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HIGH-ENERGY UNDERGROUND PHYSICS AND ASTROPHYSICS

Giorgio Giacomelli

Dipartimento di Fisica dell'Università and Sezione INFN, Bologna, Italy
CERN, Geneva, Switzerland

The present observational status of high-energy physics and astrophysics employing large underground detectors is reviewed.

1. Introduction

The study of underground muons may yield important information on the composition of ultra-high-energy primary cosmic rays [1,2], and on muon astronomy (it should be remembered that this term is not really correct; it simply means that underground detectors measure high-energy muons). In 1985 there were two reports of the possible detection of muons coming from the direction of Cygnus X-3 and having the proper phase [3]. Later results did not confirm these observations [4]. It is possible that the source is a highly intermittent one.

Large underground detectors have opened up the field of neutrino astronomy. There are two positive results: the detection of solar neutrinos [5] and the detection of the burst of neutrinos from SN1987A [6]. Larger detectors are needed in order to really open up the field of high-energy neutrino astronomy [7].

There are important connections between high-energy astrophysics and particle physics which can be studied with large underground detectors. For instance, the dark matter in the halo of our galaxy could be made of weakly interactive massive particles (WIMPs) such as neutralinos, of nuclearites, of magnetic monopoles, etc. These could concentrate in celestial bodies such as the

Earth and the Sun, and annihilate into $\nu_\mu + \bar{\nu}_\mu$ pairs; the ν_μ or $\bar{\nu}_\mu$ could interact in the rock surrounding a detector yielding a high-energy muon.

In this review results will be discussed on muon astronomy, on the composition of primary cosmic rays, on neutrino astronomy, and on a number of searches. There will also be a brief discussion on underground detectors [8]. There are obvious interconnections (and overlaps) with the general reports of Ellis, Khrenov, Wolfendale and Learned and with the reports on new data presented at this meeting [7,9-11].

2. Existing and future large underground detectors

Most of the initial underground detectors were built for searches for proton decay. Other large detectors were built for searches for rare phenomena, such as neutrinos from supernovae. Several underground laboratories were thus started. The latest addition, the Gran Sasso Laboratory, will be for the near future the largest underground non-accelerator facility [12]. The Gran Sasso National Laboratory (LNGS) of the Istituto Nazionale di Fisica Nucleare (INFN) is located on the highway Rome-Teramo, about 120 km east of Rome. The laboratory has a com-

plex of three underground tunnels, each about 100 m long, and an EAS array on top of the mountain at an altitude of 2000 m.a.s.l., about 25° off the vertical from the underground laboratory. The underground lab has a low activity environment. Three large detectors relevant to this review are or will be located there: LVD, MACRO, and ICARUS.

The large detectors for astrophysics work may be classified in two categories: a) large-mass detectors, suitable for 14 MeV neutrinos from stellar collapses, and b) large-area detectors, suitable for muon astronomy and also for high-energy neutrino astronomy.

The most important parameter of supernovae neutrino detectors is the amount of sensitive mass. Water, heavy water, and liquid scintillators are or will be used as the sensitive medium. The second parameter is energy resolution, in particular energy threshold. Some directionality is provided by Cherenkov counters.

Surface is the most important parameter for underground detectors searching for magnetic monopoles and studying high-energy muons; the area requirement is even more stringent for high-energy neutrino astronomy.

Table 1 lists present and future large-area and large-mass detectors. For each detector the table lists the detection methods, the sensitive medium, the effective area, and the sensitive mass. A few comments follow.

MACRO (Monopole, Astrophysics and Cosmic-Ray Observatory) at Gran Sasso [13] has three types of detectors: a) horizontal planes of liquid scintillators, each $(0.75 \times 0.25 \times 12)$ m³ in size; b) horizontal layers of streamer tubes, each 3×3 cm² in cross-section; between layers there are slabs of concrete absorbers; c) a track-etch detector with layers of CR39 and of lexan. The sides are sealed by one layer of scintillators and 6 layers of streamer tubes. MACRO has a modular

structure. At present 6 lower supermodules are operating with streamer tubes ($S \simeq 850$ m²) and 4 also with scintillators ($S = 570$ m², $m = 220$ t other 110 t are being commissioned). The upper part should be completed in early 1993, and MACRO will then have $S\Omega \simeq 10000$ m² sr for an isotropic flux.

The LVD (Large Volume Detector) is being installed in hall A-north at Gran Sasso [14]. It has two types of detectors: a) liquid scintillation counters, each of $1 \times 1 \times 1.5$ m³ seen by three photomultipliers; b) horizontal and vertical layers of limited streamer tubes, each 1×1 cm² in cross-section. The LVD is a scaled-up version of the smaller LSD detector (90 t) under the Mont Blanc [15]. At present one tower with 360 t of liquid scintillator is operating.

One water Cherenkov detector is operating, KAMIOKANDE-II [6].

The SOUDAN 2 fine-sampling tracking calorimeter is being assembled in the Soudan mine in Minnesota (USA) at 92.25° W, 47.28° N, at a depth of 2090 m.w.e [15, 16]. It is designed for proton decay searches. It will have a mass of 1100 t. At present it has a size of $8 \times 9 \times 5$ m³.

ICARUS (Imaging Cosmic And Rare Underground Signals) will be a large liquid-argon drift chamber, where one should 'see' tracks with a space resolution comparable with that of bubble chambers, and with many precise dE/dx samplings along the paths of the particles. A prototype of 2 t is operating and is meeting expectations.

Table 1

Main large underground detectors which study high-energy muons and search for high-energy neutrino point sources and/or neutrinos from stellar collapses. a) operating, b) approved, c) planned.

