectional area excavated over a length of nearly 100 m.

The GSL will be international in character and it will offer the possibility of installing there several large detectors to attack a wide range of problems of "Underground Science".

The financial support for the construction of the GSL and its facilities (not for the experimental set-ups) has been secured early this year. The excavation of the first hole started early in September.

3. The GUD Project

As stated at the GUD Workshop, the project under study of a Giant Undeground track-Detector (GUD) to be installed in the Gran Sasso Laboratory is already oriented towards a "calorimetric approach", as opposed to a "water Čerenkov" detector. However the actual technical solutions are by no means frozen, even though in the general lines of the project, as presented at the GUD Workshop and here, reference is made to definite techniques which appear particularly suitable for meeting the requirements of "high performance at a reasonable cost".

A set of "physics requirements" leads to the choice of a modular structure detector made of massive fine-grained track calorimeter modules, of cost compatible with the goal of overcoming the 10 Kt mass limit. This goal is one of the main justifications for a new generation experimental program in an underground laboratory of the size of the GSL, because jointly with a detector high performance (specifically a high space-time resolution) makes it possible to attack new areas of Physics and Astrophysics, such as the detailed investigation of the nucleon decay through identification of the various anticipated decay modes, study of the possible $\Delta B = 2$ transitions, sensitive searches for oscillations of atmospheric neutrinos and for extra-terrestrial neutrino sources, investigation of muon groups and other peculiar high-energy cosmic ray events, etc.

GUD can be regarded as the natural extension of the other two Western Europe experiments1) 3), in that it will also use a specific type of total absorption track detector, called "digital"6) or "hit calorimeter", in which "showering inert plates" of dense material are alternated with counter planes and the energy of the primary showering particle is derived from the recorded total number of "counter hits"7). The detector response does not depend of course on the type but only on the transversal dimensions of the counters utilized for the counter planes. Flash tubes, used in the Fréjus experiment3) (as in the first of such calorimeters7) sketched at the top-left of Fig. 2) present the basic advantage of being wireless counters of typically 0.5 cm transversal dimensions, but the drawback of requiring a "H.V. trigger" which is not needed if d.c. operated counters are used as in the Mont Blanc experiment1). Compared to the detectors employed in these two experiments1) 3), GUD should not only have a much larger mass, but it should also provide precious time information, at a few ns resolution level, and thereby the possibility of deriving in many istances the direction of motion of the recorded particles from time-of-flight measurements.

The main ingredients in the proposal already presented "more as an example" at the GUD Workshop4) are flash chambers of plastic material (PFC)8) and resistive plate counters (RPC)9). The latter are used both to trigger the chambers and to provide continuous time information.

