Experiments at Large Underground Detectors

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Some of the topics discussed during the 1997 workshop on ‘Theoretical and Phenomenological Aspects of Underground Physics’ are briefly reviewed.

1. INTRODUCTION

In this review talk I will very briefly cover a subset of the topics discussed during this very interesting and fruitful Workshop. The topics are: nucleon decay, supermassive monopoles, Neutrino Astrophysics and finally Cosmic Ray physics.

This is a partial list. I’ve left out many important topics, where large underground (hereafter shortened to UG) detectors play a major role. In particular I’ve left out the exciting fields of solar and atmospheric neutrinos, whose ‘anomalies’ are stimulating interpretations in terms of neutrino oscillations. For these subjects, the reader can refer to the review talks by F. von Feilitzsch and E. Kearns at this Workshop. I’ll touch only partly the fascinating field of UHE Neutrino Astrophysics. This topic is undoubtedly a matter of deep UG experiments and is the major goal of large underwater or under-ice Cherenkov detectors.

There is a common feature among the detectors which I’m going to describe. Each of them exploits some mixture (even if to a different extent) of tracking and calorimetric capabilities at intermediate energies (MeV through GeV range). For this reason they are generally multi-purpose experiments, covering simultaneously different fields. This feature can be easily recognized in Table 1 where the main parameters of the currently operating large underground trackers and/or calorimeters as well as the covered physics topics are listed.

2. NUCLEON DECAY

Historically nucleon decay originated the growth of UG physics in mid 1970’s. It was under the influence of Grand Unified Theories that new physics topics claimed background free environments. The nucleon instability, probably the most exciting among the new phenomena predicted by these theories, stimulated several searches for nucleon decay in UG experiments.

Even if these experiments are usually considered to mark the birth of UG physics, nevertheless one must remember that UG observations were already carried out for several years, mainly in CR and solar neutrino physics. One of them in particular, the R. Davis $^{37}$Cl experiment, can be considered the father of all large UG detectors, starting data taking since late 1960’s.

Various predictions from GUT’s are given for several decay channels. The most favorable among them, $p \rightarrow e^+ \pi^0$, can be taken as a benchmark for comparison among these theories. In minimal GUT, i.e. SU(5), the lifetime to branching fraction ratio ($\tau/B$) for this channel is predicted to be $4.5 \times 10^{29} \pm 1.7$ yr. Larger symmetries, e.g., SO(10), give higher values between $10^{32}$ and $10^{34}$ years. SUSY GUT’s make new decay channels available and then new decay patterns to be searched for. The channel $p \rightarrow \bar{\nu} K^+$, the dominant SUSY decay mode, is predicted in minimal SUSY (MSSM) to occur with $\tau/B = 10^{34.5} \pm 1.2$ yr.

Experimental limits are currently available for
### Table 1
Operating UG trackers and calorimeters

| Detector | Rock overburden (m.w.e) | Eμ at threshold (TeV) | Det. technique | Sensitive mass (KTon) | Sensitive hor. area (m²) | Low en. threshold (MeV) | Physics topics |
|----------|--------------------------|-----------------------|----------------|-----------------------|-------------------------|------------------------|----------------|
| Baksan   | 850                      | 0.22                  | Liq. scint.    | 0.38                  | 280                     | ~8                     | CR-μ, ν-SN, ν-atm, ν-astr |
| MACRO    | 3700                     | 1.4                   | Liq. scint.    | 0.56                  | 920                     | 7                      | M, CR-μ, ν-SN, ν-atm, ν-astr |
| IVD      | 3700                     | 1.4                   | Liq. scint.    | 0.56                  | 200                     | 3±6                    | CR-μ, ν-SN |
|          |                          |                       | + gas det.     |                       | (~1.8)                  |                        |                |
| Soudan2  | 2100                     | 0.7                   | Gas det.       | ~1                    | 120                     | -                      | N-dec, CR-μ, ν-atm, ν-astr |
| Super-K  | 2700                     | 1.0                   | Water Ch.      | 22.5 ±32              | ~1000                   | 6.5                    | N-dec, CR-μ, ν-sol, ν-SN, ν-atm, ν-astr |