Detector	Detection material	Effective area		Effective mass		Overburden (m.w.e.)	Primary purpose
		Now	Future	Now	Future		
		(m ²)		(t)			
a) Kamioka-2	H ₂ O	150		2140			Proton decay
IMB	H ₂ O	390					Proton decay
KGF	Tubes	240					Proton decay
Baksan	Scint.	72		200			ν stellar col.
Mt. Blanc	Scint.			90			ν stellar col.
Soudan-2	Fine grain	110 → 145	(430)			2090	Proton decay
LVD	Scint. + Tubes			360 → 1800		3700	ν stellar col.
MACRO	Scint. + Tubes	850 → 1000		220 → 1000		3700	Muons mon.
DUMAND-2	H ₂ O (sea)	→ 20000				4700	High energy ν_μ
Baikal	H ₂ O (lake)	→ 4000				1200	High energy ν_μ
b) Superkamioka	H ₂ O	~ 1000		32000			Proton decay
SNO	D ₂ O			1000			ν stellar col.
ICARUS	Ar			2 → 4000		3700	Proton decay
BOREX	Scint.			2000		3700	Solar neut.
NESTOR	H ₂ O	→ 100000				4000	High energy ν_μ
c) GRANDE	H ₂ O	31000				Surface	High energy ν_μ
NET	H ₂ O	90000				Surface	High energy ν_μ
LENA	H ₂ O	30000				Surface	High energy ν_μ
SINGAO	Tubes	10000				Surface	High energy ν_μ
Doughnuts	H ₂ O	20000				Underground	High energy ν_μ
AMANDA	H ₂ O (ice)					Under ice	High energy ν_μ

The list of future approved experiments of the water Cherenkov conventional type includes:

The **SUPERKAMIOKANDE** detector, with 32,000 t of water, will be a direct upgrade of the present Kamioka detector, using large photomultipliers [7,17].

The **SUDBURY** Cherenkov detector (SNO) will have 1000 t of D₂O, surrounded by an H₂O anticoincidence blanket. The primary purpose of this detector is the study of solar and supernovae neutrinos [18].

Larger area neutrino telescopes will be discussed by Learned [7].

3. Muon astronomy

Large underground experiments detect a sizeable downward flux of high-energy muons, single and multiple, mostly coming from high-energy cosmic rays. In muon astronomy one assumes that high-energy muons remember the direction of arrival of the parent higher energy particle and it is hoped that the parent particle has not deviated. Thus a search may be made for celestial point sources, d-c or modulated, for large-scale anisotropies, and for time variations. The interest in muon astronomy started in 1985 with reports of an excess of underground muons from the direction of Cyg. X-3. Cyg. X-3 emitted ra-

dio flares, with intensity increases of two or three orders of magnitude. Some reports of muon excesses may be connected with these flares [16].

3.1. Searches for point sources with single muons

MACRO used 1.7 million single muon events obtained with one and two supermodules [19]. Muons reaching MACRO traverse a minimum path length of 3,100 m.w.e. and an average one of 3700 m.w.e.; thus a muon must have an energy larger than 1.4 TeV to reach the detector. Using this data, an all-sky search was made for point sources of muons (in excess of the expected background). The data were binned in equal solid-angle bins $\Delta\Omega$, with $\Delta\alpha = 3.0^\circ$ and $\Delta\sin\delta = 0.04$, where α is the right ascension and δ the declination. The background was estimated from Monte Carlo runs, binned as the data. For every bin the deviation from the mean was computed, $\Delta = (n - e)/\sqrt{e}$, where n is the number of observed events in that bin and e is the expected background. The distribution of these deviations (for more than 3,000 bins) is shown in Fig. 1. Superimposed on this distribution is the best-fitting Gaussian, which has a good χ^2/DoF and is consistent with a random distribution. Upper limits for a d.c. signal were established for specific sources, Cyg. X-3, Her X1, 1E2259+59 and the Crab. The d.c. limits range from 6 to $9 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$.

For Cyg. X-3, MACRO searched for a muon signal modulated by the 4.8 h X-ray period. The phase diagram does not show any deviation larger than 2σ above background. The upper limit on a modulated signal is $F_{\text{mod}} \leq 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$. Similar limits were obtained for Her X1. In Fig. 2 a compilation of flux limits from the direction of Cyg X-3 is plotted against average detector depth.

Fig. 1. All-sky search for d.c. point sources of muons [19]. Distribution of deviations from the mean.

Fig. 2. Compilation of measurements of the modulated muon flux from Cyg. X-3 [19].

The Soudan 2 Collaboration analyzed muon data taken during the Cyg. X-3 radio flares of January 1991 [16]. The minimum surface energy that a muon must have to reach the detector is 0.6 TeV. The number of muons observed both on 20 and 23 January is 16; the expected background being 5.3 and 6.1, respectively. The angular distribution with respect to the Cyg X-3 direction for the muons observed on 20 and 23 January 1991 shows an excess of

Fig. 3. Distribution of experimental data and of the Monte Carlo isotropic background prediction on two muons in the strip $(-5^\circ, +5^\circ)$ in galactic latitude [19].

events in the first bin (32 events instead of the 11.4 expected). The excess corresponds to a flux of $7.3 \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$ at 2090 m.w.e..

The MACRO Collaboration has analysed the muons coming from a 1.5° half-angle around Cyg. X-3 for short-term variability on a time scale of one day. The agreement between the measured and simulated numbers and the absence of deviations larger than 3.9σ are indicative of outbursts that are not statistically significant in that period.

It is difficult to reach a conclusion. It is clear that more precise and more extensive data with several of the largest detectors over long periods of time are needed to clear up the situation.

It may be worth mentioning that the difficulty in explaining the original 1985 observations led some theorists to speculate on a new particle, the Cygnet, which could have been a free gluon. Free gluons have been searched for at LEP by the OPAL Collaboration assuming that they could have led to a signal similar to that from a K^0 .

These events have not been observed (above the expected K^0 signal). This has led to a limit of $V_m > 47 \text{ MeV}$ for the potential barrier which confines the gluons [20].