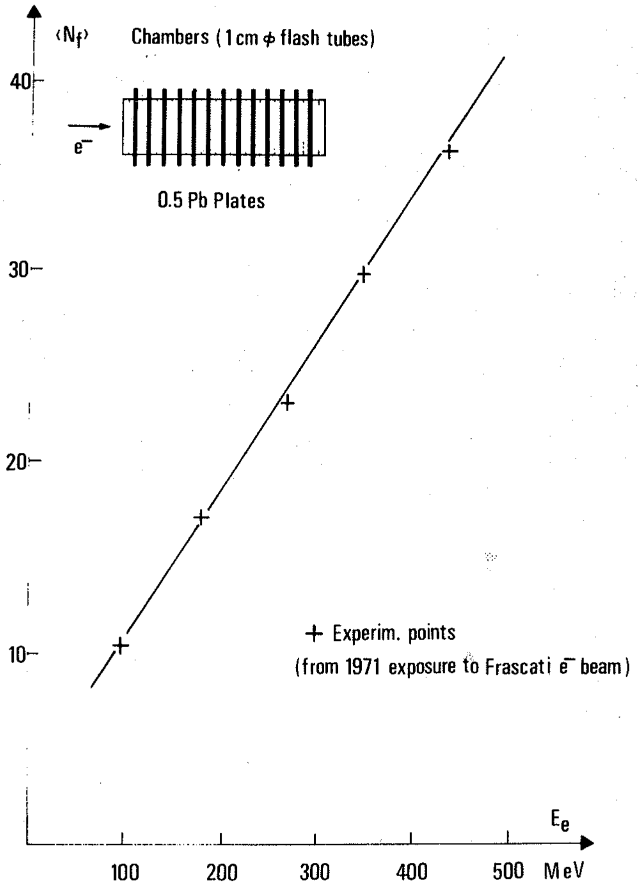

Fig. 2 - The insert at the top-left shows a sketch of first "hit calorimeter", made of counter (flash-tube) planes, alternated with thin lead plates. The straight line through the experimental points shows the linear response of this calorimeter to electrons of energies from ~ 50 MeV to ~ 500 MeV.

PFC's made of extruded polypropylene sheets, alternated with metal plates for shower sampling ("flash calorimeters")10), are now currently in use in large experiments for neutrino physics, in particular at Fermilab11) and LAMPF12). The technique is well established and I shall only recall here the following facts:

a) The energy E of a primary electron or photon can be derived from the number N_f of recorded flashes (Fig.2, from reference 7, shows the linear relationship between N_f and E up to E ~500 MeV). The r.m.s. measurement error under the conditions of the GUD project4) and for particles impinging perpendicularly on 3 mm thick iron plates (as in GUD) is given by

$$\sigma/E = \sim 7\% / \sqrt{E_{GeV}} \quad ;$$

b) The technique allows for some particle identification, as illustrated by the examples of Fig. 3 (from Ref. 10)) where the patterns of hadronic showers appear clearly different from those of electromagnetic showers.