Legenda: “N-dec”, nucleon decay; “M”, monopole search; “CR-μ”, Cosmic Ray muon flux and primary composition; “ν-sol”, solar neutrinos; “ν-SN”, neutrinos from Supernovae; “ν-atm”, atmospheric neutrinos; “ν-astr”, neutrino astrophysics

Various decay modes \[10\]. The most stringent one refers to the above quoted \( p \to e^+ \pi^0 \) mode and is \( \tau/B > 5.5 \times 10^{32} \text{ yr} \) \[11\] at 90% C.L.. This value already rules out the minimal SU(5) GUT, but room is kept for larger symmetries. The SUSY preferred mode \( (p \to \bar{\nu} K^+) \) is hard to be detected, mainly because of the unavoidable atmospheric neutrino background. The best (background subtracted) limit has been obtained by Kamiokande, \( \tau/B > 1 \times 10^{32} \text{ yr} \) \[12\].

At present two experiments are searching for nucleon decays, Soudan 2 and Super-Kamiokande (Super-K). The latter is already operational since 1996 and produced remarkable results on solar and atmospheric neutrinos. No results have been yet reported on nucleon decay search, which is under analysis. The expectations are anyhow very impressive, taking into account that the sensitive mass has been increased roughly by a factor 10 and the track reconstruction has been strongly enhanced with respect to the previous water Cherenkov experiments (Kamiokande and IMB). If no signal is found, Super-K expects to set new limits after 5 years of data taking at \( \sim 10^{34} \text{ yr} \) and \( \sim 10^{33} \text{ yr} \) for the \( p \to e^+ \pi^0 \) and the \( p \to \bar{\nu} K^+ \) modes respectively.

New results on nucleon decay have been recently reported by the Soudan 2 Collaboration \[13\]. This preliminary analysis covers three decay classes:

- \( \bar{\nu} K^+ \) analysis. In Soudan 2 this decay mode is recognized identifying the kaon track (up to its stop), the decay muon track and its subsequent decay. Kinematical cuts reduce the background to values not achievable with water Cherenkov techniques. After an exposure of 2.87 KTon yr no candidate has been found with a background estimate of \( \sim 1 \) event. The overall detection efficiency times the branching fraction for this mode is \( \sim 0.16 \). From this one gets \( \tau/B > 3.5 \times 10^{31} \text{ yr} \).

- 3-4 prong events. A special effort has been dedicated to this class of events for which Soudan 2 takes advantage from its good tracking capability and vertex reconstruction (±1 cm). Many decay channels with this topology are still uninvestigated (a complete list of the examined modes can be found in ref. \[13\]). Intranuclear effects (rescattering or absorption of hadrons inside the nucleus) have been calculated with Monte Carlo simulation. In an analysis of 3.3 KTon yr there are 12 of these events. All of them but one have far too much energy to be nucleon decay candidates and are consistent with neutrino multiparticle pro-


duction. The only kinematically compatible event is the $n \to e^+ \pi^+ \pi^- \pi^-$ candidate shown in Fig. 1. Nevertheless this topology has inherently low probability to be detectable ($c_d \approx 2\%$), on account of the high intranuclear absorption probability.

- **Exclusive decay modes.** In addition to the decay channels discussed above, Soudan 2 has undertaken searches for the modes $\nu K^0_S$, $e^+ K^0_S$, $\mu^+ K^0_S$, $\nu\pi$, $\nu\pi^0$, $\nu e^+ e^+ \pi^0$, setting limits ranging from 0.2 through 0.9 $10^{32}$ yr.

\[ \begin{array}{cc}
\text{Figure 1. Candidate decay } n \to e^+ \pi^+ \pi^- \pi^- \text{ in Soudan 2.} \\
\end{array} \]