3.2. Searches for point sources with double muons

The possibility of detecting gamma rays from cosmic point sources with a large underground detector through photoproduced muons was discussed in 1984 in connection with Cyg X-3 [21]. In 1988 it was noted that above 3 TeV the QED pair production cross-section becomes larger than the photonuclear cross-section [22]. The above points suggested the investigation of double muon events with MACRO. This method of looking for point sources is limited by the large background produced by the interaction of cosmic ray primaries.

A sample of 83500 double muon events collected with 1, 2 and 6 MACRO supermodules in the period may 1990-november 1991 was used [19]. For each double muon event detected at a certain sidereal time t_j were simulated 100 random arrival time directions according to the experimental distribution observed in that particular run. This gives the expected distribution of the isotropic cosmic ray background.

Figure 3 shows the experimental distribution and the Monte Carlo isotropic distribution for double muons projecting the strip in galactic latitude $(-5^\circ, +5^\circ)$. The experimental distribution was searched for point sources using the maximum likelihood method developed by Pollock et al. in the search of gamma ray sources in the COS-B survey. No Statistical significant source was found. One thus can establish the following limits at 99% confidence level:

$$\text{Point sources: } \phi_{2\mu}(E_{\mu 1}, E_{\mu 2} > 1.4 \text{ TeV}) \leq 3 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}; \text{ luminosity of galactic disk}$$

Fig. 4. Distribution of the time separation between two consecutive muon events ($t_1 - t_0$) for a) single and b) multiple muons measured by two MACRO supermodules [19].

$$\frac{d\phi}{d\Omega}(E_{\mu 1}, E_{\mu 2} > 1.4 \text{ TeV}) \leq 2 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}.$$

3.3. Time correlations

It is generally assumed that galactic cosmic rays have a random arrival time distribution. But there may be mechanisms, local sources, which introduce time modulations, as suggested by Weekes [23]. For charged primary cosmic rays, the magnetic fields between the source and the Earth will reduce or eliminate such modulation, with the exception of the highest energy cosmic rays. Some experiments have reported a non-random component in the arrival times of very-high-energy cosmic rays; other experiments have not found any signal [24].

The MACRO Collaboration reported the time distributions of single and multiple muons detected by the streamer tube system of the first two supermodules and by the scintillators of the first supermodule (about 10^6 muons) [19]. For each muon arriving at time t_0 , the time differ-

ence between the time of arrival of the next muon ($t_1 - t_0$) and the following four muons, ($t_2 - t_0$), ($t_3 - t_0$), ($t_4 - t_0$), and ($t_5 - t_0$) was studied. The data were compared with the Gamma Function (Poissonian of order M)

$$G(t; \lambda, M) = N \frac{\lambda(\lambda t)^{M-1} e^{-\lambda t}}{(M-1)!}, \quad (1)$$

where λ is the inverse of the mean value of the difference ($t_1 - t_0$) between the arrival of two consecutive muons, M is the order of the distribution, and N is a normalization factor. For the ($t_1 - t_0$) fits, $1/\lambda$ was left as a free parameter. For $M = 1$, formula (1) reduces to an exponential function

$$G(t; \lambda, 1) = N \lambda e^{-\lambda t}. \quad (2)$$

The fits of the ($t_1 - t_0$) data to Eq. (1) have reasonable χ^2/DoF . The λ coefficient is found to be the same for all orders of distribution of the same period.

Figure 4 shows the distributions of the separation in time between consecutive (a) single and

Fig. 5. Right ascension distribution for 1.7 million muons: data (histogram), and Monte Carlo simulation (dashed line) [19].

(b) multiple muon events. The multimMuon selection corresponds to selecting higher energy primaries. The distributions are clearly exponential, indicating the random nature of the majority of cosmic-ray muon arrival times. The higher-order correlations have a smooth appearance, with no indication of structures and are well fitted by the random distribution with $M = 2 - 5$.

3.4. Search for sidereal (large-scale) anisotropies

Figure 5 shows the right ascension distribution for 1.7 million single muons in MACRO. The dashed line is the Monte Carlo prediction: there is very good agreement between the Monte Carlo and real data. Since the times of the events in the simulation were chosen on the basis of a Poisson distribution, the simulation does not contain sidereal anisotropies. The good agreement between the Monte Carlo and the data indicates that there is no sidereal anisotropy in the data, to the level of 1%. The Rayleigh test confirms this conclusion.

Fig. 6. Plot of a) $\langle s_{||} \rangle$ and b) $\langle s_{\perp} \rangle$ distributions for two muon events. The experimental data are compared with a MC simulation which does not include the effects of the geomagnetic field. The inclusion of this field leaves unmodified the prediction for $\langle s_{||} \rangle$ and changes that for $\langle s_{\perp} \rangle$.

4. Effect of the earth magnetic field on underground muons

In a paper submitted to this Conference by the MACRO collaboration [25] the effect of the earth magnetic field on events with two muons is discussed. About one half of these dimuon events are expected to be of opposite sign; their separation will be influenced by the earth magnetic field and they will be slightly deflected in opposite directions. The same sign dimuons will not be affected by the field and their presence will thus dilute the effect. About 36000 dimuon

events with average zenith angle smaller than 60° were taken with two supermodules, corresponding to a detector dimension of $12 \times 24 \text{ m}^2$.

The experimenters measured the separation of the two muons in a plane orthogonal to their average direction and they decomposed this separation in a component perpendicular and in one parallel to the magnetic field. One expects that the separation in the 'perpendicular' direction $s_\perp$, will be larger than that in the 'parallel' direction, $s_\parallel$. The distributions of the two projections of the separation are affected by the shape of the detector. It is thus not possible to infer any conclusions before comparison with the Monte Carlo simulation.