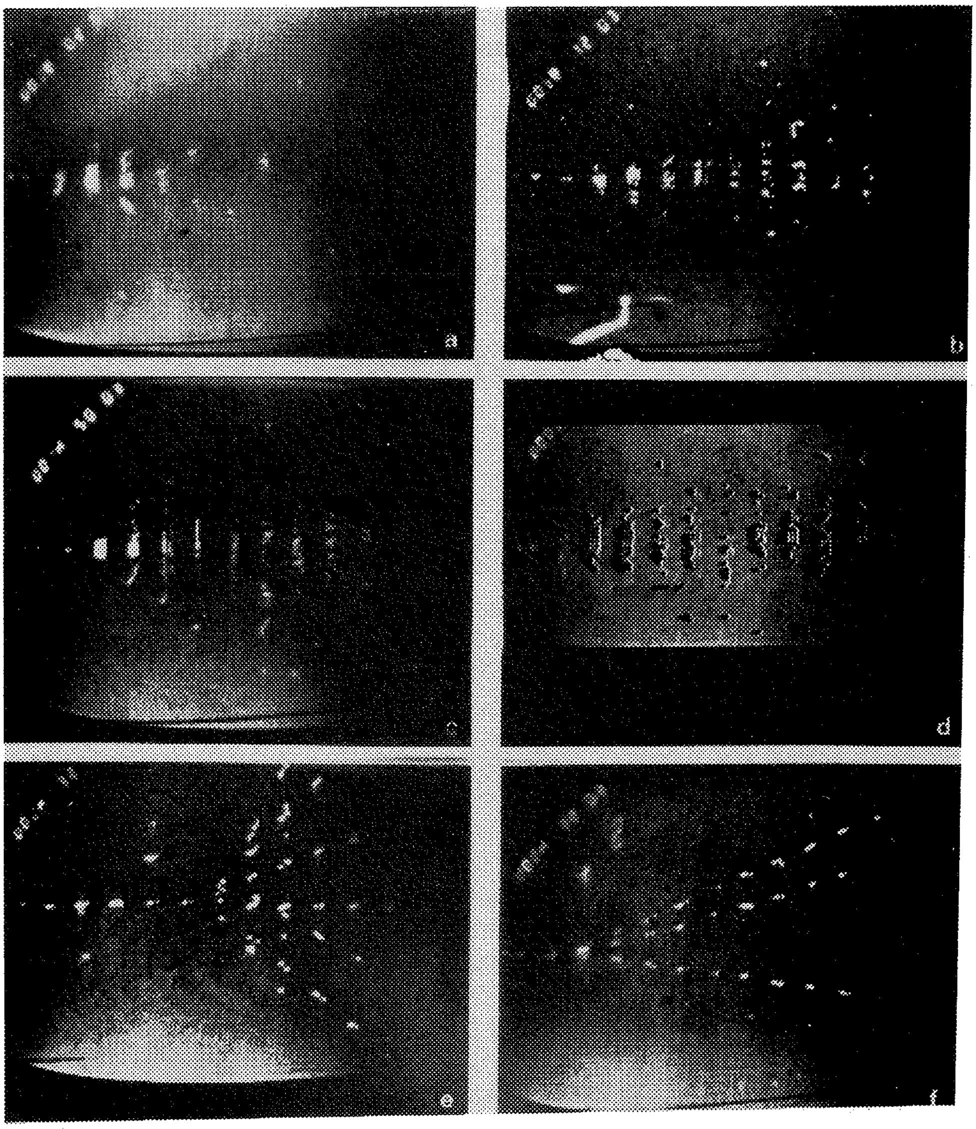

Fig. 3 - Response of the "plastic flash calorimeter" of Ref. 10 to electrons and pions of various energies. Videograms a) to d) show showers initiated by e^- of 0.5, 1, 1.5, 3, 4 GeV/c; videograms e) and f) show showers initiated by pions of 4 GeV/c and 5 GeV/c, respectively.

c) Muon identification is unambiguous (straight track), and accurate energy determination is obtained from range measurements if the muon stops in one of the calorimeter plates.

d) The muon charge can be determined from the $\mu^+ \rightarrow e^+$ decay (μ^-'s being captured in iron in 98% of the cases) provided that the chambers are operated with a sensitive time of a few μs.

RPC's have been developed only recently[9) 13)] and will be used for the first time in a search on neutron-antineutron oscillations at the Pavia reactor[14)]. They are fast, wireless, d.c. operated counters made of parallel electrodes of high resistivity ($\sim 10^{10}$ Ωcm), between which a gas mixture, typically 50% argon and 50% butane, flows at atmospheric pressure. Their principle of operation is similar to that of the "Pestov counter"[15)], but differently from the latter they can be built in large areas at a low cost. At any particle traversal, which is recorded with 99% efficiency, they yield pulses of up to 1 volt, 2-3 ns risetime, on inductive pick-up aluminium-foil strip lines of 50Ω impedence, placed on the counter walls as shown in Fig.4. Under the effect of the strong electric field (~50 kV/cm) present in the 2 mm gap between the resistive plate electrodes, the ionization electrons freed by the primary particle develop quickly into an avalanche, and then into a local streamer which, however, does not propagate via photoionization processes (as in Geiger counters or flash tubes) because of the butane photon absorption, nor does it evolves into a spark because of the high resistivity of the electrodes.

When the RPC's are used as trigger counters of very large area it is important to couple two RPC's into a single unit, as shown in Fig.4, in order to reduce the single counting rates, and therefore the accidental rate of twofold coincidences between pairs of these coupled units. One such unit, of 15 cm x 220 cm useful area and over-all thickness ~2 cm, with pick-up strip lines 3 cm wide, has recorded a "single" counting rate of less than 1/s at a position under the Gran Sasso tunnel not far from that forseen for the undeground laboratory.