3. MAGNETIC MONOPOLES

The search for magnetic monopoles has been pursued for long time following the Dirac paper \[14\] in 1931. In 1974 t’Hooft \[15\] and Polyakov \[16\] showed that within the framework of Grand Unified Theories magnetic monopoles emerge naturally from the symmetry breaking of the grand unified group into the strong and electroweak groups. It is possible that this occurred in the early stages of the big bang \[17\], producing a residue of primordial monopoles, for which GUT’s predict a mass of the order of $10^{16}$ to $10^{17}$ GeV/c². Relic monopoles are expected to have been cooled down and now they are gravitationally trapped to the solar system or the Galaxy. Under these circumstances, their velocities relative to the Earth range from $\beta \sim 10^{-4}$ to $\beta \sim 10^{-3}$, but acceleration mechanisms can be envisaged to allow for higher velocities. GUT’s do not provide any definite prediction about the flux of magnetic monopoles. Astrophysical arguments based upon the persistence of the interstellar magnetic field \[18\] give an upper limit to this flux, $\Phi_M \leq 10^{-15}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$, usually referred to as the “Parker Bound”. This low flux and the difficulty to detect slow moving magnetic particles make this search possible only in large area underground detectors. The only detector currently active in this field is MACRO.

The MACRO detector is optimized to search for GUT magnetic monopoles from $\beta \sim 10^{-4}$ to $\beta = 1$. The design goal is to reach a sensitivity an order of magnitude below the Parker Bound for a five years’ exposure. Redundancy and complementarity among separate detector subsystems are a central feature of the MACRO experiment. Three different techniques are used to reach this goal: i) He/n-pentane gas-filled streamer tubes; ii) liquid scintillator counters and iii) nuclear track-etch detectors. Independent stand-alone (i.e., obtained with single subdetectors) analyses \[19\] were already performed for the different $\beta$ intervals. The most recent analysis \[20\] gives a global MACRO limit, as the “OR” combination of the separate results. This flux limit is shown in Fig. 2, compared with upper limits by other experiments. The MACRO limit has surpassed the Parker Bound by a factor 2 for $\beta > 10^{-4}$ and is the best existing for $10^{-4} < \beta < 5 \times 10^{-2}$.

The results obtained using the liquid scintillator and the track-etch subdetectors can be, at least in part, extrapolated to the search for nuclearites \[21\]. The flux upper limits are $\sim 10^{-15}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for nuclearites of mass $M_N > 0.1$ g and about 2 times higher for $M_N < 0.1$ g.
4. NEUTRINO ASTROPHYSICS

This is a very wide field which is approached with very different detection methods and techniques. Large underground detectors are in particular active, and in some cases play a major role, in the following searches: i) \( \nu \)-emitting point-like sources, ii) indirect search for weak interacting massive particles (WIMP’s) and iii) neutrino bursts from Supernovae. The interest of neutrino astrophysics is addressed to many different objectives, which can be relevant either to astrophysics, as in i) and iii), or particle physics, as in ii) and iii) (e.g., properties of dark matter candidates or neutrinos).

4.1. Neutrino Astronomy

Because of their low cross-section, neutrinos are not absorbed at the creation sites and can reach us directly from the core of the astrophysical objects, bringing directly information about them. It is expected that astrophysical beam dumps which produce \( \gamma \)-rays from \( \pi^0 \) decay, should also produce neutrinos from \( \pi^\pm \) decays. Possible high energy neutrino point-like sources are X-ray binary systems, SN remnants, AGN’s and other sources with significant \( \gamma \) emission in the TeV range \[23\].

UG experiments detect these neutrinos looking at upward-going or nearly-horizontal muons. Muons from high energy neutrinos preserve their parent direction (within few degrees). The restriction to zenith angles larger than 90° allows one to detect neutrinos in a roughly background free environment (the background being given by almost isotropical atmospheric neutrinos).

MACRO reported a recent search \[22\] for neutrinos from several known sources. No significant cluster of events has been found around any observable direction and the largest signal found is of 2 events from Kepler 1604 (0.54 are expected). The muon and neutrino flux limits for some sources are given in Table 2 and in some cases they improve previous limits already given by Baksan \[23\] and IMB \[24\]. It has to be remarked that these upper limits are one to two order of magnitudes higher than the expected neutrino fluxes (e.g., Gaisser \[25\] calculated for the SN remnant Vela Pulsar a muon flux of the order of \( 0.03 \times 10^{-14} \) cm\(^{-2}\) s\(^{-1}\) above \( \sim 1 \) GeV). A search for correlation with \( \gamma \)-ray bursts from BATSE catalogs is also reported in ref. \[22\].