Figure 6a shows the $s_\parallel$ distributions for the experimental data and for the 'field-off' Monte Carlo. The introduction of the field does not change the Monte Carlo distribution, which is in good agreement with the experimental one.

Figure 6b shows that the experimental data for the $s_\perp$ distribution is systematically larger than the Monte Carlo distribution with 'field-off'. Inclusion of the field improves considerably the agreement of the Monte Carlo prediction with the experimental data.

A detailed analysis of these results leads to the conclusion that the distribution in $s_\perp$ is enlarged by about 50 cm by the presence of the earth magnetic field. Thus this correction must be taken into account when high precision data will become available in the near future.

5. Composition of high-energy cosmic rays

The rates of multimuons of different multiplicities in deep underground experiments are sensitive to the energy spectrum and to the chemical composition of primary cosmic rays with energies larger than 100 TeV. The sensitivity to composi-

Fig. 7. Experimental uncorrected distribution of the distance between two muons in double muon events measured in MACRO with 1,2 and 6 supermodules.

tion arises from the fact that heavy nuclei are more effective than protons in producing multiple muons.

The transverse momentum distribution of the energetic secondaries determines the lateral size of the muon bundle and the fraction of muons that hits the detector. If the detector is large, it is easy to correct the experimental distribution and obtain the spatial decoherence of multiple muons.

Assuming a specific model of high-energy nucleus-nucleus interactions, it is possible to determine the composition of primary cosmic rays on the basis of a comparison of muon multiplicity measurements with an accurate Monte Carlo simulation.

The MACRO Collaboration presented the analysis of 73,500 multimuons [1] obtained with 1 and 2 supermodules. Preliminary results are available also with 6 supermodules. Figure 7 shows the lat-

Fig. 8. Corrected separation distribution for double muon events measured with 1, 2 and 6 MACRO supermodules. Notice that below 20 m the curves agree.

eral separation distribution for one, two and six supermodules, each of $12 \times 12 \times 4.8 \text{ m}^3$. The distribution of two supermodules is slightly larger than that obtained from one supermodule, and still larger with 6 supermodules (Fig. 7). After corrections for projected area, detection probability (computed by two independent methods), and for the unobserved multiplicity, the data with one, two and six supermodules agree well. The corrected lateral decoherence function is in good agreement with the prediction of a Monte Carlo [26], confirming that the model of hadronic interactions assumed is all right (Fig. 8).

The observed multiplicity distribution was corrected by visual scans of high-multiplicity events. The ratio $R = (\text{multimuons}/\text{single muons})$ is 3.9% for one supermodule, 4.9% with two supermodules and 5.3% with six supermodules. A full Monte Carlo simulation was made with: i) a physics generator which includes the features of high-energy interactions, the energy spectrum,

Fig. 9. Comparison between the integral multiplicity distributions of the one and two supermodule data and the Monte Carlo predictions. The Monte Carlo predictions for the 'heavy' and 'light' composition models include systematic uncertainties.

and the elemental composition of the primary cosmic radiation; ii) a description of the rock depth; iii) a GEANT-based simulation of the apparatus, which produced 'Monte Carlo data' with the same format as the real data. These were processed with the same off-line programs, thus yielding evaluations of acceptance and reconstruction efficiencies.

The analysis was performed using two composition models, the so called light composition model and the heavy composition model. The data favour the lighter composition [1] (Fig. 9). More work is in progress.

5.1. EASTOP-MACRO correlations

The MACRO detector was operated in off-line coincidence with the array EASTOP, located on the top of the Gran Sasso mountain [2]. It is thus possible to correlate the muon multiplicity with the shower size and therefore with the energy of the primary cosmic rays.

The timing of each event was provided by rubidium clocks with a relative accuracy of $1 \mu\text{s}$. Figure 10 shows one coincidence event as seen by

Fig. 10. One EASTOP-MACRO coincidence event as seen by EASTOP: E indicates the core location, M is the muon bundle core as extrapolated by MACRO to EASTOP [2]. The numbers represent local particle densities.

EASTOP; E and M are the cores of the events as seen by EASTOP and MACRO, respectively. For the following analysis only the EASTOP 'internal events' are considered, that is events for which the core of the shower lies within the boundaries of the array.

Figure 11 shows that the EASTOP-MACRO muon multiplicity distribution is broader than that of MACRO alone. The coincidence rates (5.8 events per day) have been compared with the predictions of a Monte Carlo assuming simple primary cosmic-ray compositions, pure protons (7.7 events per day) or pure iron (3.8 events per day). Given the large uncertainties, this result is compatible with the results obtained by MACRO alone. This preliminary analysis is indicative of the possibilities of the method.

Fig. 11. Measured muon multiplicity distributions for MACRO and for coincident internal events (see text) [2].

6. Neutrino astronomy

The interest in neutrino astronomy is connected with the great penetrating power of neutrinos, which allows to look directly at their sources. Low-energy neutrinos of ~ 1 MeV come continuously from the interior of stars like the Sun; slightly-higher-energy neutrinos (~ 14 MeV) come in bursts from supernovae explosions. High-energy neutrinos, with hundreds of gigaelectronvolts, may come from non-thermal point sources. Thus the number of neutrinos in the Universe is increasing. The Universe, moreover, should be filled with 'fossil' low-energy neutrinos from the Big Bang. Neutrinos of (1–100) GeV may also come from the Sun and from the Earth, where annihilations of (WIMPs) could take place.

6.1. Neutrinos from stellar collapses

Massive stars, $m > 6 m_{\odot}$, on the main sequence, evolve gradually as increasingly heavier nuclei are produced and then burnt at their

centres in a chain of thermonuclear processes, ultimately leading to the formation of a core composed of iron and nickel. Further burning in the shells surrounding the core may make the core mass exceed the Chandrasekar limit, $m_{\text{ch}} = 5.76 y_e^2 m_{\odot}$ (y_e = lepton fraction in the core, $y_e < 0.5$). In such a case the core implodes in a time slightly longer than the free-fall time and leads to the formation of a neutron star.