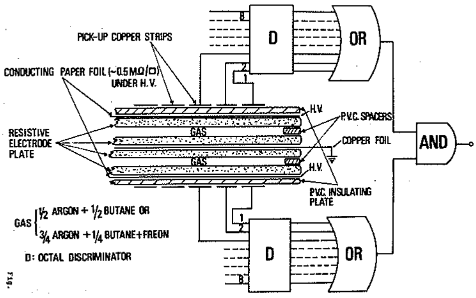

Fig. 4 - Sketch of double-layer "resistive plate counters"[9)] with incorporated "cheap electronics" twofold coincidences, to provide a unit of low "single" counting rate.

The combination of the PFC and RPC techniques should provide a remarkable over-all space-time resolution at a cost per detector-ton low enough, so as to make realistic the reaching of the 10 Kt mass goal for GUD.

Fig. 5 shows a small portion of one of the GUD modules with the structure already discussed at the GUD Workshop[4)]. PFC's are alternated with 3 mm thick iron plates (as in the Fréjus experiment) and RPC's are interleaved at a distance which leaves ~12 g/cm^2 of material between any pair of contiguous RPC planes. Under these conditions the energy trigger threshold is low enough to secure a high detection efficiency even for low energy events.

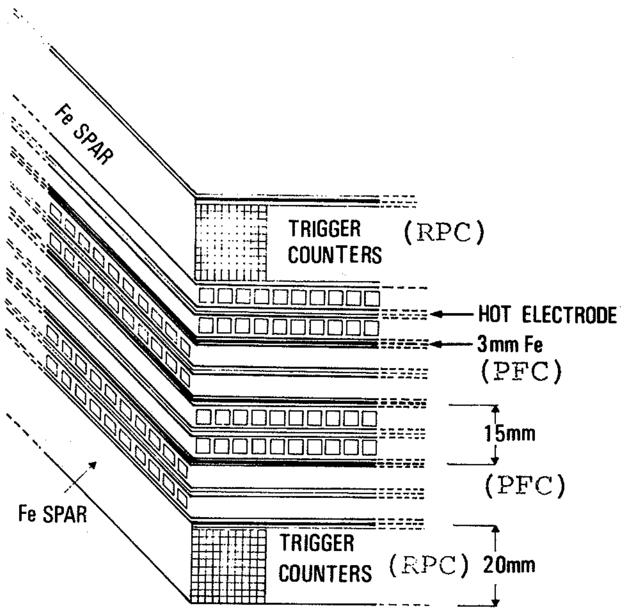

Fig. 5 - Showing a small portion of a corner of one of the $(9\ \mathrm{m})^3$ GUD modules, to illustrate a possible module structure with low energy trigger threshold (~ 12 $\mathrm{g/cm^2}$ of material between trigger counter planes). The trigger counters are RPC[9)]: fast enough to provide also time-of-flight measurements. They are coupled in double layers (see Fig.4) in order to drastically reduce the accidental trigger rate ("twofold" coincidences between contiguous counter planes). The chambers (PFC) are made of two extruded polypropylene plates incorporating the "hot electrode". They contain the sensitive "flash cells", of 9 m length and $(4\ \mathrm{mm})^2$ cross sectional area. A $(9\mathrm{m})^3$ module (~1.4 Kt mass) contains ~1.5 million sensitive cells.

Under the new conditions of the Gran Sasso Laboratory project (Fig.1) the disposition of the GUD modules need to be changed with respect to that reported at the GUD Workshop[4)]. For example ten modules of the same structure, of $(9\ \mathrm{m})^3$ volume and ~2 $\mathrm{g/cm^3}$ density, could be aligned along one of the three GSL main holes to total 14 Kt.