Soudan 2 presented preliminary results \[26\] on a search for high energy neutrinos from AGN’s. The method follows a previous search from the Frejus experiment which led to a limit on diffuse neutrinos at \( 7 \times 10^{-13} \) cm\(^{-2}\) s\(^{-1}\) \[27\]. As UHE neutrinos from AGN’s (>10 TeV) traverse the Earth, they can undergo charged-current interactions and produce muons. These muons are likely to produce catastrophic energy loss by radiative processes, which dominate for energies in excess of 1 TeV. Neutrinos from AGN’s are then searched looking at nearly horizontal muons exhibiting energy losses above 10 GeV. Efficiencies for measuring such energy deposition is calculated with Monte Carlo simulation at various muon energies. They observe no events and set a preliminary 90% C.L. upper limit on diffuse AGN \( \nu \)-induced muon flux at the level of \( 10^{-13} \) cm\(^{-2}\) s\(^{-1}\) above 5 to 100 TeV of muon energy. This upper limit rules out or at least severely constrains some of the AGN models (see e.g., ref. \[25\]).

4.2. Indirect dark matter searches

Deep UG muon detectors can also look for exotic forms of dark matter, in particular WIMP’s.
Table 2
MACRO flux limits for some sources at 90% c.l. ($\mu$-flux limits in $10^{-14}$ cm$^{-2}$ s$^{-1}$, $\nu$-flux limits in $10^{-5}$ cm$^{-2}$ s$^{-1}$).

| Source         | $\delta$ | Events | Backg. | $\mu$-flux limits | Published $\mu$ limits | $\nu$-flux limits |
|----------------|----------|--------|--------|-------------------|------------------------|-------------------|
| Cyg X-3       | 40.6°    | 0      | 0.05   | 10.50             | 4.1 Baksan [23]        | 4.25              |
| MRK 421       | 38.1°    | 0      | 0.07   | 7.74              | 3.3 IMB [24]           | 3.87              |
| MRK 501       | 38.45°   | 0      | 0.06   | 7.96              | -                      | 3.98              |
| Crab Nebula   | 22.0°    | 1      | 0.28   | 3.64              | 2.6 Baksan             | 1.82              |
| Vela Pulsar   | −45.1°   | 0      | 0.86   | 0.61              | 0.78 IMB               | 0.30              |
| Kepler 1604   | −21.3°   | 2      | 0.54   | 1.71              | -                      | 0.85              |

The most plausible WIMP is considered the neutralino, $\chi$, the lightest SUSY particle, which is stable if R-parity is conserved. The idea is the following: WIMP’s in the halo get gravitationally trapped and then accumulate in the center of the Sun, Earth and other astrophysical bodies. Annihilation of these particles with their anti-particles produce neutrinos of various flavors, originating either from the decays of gauge or Higgs bosons or from the semileptonic decays of heavy quarks produced at annihilation. Some of these neutrinos are detectable as upward-going muons by a directional analysis. In practice the only background to be faced is the one coming from atmospheric neutrinos.$^1$

The angular spread between the parent neutralino and the detected muon is determined by the kinematics of the neutrino interaction, by multiple scattering of the muon from the interaction point to the detector and, for extended sources, by the dimensions of the annihilation region. In principle this angle depends on the details of the final states of the annihilation, but in practice the main parameter is the neutralino mass.

Data on upward muons from the Earth and the Sun have been measured by several experiments, notably Baksan [28], IMB [29], Frejus [30], Kamiokande [31] and MACRO [32]. The most recent analysis has been presented by MACRO [22] at this Workshop. The upper limit from the Sun they reported is at the level of $10^{-14}$ cm$^{-2}$ s$^{-1}$ for $m_\chi \geq 30$ GeV/c$^2$. This value has been compared with muon fluxes obtained from neutrino fluxes calculated by Bottino et al. [33], for various allowed MSSM parameters.