The total energy released during a stellar collapse is at least the gravitational binding energy of the residual neutron star, $E = 3 \times 10^{53} (m/m_{\odot}) (10 \text{ km}/r) \text{ erg}$, that is typically $10^{53} \text{ erg} = 0.1 m_{\odot}$, mostly in the form of neutrinos with an average energy of 10–14 MeV. Thus typically 4×10^{57} neutrinos of each species are emitted. Three stages of neutrino emission may be identified as follows:

Neutronization: $e^- p \rightarrow n \nu_e$. Only ν_e are emitted at this stage, which lasts a few milliseconds.

Deleptonization: $e^- e^+ \rightarrow \nu_e \bar{\nu}_e$ leads to ν_e and $\bar{\nu}_e$, which leave the core. The more abundant reactions $e^+ e^- \rightarrow \gamma \gamma$ lead to γ 's recreating $e^+ e^-$ pairs. This phase lasts about 1 s.

Cooling: The neutron star is very hot and is cooled by escaping neutrinos. Thermal neutrino emission from the 'neutrinosphere' lasts about 10 s. Most neutrinos, of all types, are emitted during this phase.

All types of neutrinos may be detected via their neutral current interactions with electrons, $\nu_e e^- \rightarrow \nu_e e^-$, $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$, etc., with a cross-section $\sigma = 1.7 \times 10^{-44} E_{\nu} (\text{MeV cm}^2)$, which leads to a small number of events. The dominant observed reaction, $\bar{\nu}_e p \rightarrow n e^+$, with $\sigma = 7.5 \times 10^{-44} E_{\nu}^2 (\text{MeV}^2 \text{ cm}^2)$, is energetically possible only on free protons, as in H_2O and in $\text{C}_n \text{H}_{2n+2}$ detectors. The produced positron annihilates immediately, $e^+ e^- \rightarrow 2\gamma$, whilst the neutron is moderated and captured after a mean time of about 180 μs ($n p \rightarrow d \gamma$, with $E_{\gamma} \simeq 2.2 \text{ MeV}$).

Detectors with D_2O may also detect $\nu_e n \rightarrow p e^-$. Because of the dependence of the cross-section on neutrino energy, the average e^- or e^+ energy is about 2 MeV larger than the average neutrino energy.

Supernova 1987A produced bursts of neutrinos in the Kamioka (12 events), in the IMB (8 events), and in the Baksan detectors (3 events). The Mont Blanc detector observed 5 events, 4 h earlier. The neutrinos arrived within 10 s, a few hours earlier than visible light. A collapse at the centre of our galaxy should yield 25 times more neutrinos.

Many detectors will be capable of yielding information on supernovae neutrinos (see Table 1). For future work a crucial point is the expected rate of type-II supernovae in our galaxy. An optimistic estimate is a rate of one every 10–20 years. Thus, ideally, the detectors must all be kept alive all the time and a worldwide cooperation, a supernova watch, seems to be important.

The LSD and MACRO Collaborations presented papers dealing with technical aspects and with a search for supernova neutrinos in the last few years [15, 27]. Some of the technical aspects concerned calibrations of the scintillation counters. Once a trigger (primary) takes place in a counter, the threshold on that counter, and on neighbouring ones, is reduced from 6–7 MeV to 0.8 (1.5) MeV for 1 ms in LSD (MACRO). Thus both experiments are sensitive to the delayed 2.2 MeV γ -ray from neutron capture. The efficiency for detecting such a γ -ray is globally 40% in MACRO and 50% in LSD. The search was carried out using 44 t of scintillators in MACRO and 90 t in LSD. The LSD trigger rate was 14.8 triggers per hour. The analysis was performed counting the number of events in 2 s, 3 s, ..., 10 s sliding windows. No candidate supernova was observed in the last 3 y. Also the other large detectors did not see any candidate after SN1987A.

Fig. 12. Upper limits to the relic SN antineutrinos as a function of the temperature of the neutrino sea.

LSD and Kamiokande II also searched for diffuse neutrinos from past supernovae [17]. The upper limits are shown in Fig. 12.

MACRO, running with the scintillators of 4 lower supermodules for a total scintillator mass of 220 t, started a supernova watch: it includes a continuous recording on-line, an alarm, a quick off-line analysis, and a number of quick checks.

6.2. High-energy neutrino astronomy

High-energy muon neutrinos can be detected through their charged-current interactions in the rock surrounding the detectors leading to upgoing muons. Downgoing muons from neutrino interactions are indistinguishable from the more abundant cosmic-ray muons. Upward-going muons are seen directly in Cherenkov detectors and may be separated by time-of-flight from downward-going muons in scintillators. At very high energies the ν - μ angle is small and the effective target mass is large. In order to see point sources

Fig. 13. A sky plot of the upward going muon data for (a) the IMB experiment (the dashed line indicates the location of the galactic plane) and (b) the Kamiokande experiment.

of neutrinos it is necessary to have angular resolutions of about 1° , which is slightly larger than the effective muon multiple scattering angle in the rock.

In recent years X and γ -ray astronomy suggested powerful acceleration mechanisms in many astrophysical bodies; a large flux of energy seems to be radiated by non-thermal processes. High-energy muon neutrinos may be emitted by X-ray binaries and by expanding supernovae shells [28].

The search for extraterrestrial sources may be performed by plotting the neutrino induced

muon events on a sky plot of declination versus right ascension. A source would reveal itself as an excess of events (in a certain direction) above the atmospheric neutrino background.

Several large underground experiments performed such a search with negative results. Fig. 13a shows the sky plot for the IMB data, which corresponds to a total live time of 885 days. In the figure are indicated a number of potential source locations; the dashed line indicates the location of the galactic plane. Similar results were obtained by Kamiokande, Fig. 13b.