For a total GUD mass of about 10 Kt the number of sensitive cells of $(4\ \mathrm{mm})^2$ cross-sectional area and of ~9 m length is in excess of 10^7. This is indeed a huge number; in fact unrealistically large from the stand-point of both cost and work required, should the wireless flash tubes be replaced by any type of wire counter(*). Thus it appears that if the 10 Kt mass limit has to be reached using "hit calorimeter"

(*) It is worthwhile to stress that the extruded plates of polypropylene currently used in large flash calorimeters are commercially available at very low cost in sheets 1.5 m wide, of arbitrary length. Each sheet contains some 350 tubular cells of $(4\ \mathrm{mm})^2$ cross-sectional area and any desired length and thus it provides quite naturally, in the form of <u>wireless</u> detectors, the counters needed for the "hit calorimeter" counter planes.

modules, the solution proposed is still the best. This conclusion is reinforced by the great choice of read-out systems[4,16)] offered by such a solution[4)], including serial magnetostrictive[11)] and capacitive[12)] read-outs. However, for a 10 Kt detector formidable mechanical problems need still to be solved, especially if a horizontal disposition is chosen for the module chamber and counter planes. Also the need to sensitize so massive detector modules by the application of a ~5 KVolt high voltage pulse, as well as the selection of the triggering signal, represent technical challenges which should not be underestimated.

4. Physics and Astrophysics with GUD

A 10 Kt detector of the type outlined in the previous section (see Ref. 4) for more details) would only occupy a fraction of the GSL volume, but it would still offer the possibility of attacking a number of fundamental problems of Physics and Astrophysics, as discussed already at the GUD Workshop. In what follows I shall only briefly mention some of the open possibilities.

4.1 Nucleon Instability

The problem of the detection of individual nucleon decay modes and their separation from background induced reactions has been discussed at the GUD Workshop[17)] by comparing three proton decay detectors of different space resolution and granularity: the Kolar Gold Field detector[18)], the Nusex calorimeter[1,19)] and a fine grained track detector of the GUD type but without time information, as originally proposed by Grant and Tallini[20)]. The conclusion of this analysis is that the detector space resolution is at least as important as fine sampling in radiation length, and that adding the time-of-flight information as proposed for GUD, the latter could separate out decay modes at the 10-20% level.

I shall not discuss again the "usual" electromagnetic proton decay mode ($p \rightarrow e^+ \pi^\circ \rightarrow e^+ \gamma\gamma$) but merely recall[4)] that GUD would not only allow one to "see" the topological structure of the event, but also to determine the energy of the final state with a resolution of $\pm$ 17%. The GUD fiducial mass for this type of event can be made nearly equal to the total mass by the method explained in Ref. 4).

In the so-called supersymmetry ("Susy") theories[21)] the nucleon decay modes $p \rightarrow e^+\pi^\circ$, $n \rightarrow e^+ \pi^-$,... are strongly suppressed, whereas decays involving strange mesons are favoured. The proton decay mode $p \rightarrow \mu^+ K^\circ \rightarrow \mu^+\pi^+\pi^-$, which is expected to occur in both standard and supersymmetric theories, could appear in GUD as shown by the Monte Carlo simulation reported in Fig. 6. The track of the positron from the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay sequence (not shown in the figure) could also be observed in GUD if the flash chambers are efficiently operated with a few μs sensitive time.

Fig. 7 shows sketches of some "Susy" decay modes as expected to appear in GUD under favourable conditions. In addition to the topological information GUD would provide also a measurement of the K^+ and μ^+ decay times, and of the energy release. Of course the "energy signature" is not as good here as in the previous cases, due to the large amount of "invisible energy" carried off by ν's.

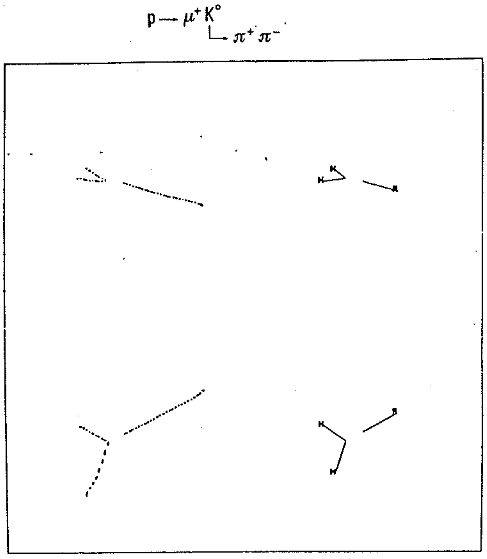

Fig. 6 - Simulation on GUD(17) of the proton decay mode $p \rightarrow \mu^+ K^\circ \rightarrow \mu^+ \pi^+ \pi^-$. The track of the positron from $\mu^+ \rightarrow e^+$ decay (not shown) can be observed too if the chambers are operated with a few μs sensitive time.