4.3. Neutrinos from Supernovae

Supernova explosions allows one to study the evolution end of very massive stars from different points of view. It’s still an ungranted dream of physicists to make combined observations of optical, neutrino and gravitational wave radiations from a SN explosion. These are extraordinary events, at least in our Galaxy. The occurrence rate depends on the detection method used: optically visible historical SN’s have been seen at a rate of $\approx 0.5$ century$^{-1}$; $\nu$-visible SN’s are estimated at $\approx 2 \div 10$ century$^{-1}$ [34]. Although these events are so rare and unpredictable, the last ten years saw an unprecedented effort to build-up and continuously run detectors capable to record such events. In particular, a network of massive underground neutrino detectors is presently active, whose combined sensitivity to a galactic neutrino burst will confirm and strongly improve the successful observations [35,36] from the SN1987A explosion.

The $\nu$-radiation from SN’s is detectable as a neutrino burst with the following characteristics: initially there is a short and intense burst of $\nu_e$, due to the ‘neutronization’ of the star, then cooling down is achieved through a longer ‘thermal emission’ of almost ‘equipartitioned’ neutrinos (among the 6 flavors). The time scale of the neutronization burst is few milliseconds, the thermal burst lasts of the order of 10 sec. As a whole of the order of $10^{57}$ $\nu$’s are emitted with an aver-

$^1$The signal from the Sun can be observed only at night, when the Sun is below the horizon. Only if the muons are upward-going they can be distinguished from the much larger flux of atmospheric muons produced in cosmic ray showers.
age energy of \( \approx 10 \text{ MeV} \).

It’s a difficult task for detectors to be sensitive to all of these neutrinos. A complete analysis of the possible signals which are detectable in the existing underground experiments can be found in ref. [37]. The detectors are of two types:

- **Liquid scintillator detectors.** These detectors (like Baksan, LSD, LVD and MACRO) use large masses \((M \sim 1 \text{ KTon})\) of liquid scintillator, segmented in some hundred counters (observed by two or more PMT’s for each) or enclosed in a container and observed by an array of PMT’s at the boundary of the active volume. Good timing \((\sigma_t \sim 1 \text{ ns})\) and energy \((\sigma_E/E \sim 10\% \text{ at } 10 \text{ MeV})\) resolutions are the most important features of these detectors. The segmented scintillator detectors have a good compatibility with tracking systems. This allows them to reject the cosmic ray background. Liquid scintillator experiments are mainly sensitive to ‘thermal’ \(\bar{\nu}_e\)’s by inverse beta reactions on protons. The scintillation counters have generally a large light yield and this makes the delayed secondary reaction \(n+p \to d+\gamma, E_\gamma = 2.2 \text{ MeV}\) detectable in these experiments. The \(\gamma_{2.2}\) signal gives a powerful further signature of the \(e^+\) event from the primary reaction.

- **Water/Heavy water Cherenkov detectors.** Experiments of this type (like IMB and Kamiokande in the past, Super-K at present and SNO in near future) use large volumes of highly purified water (heavy water), equipped with an array of inward-looking phototubes to detect the Cherenkov light produced by relativistic charged particles. The Cherenkov detectors have a continuous active medium and are self-shielded from the external radioactivity background. The energy threshold of these experiments is in the range \(5 \div 10 \text{ MeV}\). The two new detectors (Super-K and SNO) can remarkably enrich the knowledge about the neutrino burst. In particular Super-K for the first time can collect a sizeable amount of \(\nu_e\)’s from the ‘neutronization’ phase, whereas SNO will be sensitive to the neutral current interactions on Deuterium, thus allowing to detect neutrinos of different flavors.

No SN neutrino burst has been detected after 1987 by any of the operating detectors. The analysis of the event clusters is compatible with the background measured at the different sites. More recently a special effort is dedicated to provide experiments with online “Early Warning” systems. MACRO published a paper [38] showing its online SN watch monitor. The motivation for this system derives from the hope that a notification of a neutrino burst given within a short time (\(\sim \text{one hour}\)) increases the chance of observing the onset of the optical signal. Furthermore, coincident alarms emanating from more than one neutrino observatory merged into a centralized computer repository offers enhanced sensitivity and directional information.