In order to establish a flux limit for a specific source one may consider an error circle corresponding to the resolution of the detector about that direction (5° for the IMB experiment), determine the number of events in that circle and subtract the corresponding number of events expected from atmospheric neutrinos. The 90% luminosity limits are at levels corresponding to 10^{39} erg/s for the Crab Nebula and Hercules X-1, about 10^{42} for SN1987A. Kamiokande quotes limits from point sources which range from 2×10^{14} cm⁻² s⁻¹ for Vel X-1 to 8.5×10^{-14} for Her X-1.

Detectors like MACRO and Dumand should be able to yield a glimpse of high energy neutrino astronomy.

Larger detectors will be required to really attack this field [7].

7. Neutrinos from WIMPs annihilating in the Sun or in the Earth

Several astronomical observations indicated the presence of non luminous, dark matter, since several decades. The presence of dark matter (DM) in our galaxy is suggested by the rotation curves of stars in the galaxy halo (Another interpretation could be a breakdown of Newton's

law). The nature of the dark matter remains a mystery. In what follows we shall be interested in *cold heavy dark matter* in the form of heavy particles, typically with masses of tens of GeV. These could be detected directly with germanium type detectors which have high resolution and low background, through coherent scattering of the WIMPs with the nuclei of the detector. Other methods are indirect. We are here interested in WIMPs which could be trapped inside the Sun of the Earth, would annihilate and would give a flux of high energy neutrinos.

The dark matter particles considered here would have been generated in the Early Universe and would have decoupled from ordinary particles before the time of the QCD phase transition at the temperature of few hundred MeV. Examples of such particles could be heavy Dirac or Majorana neutrinos and the lightest supersymmetric particles.

These particles should be located in the galactic halo, their abundance in the vicinity of the solar system should typically be 0.3 GeV/cm³ and their velocity would be 300 km/s.

The WIMPs would be captured by the Sun (Earth) by coherent scattering with nuclei, would concentrate in the center of the Sun (Earth) and would annihilate into heavy quark-antiquark pairs or tau leptons. These would subsequently decay into high energy neutrinos. The heavy Dirac neutrinos would in addition directly give rise to ordinary neutrinos.

One interesting WIMP candidate is the supersymmetric particle with the smallest mass. In the Minimal Supersymmetric Standard Model (MSSM) there are four neutralino mass eigenstates which can be expressed as linear combinations of superpartners of the gauge bosons and of the neutral Higgses:

$$\chi = c_1 \tilde{\gamma} + c_2 \tilde{z} + c_3 \tilde{H}_1^0 + c_4 \tilde{H}_2^0 . \quad (3)$$

Fig. 14. (a) Zenith angle distribution of upward going muons in the Kamiokande detector. (b) Correlation of upward going muons with the direction of the sun. The solid lines are the Monte Carlo results.

For certain parameter combinations the neutralino may coincide with the photino ($\tilde{\gamma}$) or the higgsino ($\tilde{H}^0$). There are three independent parameters in the MSSM; they may be taken to be the mass parameter M_2 the Higgs mixing parameter μ and the parameter $\tan\beta = v_2/v_1$, where v_1, v_2 are the vacuum expectation values for the two Higgs doublets. Neutralino masses below 40 GeV are excluded by the LEP experiments. The interpretation of the searches for neutralinos from the Earth necessitates many hypotheses, which will be summarized here: the neutralino dark matter density near the Earth is taken as $\rho_x = 0.3 \text{ GeV/cm}^3$ and their velocity as $v_x \sim 300 \text{ km/s}$. Capture of neutralinos by the Earth is due to coherent interac-

Fig. 15. The excluded regions in the (μ, M_2) space at 90% CL for the MSSM, with the assumptions indicated and with the Higgs-nucleon coupling from the paper by T.P. Cheng and H.Y. Cheng. The regions with horizontal hatchings are excluded by experiments at LEP. The regions with stars are excluded by Kamiokande.

tions with nuclei, and the capture rate is particularly high for neutralinos with masses close to those of the atomic nuclei in the Earth (30–80 GeV). Neutralinos and anti-neutralinos should then concentrate towards the centre and annihilate into neutrinos. The calculation of these processes requires a complicated Monte Carlo which includes evaluation of the contribution from atmospheric neutrinos.

Limits were obtained by Kamiokande [29] and MACRO, see Fig. 14.

Until now no signal has been detected which can be attributed to neutralino. The results may be used to place constraints in the models parameters [29–31], Fig. 15. It may be that the limits are already at such levels that in part of the parameter space the neutralino hypothesis cannot provide the total amount of invisible matter of the galactic halo.

The Kamioka, Frejus, IMB, Nusex and Macro detectors have looked for neutrinos coming from the Sun. No signal was detected Fig. 16. Together with LEP results and with the results of direct searches these experiments have essentially ex-

Fig. 16. Number of muons expected from massive neutrino dark matter annihilation in the earth/sun and the limits from upward-going muons in Kamiokande, plotted as a function of assumed neutrino mass, a) for Dirac neutrinos, b) for Majorana neutrinos.

cluded the Dirac heavy neutrino with masses up to 300 GeV as an important component of the dark matter. Majorana neutrinos are also excluded.

8. Neutrino oscillations

Atmospheric neutrino events are usually considered to be the source of unavoidable background for many subjects of underground experiments, from the search of proton decay to the study of high energy neutrino astronomy. But atmospheric neutrinos are sensitive to neutrino oscil-

lations and thus may provide important informations on neutrino properties. The search for neutrino oscillations is rather sensitive because of the large range of distances traveled by atmospheric neutrinos.

Most underground experiments detect muon neutrinos via their interaction in the rock surrounding the detectors: in practice only upward going muons are usable for this purpose and only high energy muons are detected with high efficiency. Some experiments detect also muon neutrinos and electron neutrinos via their interactions inside the detector (contained events).