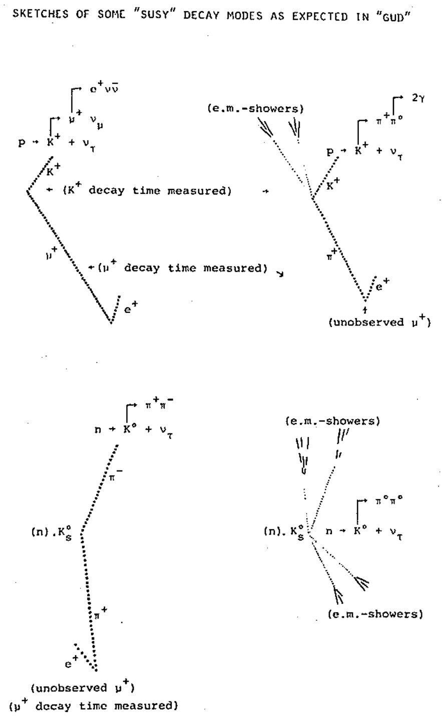

Fig. 7 - Sketches of some "supersymmetric" nucleon decays modes as expected to appear in GUD under favourable conditions.

4.2 $\Delta B = 2$ Transitions

Such transitions, forseen in various theoretical models22), should be mediated by some massive boson in the "SU(5) desert" from ~100 GeV to ~10^{15} GeV. The events searched for ($NN \rightarrow$ pions) should be characterized by a clear signature due to the large amount of energy release. These transitions, however, are better investigated as a 1st order effect searching for neutron-antineutron oscillations in reactor experiments. As an example, a 10 Kt detector of the GUD type has an estimated sensitivity comparable to that expected for the $n \leftrightarrow \bar{n}$ oscillation experiment in preparation at the Pavia reactor14).

4.3 Neutrino Oscillations

Neutrinos are generated in the Earth atmosphere (as sketched in Fig. 8) by primary cosmic rays mostly through pion production and subsequent decays, $\pi \rightarrow \mu\nu_\mu$ and $\mu \rightarrow e\nu_e\nu_\mu$. Hence these atmospheric neutrinos are prevalently ν_μ's. Since the Earth is virtually transparent to all ν's of the energies involved (which are in the GeV region) a detector like GUD will be equally exposed to ν's coming from the nearby atmosphere and from the opposite side of the Earth atmosphere. These latter ν's may have travelled over distances of the order of 10^4 km and might therefore have changed their flavour through the phenomenon of neutrino oscillations23), which is possible for massive neutrinos.

GUD can be then applied, of course, to search for these neutrino oscillations. Its sensitivity, as reported at the GUD Workshop24), should allow to record a 3σ effect after ~1 year of data taking for the quantity $\Delta^2 = |m_1^2 - m_2^2|$ in the range $10^{-3} - 10^{-4}$ $(\mathrm{eV})^2$, m_1 and m_2 being the masses of the neutrino base states. This represents a considerable improvement with respect to the present limit of ~ 1 $(\mathrm{ev})^2$ for Δ^2.