5. COSMIC RAYS

UG experiments study Cosmic Ray physics through the detection of the penetrating components of air showers (EAS). Only muons and neutrinos penetrate to significant depths underground. Apart from neutrino detectors (e.g., water Cherenkov or fine-grained calorimeters) which are capable to identify GeV neutrino interactions in contained (or semi-contained) events, all other detectors measure only through-going muons, both atmospheric and neutrino-induced. These measurements pertain to different depth intervals: up to \(\approx 10 \text{ Km.w.e.} \) atmospheric muons are dominating, at higher depths neutrinos constitute the only residual cosmic ray component. This is illustrated in fig. 3 which shows the vertical muon intensity as a function of depth [40].

Large UG detectors collect copiously TeV muons, in a good fraction grouped in muon bundles, and these are used for two major physics topics: i) study of primary CR spectrum and composition and ii) study of hadronic interaction mechanisms. It is possible to decouple, at least partly, the two sources in large area detectors: the main requirement is that their lateral sizes be large with respect to the lateral spread of the muon bundles (typically of the order of a few me-
The measurement of the primary composition at high energies (≥ 100 TeV) and of its possible variations around the steepening of the primary spectrum (the “knee”, at about 2×10^3 TeV), is one of the main experimental problems in Cosmic Ray physics. Due to low fluxes, measurements must be indirect, i.e., through the study of the EAS components. In particular, the analysis of muon events detected deep underground is one of the most interesting tools for the indirect study of primary composition, since it can be shown that the muon multiplicity, for a given energy threshold of muons, is sensitive to both the energy and mass number of the primary particle. Measurements are in general sensitive not only to the primary spectrum and composition, but also to the interaction properties.

There have been two recent papers on primary composition studies with UG muons, from Soudan 2 and from MACRO.

The Soudan 2 Collaboration performs a standard multimuon analysis by a comparison of the measured muon multiplicity distribution with predictions from trial composition models. They use three compositions, two of which are physically motivated by the assumption of a new CR source, as extension of the basic supernova acceleration mechanism. The muon multiplicities used for this analysis range from 6 to 12, roughly corresponding to primaries between 8×10^2 and 1.3×10^4 TeV. They conclude that, out of the three compositions analysed, their data favor the lightest one (lower average mass). I would like to remark that the average mass evolution of the three models is considerably different above the knee, but the strongest difference, in the energy region covered by this analysis, is between the heaviest composition and the other two. Therefore I would prefer to interpret their results as a definite inconsistency with the predictions of an asymptotically Fe-dominated composition.

The MACRO Collaboration has derived the chemical composition making use of a best fit of the multimuon rates, based on five elemental spectra described by two-power law functions and a rigidity dependent cutoff. The large MACRO detector acceptance and its good tracking capability allows them to perform a study of multiple muon events at high muon multiplicities (up to about 40 muons) and large separations, essentially unaffected by finite detector size biases. From their best fit analysis they estimate the primary composition parameters on a wide energy interval (ranging from a few 10 TeV up to 10^5 TeV). A remarkable feature of the reconstructed all-particle spectrum, which derives from the fitting procedure, is the sensitivity of MACRO data to the knee and a good consistency with EAS array measurements. However the fitted spectrum is higher and flatter than the one obtained

\[^2\text{For the first time it is shown that UG muons do “see” the knee. Previous UG studies used composition models already incorporating the knee, but didn’t clearly showed requirement of it.}\]
from direct measurements (≈15% at 10 TeV up to ≈50% at 100 TeV). This disagreement, as well as similar differences in the TeV muon yield, may be due to possible inadequacies of the hadronic interaction model (see below). In fig. 4 the average mass number is displayed as a function of primary energy and compared with other measurements. \(<A>\) shows little dependence on the primary energy below about 1000 TeV. At higher energies the best fit average mass shows a mild increase with energy, even though no definite conclusion can be reached taking into account the increasingly large uncertainties deriving from the fit.