The measured rates of atmospheric neutrino events have to be compared with the rates calculated on the basis of the knowledge of the neutrino flux, of the cross sections and of the experimental apparatus. The fluxes of atmospheric neutrinos calculated by a number of authors differ by at most 30%.

For massive proton decay detectors it is more interesting to measure the ratio of the number of contained muon neutrino events to electron neutrino events because this eliminates a number of uncertainties in the determination of the neutrino flux and in the low energy cross-sections. The ratio is expected to be about 2 because a charged pion or charged kaon decay yields one muon neutrino and one muon; the muon decays into a muon neutrino and an electron neutrino. The relevant cross-sections of neutrinos in matter, specifically on O^{16} of the water Cherenkov detectors, are well known, with the exception of low energies, $E_\nu < 0.2$ GeV, where nuclear effects alter the cross-sections.

In a recent preprint the Kamiokande collaboration presented results from a global exposure of 4.92 kton year [29–32]. The contained events were classified in showering [electrons, photons] and non showering [muon] events. The sample has 159 electron events with momenta be-

Fig. 17. Number of e -events and μ -events versus momentum for atmospheric neutrinos detected in the Kamiokande detector (black points). The histograms represent the predictions of various Monte Carlos.

tween 0.1 and 1.33 GeV/c and 151 muon events with momenta between 0.2 and 1.5 GeV/c (see Fig. 8). The momentum spectra of the events are shown in Fig. 17. For the electron events the Monte Carlo simulations using the lowest predicted flux reproduce fairly well the experimental distribution and the integrated number. On the other hand, there seems to be a deficit of observed muons compared with the Monte Carlo predictions. The highest predicted flux raises the Monte Carlo predictions by about 30%. One may say that the experimental μ flux is better reproduced, while the ratio remains unchanged.

The authors consider the ratio $R_{\nu_\mu/\nu_e} = R_{\text{data}}/R_{\text{montecarlo}}$, where $R_{\text{data}} = (\text{observed num-}$

ber of muon events)/(\text{observed number of electron events}) and similarly $R_{\text{montecarlo}} = (\text{MC expected number of muon events})/(\text{MC expected number of electron events})$. The R ratio is expected to be less dependent on absolute normalization. From the momentum dependence of this ratio shown in Fig. 17 one sees that on the average experimentally it is 0.60, instead of the predicted value of about 1. The departure from unity is essentially due to the muon deficit.

The authors analyze in detail possible experimental uncertainties, in particular those connected with particle identification in a Cherenkov water detector. From the analysis of the two independent methods used they estimate a systematic uncertainty of 0.05 in the ratio. Thus their experimental value is $R(\nu_\mu/\nu_e) = 0.60 \pm 0.07 \pm 0.05$.

The above value is comparable to the value $R(\nu_\mu/\nu_e) = 0.67 \pm 0.17$ found by IMB-3, where the error combines statistical and systematic uncertainties. The Frejus experiment did not find any effect. The comparison with the Frejus results is less straightforward because the Frejus data include also inelastic events and the energies involved are slightly larger. The data from NUSEX and Baksan have smaller statistics.

The Kamiokande and IMB groups have also measured upward going muons from neutrinos interacting in the rock below the detectors. The data, Fig. 14a, do not directly confirm the probable deficit of muons suggested by the contained events. Consequently, "additional study is required before it can be concluded that an inconsistency exists between the results derived from the contained event sample and the upward-going muon sample".

If the contained data are interpreted in terms of neutrino oscillations, in particular in terms of two possible and independent channels, $\nu_\mu \leftrightarrow \nu_e$, $\nu_\mu \leftrightarrow \nu_\tau$, one has the contour limits of

Fig. 18 in the plane $(\Delta m^2, \sin^2 2\theta)$. Assuming that the other experiments have only limits, while Kamiokande has a signal, the allowed regions of the parameters $\Delta m^2 - \sin^2 \theta$ are those in the cross hatched areas. Assuming dominance of the $\nu_\mu \rightarrow \nu_\tau$ channel, one has $\Delta m_{\nu_\mu \nu_\tau}^2 = 0.8 \times 10^{-2}$ and $\sin^2 2\theta_{\nu_\mu \nu_\tau} = 0.87$ (with parameters $\alpha = -7\%$ and $\beta = 0\%$). "Additional evidence is necessary however, because the inference drawn from atmospheric neutrino results has the inherent weakness that it rests on a comparison of data with a calculated expected value".

9. Nuclearites

The hypothesized stable phase of quark matter, called strange quark matter or "nuclearites", may be the true ground state of QCD and may have a mass ranging from a few gigaelectronvolts to the mass of a neutron star. Because of this wide range, its search was performed by a variety of experimental techniques. These include cosmic-ray searches, carried out with scintillation detectors, ancient mica, plastic track-etch detectors, gravitational wave detectors, etc..

The MACRO search yielded an upper limit for $\beta > \text{a few } 10^{-4}$ at the level of $6 \times 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ for nuclearites with mass larger than 0.1 g (which can penetrate the Earth); the limit is 12×10^{-15} for nuclearites with $m < 0.1$ g which cannot penetrate the Earth. (Fig. 19) [33].

Figure 20 shows a compilation of flux limits for nuclearites as a function of their mass.