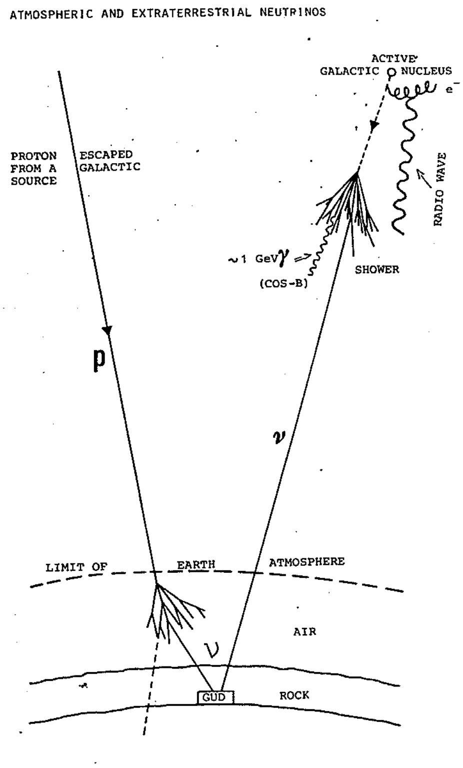

Fig. 8 - Illustrating generation of "atmospheric" and "extraterrestrial" neutrinos.
GUD can be oriented in the GSL so as to make possible to investigate ν-oscillations also with ν's from CERN lab., e.g. as suggested in the last Section of Reference 10.

4.4 Search for Extra-terrestrial Neutrino Sources[25)]

Most luminous objects in the sky (Pulsars in our Galaxy, and extragalactic "active nuclei") radiate electromagnetic energy with a non-thermal spectrum extending from radio waves to gamma rays. The energy is liberated from "point-like" sources (on an astronomical scale), in the form of relativistic particles: e^-, which radiate the observed electromagnetic spectrum, and protons. Protons are accelerated up to several TeV and generate energetic ν's and γ's through $\pi^{\pm}$ and π° production and decay. The discovery of tens of γ-ray sources by satellite observations (COS-B, etc.) has confirmed this general picture.

Observation of ν's from such sources (see Fig. 8) would be of the greatest astrophysical interest, since these ν's would transport "unaltered information" from the interior of the source due to their very small cross section. A new field of Neutrino Astronomy in the energy region from about 0.1 GeV to ~100 GeV, could be thus investigated, complementing the exploration eventually made in the TeV region by DUMAND (the "Deep Underwater Muon And Neutrino Detector" in project in the Hawaii, which detects the Cerenkov light radiated by μ's from very high energy charged-current (c.c.) ν -events).

According to what reported at the Rome Workshop[25)] GUD is expected to record a rate of ν_{μ} -events comparable to or even greater than that expected for DUMAND, depending on the exponent of the assumed power-law ν-energy distribution. It should also detect medium and high energy c.c. ν_e-events, and allow one to measure the electron energy by counting the flashes produced by the associated electromagnetic shower.

GUD angular resolution is estimated to be 4° x 10° for inelastic ν -events, and of order $E_{\nu}/M_p c^2$ for elastic c.c. ν-events (dominant below $E_{\nu} = \sim 1$ GeV). Hence correlation with γ-ray sources should be possible.

4.5 Monopoles[*)]

According to current theoretical ideas, monopoles of mass as large as $\sim 10^{16}$ GeV/c^2, generated at the very early stage of Universe formation ($< 10^{-35}$s), might nowadays exist as relics characterized by very small velocities ($\beta = \sim 10^{-3}$) and extremely high energies ($\sim 10^{20}$ eV) acquired through acceleration in the galactic magnetic field. These slow energetic "heavy monopoles" should be able to traverse the Earth with no appreciable energy loss. The arguments presented by Glashow at the Rome Workshop for "no monopoles at GUD"[26)] need of course to be revised if the single event consistent with one Dirac unit of magnetic charge recently reported[27)] is not considered as an exceptionally large time fluctuation. Let us see now what could we get by the GUD detector.