This study shows how high statistics and good quality of data can provide enough discrimination power to make a real composition measurement and not only a mere comparison with trial models. Nevertheless, for this kind of analyses, based on a single measured parameter (in this case muon multiplicity), the deconvolution of the primary spectrum from the experimental data is to some extent dependent on the particular nuclear interaction model used. These models are built-up in such a way to reproduce available experimental data, which are anyhow limited in energy (\(\sqrt{s} \leq 1\) TeV, corresponding to a proton Lab energy \(E_p \leq 500\) TeV) and in the knowledge of nuclear interaction mechanisms at high energies. Therefore one could believe that possible inadequacies of interaction models are increasing with energy, but are virtually absent in the energy region below the knee. A more careful study about the relevant kinematical region (e.g., the Feynman-\(x\) interval) accessed by CR primaries producing UG muons shows that possible uncertainties are also present at lower energies. In particular one can see that multimuon events originating from primaries below the knee are preferentially produced from parents in the very forward fragmentation region, yet very little data are available at \(x_F\) exceeding 0.1.

![Figure 4. Average primary mass arising from MACRO fit (solid line: central value; dashed line: value at one sigma error) compared with other measurements. \(<A>\) is displayed up to \(\sim 10^9\) GeV, exceeding the region covered by MACRO by more than one decade, in order to include the composition results from Fly’s Eye in the EeV region.](image)

A certain reduction of the dependence of the analysis on the interaction model is achieved making multiple measurements of at least two components of the EAS (one of them being usually the electromagnetic component). The discrimination power of the analysis is strongly enhanced with respect to the previous approach and therefore the measured composition is generally less dependent on EAS modeling through the air. This approach is followed in most of the CR studies from surface detectors (EAS arrays, air Cherenkov, fluorescence detectors, generally combined in the same site) \([48]\). In few sites it is possible, and it is indeed realized, to make observations combining UG muons and surface EAS parameters: EAS-TOP/MACRO, EAS-TOP/LVD, AMANDA/SPASE/VULCAN, Soudan-2/Air-Cherenkov and Baksan/Air-Cherenkov. Among these the experimental programs at Gran Sasso are probably the most advanced. In particular, EAS-TOP/MACRO pre-
sentented two recent analyses performed combining the shower size $N_e$ at surface (from EAS-TOP) with the UG muon multiplicity $N_\mu$ (from MACRO). Two classes of events are selected: high energy coincidence events and low energy triggers/anticoincident events. Events belonging to the first sample (above 100 TeV) are fully reconstructed from both experiments and are analysed in terms of primary composition [49]. The second group contains events in a limited interval of primary energy (2 TeV to a few tens of TeV) and then represents an ideal sample of UG muons to test predictions of different hadronic interaction models [50]. This provides a unique link between the EAS and the CR direct measurements.

6. CONCLUSION

Large UG detectors showed capability to detect rare signals difficult to be observed in other experiments. This can be easily recognized looking at the extraordinary variety of physics topics investigated by these detectors, including those discussed in this paper and other fundamental studies covered by other papers (e.g., on solar and atmospheric neutrinos, and UHE Neutrino Astrophysics). The conclusion of this review is that the prospects for very interesting developments in the near future are excellent.

Apart from new results from experiments already in operation (in particular, Super-K will play a leading role among them), we wait remarkable progress in two main directions:

- Among natural sources, solar neutrinos will be captured by a new generation of detectors, like SNO and BOREXino. These new experiments are expected to enrich our knowledge about the Sun and neutrinos originating from it.

- New ‘artificial’ sources will illuminate UG detectors. At this Workshop reports have been given about Long Baseline neutrino beams towards three major UG sites: i) from KEK PS to Super-K (K2K [51]), ii) from Fermilab Main Injector to Soudan (MINOS [52]) and iii) from CERN SPS to Gran Sasso (ICARUS [53], NOE [54], RICH [55,...]). This is a newly growing field which is crucial for the understanding of the atmospheric neutrino ‘anomaly’ [56].

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