When traversing matter, heavy monopoles with $\beta = \sim 10^{-3}$ should undergo ionization lossees close to, or according to some authors[28)] even considerably larger than that of a charged particle of minimum ionization. Hence they could be detected by the GUD RCP-planes as a sequence of electric pulses well separated in time ($> \sim 0.3$ μs). This sequence of pulses should not only allow to obtain roughly the track

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[*)] I wish to acknowledge a fruitful discussion with Dr. Daniele Fargion on this subject (with an accuracy depending on the width of the RPC pick-up strips), but also to determine the direction of motion of the monopole. With ten modules of $(9\ \mathrm{m})^3$ volume aligned as indicated at page 8 of the present paper, GUD would cover an area of $\sim 800\ \mathrm{m}^2$. For a flux corresponding to the "astrophysical upper limit" of $\sim 10^{-14}/\mathrm{cm}^2.\mathrm{s.ster}$, as estimated(29) for monopoles of mass $10^{16}\ \mathrm{GeV/c}^2$ and velocity $\sim 10^{-3}c$, GUD should then record some 10 events per year. If no event were found in a one-year exposure, GUD would yield for the flux of such monopoles an upper limit at least 10 times smaller than the smallest obtained so far(30) (Bakstan).

According to some theoretical estimate, the predicted monopole-induced nucleon decays(31) might occur in GUD along the monopole track even at distances comparable to or smaller than GUD linear dimensions. If so, these decays, detected by GUD, might provide a "monopole signal". Finally, the possible genetion of ~ 1 GeV antineutrinos due to monopole-induced nucleon decays in the Sun(32) might again give rise to a "monopole signal" well detectable by GUD, which is well suited to record neutrinos of those energies, yielding also the neutrino direction of motion (see Section 4.4.).

4.6 Neutrino Bursts from Stellar Collapse

Gravitational collapse is expected to occur for stars of mass in excess of about 1.2 solar masses as the last phase of stellar evolution, when the nuclear fuel is exausted. The subsequent "neutronization process" ($e^- p \rightarrow n \nu_e$) then leads to a "neutron star", or to a "blackhole" if the star mass is large enough. The phenomenon is very complex(33) and it is presumably accompanied by emission of electromagnetic waves, bursts of neutrinos and other particles, and also of gravitational waves if the collapse does not occur under conditions of spherical symmetry (i.e. if $d^3 Q_{\alpha\beta}/dt^3 \neq 0$, where $Q_{\alpha\beta}$ is the mass quadrupole tensor).

Theoretical models in general agree in predicting the emission of neutrino bursts peaked at the instants of the successive "bouncing points" characteristic of the implosion mechanism. Thus neutrino bursts of $\sim$ 1 ms duration, separated by time intervals of the order of 0.1 s, should accompany each stellar collapse. The total neutrino energy, $E_{tot}^{(\nu)} = 10^{53} - 10^{54}$ erg, is nearly independent of the mass of the collapsing star.

The energy E_ν of the single ν's is expected to extend from ~ 10 MeV to $\sim$ 60 MeV, with an average value $\langle E_\nu \rangle = \sim 20$ MeV. Under the experimental conditions of the GUD project a fraction of the ν's belonging to this spectrum could be recorded as electrons (from $\nu_e\ \mathrm{Fe} \rightarrow \mathrm{Co}\ e^-$) of energy greater than the GUD energy threshold. For a stellar collapse at the center of our Galaxy (8.5 Kpc = 2.6×10^{22} cm) and for a 10 Kt GUD total mass there should be $\sim 10^3$ such electrons, and their space and time distributions could be recorded by the d.c. operated RPC's. The correlation of such an event with that recorded elsewhere by a detector of gravitational waves would be clearly of the greatest interest(34).

However, the rate of stellar collapses within our Galaxy is expected to be only ~ 0.5/year according to "optimistic estimates" based on pulsar data. On the other hand, with the known distribution of the surrounding galaxies, no substantial increase can be achieved for this rate, unless one can reach distances that include the Virgo Cluster (d = 1.9×10^7 pc = 5.9×10^{25} cm) for which, however, the signal of the neutrino burst could only be recorded, unfortunately, by detectors of mass in the megaton region.

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