10. Magnetic monopoles

Grand Unified Theories (GUTs) of strong and electroweak interactions predict the existence of

Fig. 18. Summary of available data for the neutrino oscillation channels $\nu_\mu \rightarrow \nu_x$ and $\nu_e \rightarrow \nu_x$ bearing on the $\Delta m^2 - \sin^2 2\theta$ region shown. The shaded areas are allowed for neutrino oscillations.

magnetic monopoles with large mass, $\sim 10^{16}$ GeV, and magnetic charges $g = ng_{\text{Dirac}} = nc/2e = n68e$, with $n = 1, 2, \dots$. However, these theories leave completely open the question of monopole abundance. Standard cosmology predicts too many monopoles, whereas models with inflation at the GUT phase transition predict very few. Several superstring models predict the existence of multiply charged magnetic monopoles ($n = 3$) with the same large mass. In some models, the primordial monopoles appeared when the temperature of the Universe reached rela-

Fig. 19. Flux limits on nuclearites versus their $\beta = v/c$ [MACRO experiment].

Fig. 20. A compilation of flux limits for nuclearites as a function of their mass.

Fig. 21. Charge resolution of CR39 track-etch detector.

tively low values. These monopoles should not have been diluted by inflation in the early Universe; other mechanisms may have diluted the flux, but at values which should be observable. The existence of large-scale magnetic fields, on the galactic scale, leads to an astrophysical constraint, the so-called Parker bound, with an upper limit on the monopole flux at the level of $10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. This limit becomes 3×10^{-16} for $n = 3$ monopoles.

Figure 21 shows the charge resolution which may be obtained by track-etch detectors of the type used for monopole searches. The figure is relative to 14,5 GeV/nucleon silicon ions and their fragments. The measurements concern 10 faces.

The present limits on cosmic monopoles are summarized in Fig. 22.

Fig. 22. Compilation of upper limits on the flux of cosmic GUT monopoles of unit Dirac charge plotted against monopole velocity for different types of detectors.

11. Conclusions

An impressive amount of experimental work is going on in the field of high-energy astrophysics with large underground detectors. There are many interesting problems at the interface of nuclear physics-particle physics-astrophysics. All measurements and all limits in this field are continuously improving. Nevertheless, the results on muon astronomy are not conclusive.

The first results on the composition of very-high-energy charged primary cosmic-rays are encouraging and it is hoped to solve the problem in the not-too-distant future.

Larger underground detectors are needed for high-energy neutrino astronomy.

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References

- [1] S. Ahlen et al., MACRO Collab.,
- Measurement of the muon decoherence function with the MACRO experiment at Gran Sasso; LNGS 92/29 (1992) and this symposium.
- Study of the ultra high energy primary cosmic ray composition with the MACRO experiment LNGS 92/25 (1992).
- [2] The EAS-TOP and MACRO Collaborations,
Measurements of electromagnetic and TeV muon components of extensive air shower, LNGS 91/06 (1991).
- Study of high energy cosmic rays through the measurement of the electromagnetic and TeV muon components of extensive air shower, LNGS 91/07 (1991).
- [3] M.L. Marshak et al., Soudan 1 Collab., Phys. Rev. Lett. **54** (1985) 2079 and **55** (1985) 1965.
G. Battistoni et al., NUSEX Collab., Phys. Lett. **B155** (1985) 465.
- [4] Y. Oyama et al., Kamiokande Collab., Phys. Rev. Lett. **56** (1986) 991.
Ch. Berger et al., Frejus Collab., Phys. Lett. **B174** (1986) 118.
- [5] R. Davis Jr, Proc. 7th Workshop on Grand Unification, ICOPAN'86 (World Scientific, Singapore, 1987, p. 237).
P. Anselmann et al., GALLEX Collaboration LNGS GX 1 and GX 2(1992) and this symposium.
SAGE collaboration, this symposium.
- [6] K. Hirata et al., Phys. Rev. Lett. **58** (1987) 1490.
R.M. Bionta et al., Phys. Rev. Lett. **58** (1987) 1494.
M. Aglietta et al., Europhys. Lett. **3** (1987) 1315.
E.N. Alexeyev et al., Phys. Lett. **205B** (1988) 209.
- [7] J.G. Learned (High energy neutrino astronomy and astrophysics: an outlook into the future) this symposium.
- [8] G. Giacomelli, High energy astrophysics-status of observations at large underground detectors, Nucl. Phys. **B666** (1992) 1.

- K. Nakamura, Present status and future prospects of underground physics experiments, Proc. Int. Symposium on Underground Physics Experiments, Tokyo, 1990.
- K. Nakamura, Non-accelerator particle physics, ICRR-Rep 224-90, 17th High Energy Int. Conf., Singapore, 1990.
- B. Barish, Non-accelerator physics, Lepton-Photon and High Energy Phys. Conf., Geneva, 1991.
- [9] J. Ellis (Cosmological and astrophysical aspects of the Early Universe) this symposium.
- [10] B. Khrenov (Spectrum and composition of the high energy cosmic rays) this symposium.
- [11] A.W. Wolfendale (Ultra high-energy cosmic rays) this symposium.
- [12] E. Bellotti, ESO/CERN Symposium, Bologna, 1988.
- A. Zichichi, The Gran Sasso Project, Int. Workshop ICOMAN'83, Frascati, 1983.
- G. Giacomelli, Physics program at the Gran Sasso Lab., ICTP Summer School in High Energy Physics and Cosmology, 1990.
- [13] M. Calicchio et al., Nucl. Instrum. Methods **A264** (1988) 18 and LNGS 92/34 (1992).
- [14] The LVD Collaboration (Preliminary results and low energy events with the LVD experiment at Gran Sasso) this symposium.
- [15] T. Kafka, The Soudan 2 experiment, TAUP Conf., Toledo (1991).
- [16] M.A. Thompson et al., Soudan 2 Collab., The observation of underground muons from the direction of Cygnus X-3 during the January 1991 radio flares, TAUP Conf., Toledo (1991).
- [17] K.S. Hirata et al., Search for supernova neutrinos at Kamiokande II, ICRR-Report-239-91-8 (1991).
- [18] The SNO Collaboration, this symposium.
- [19] R. Bellotti et al., MACRO Collab., TAUP conf., Toledo (1991). A search for sidereal anisotropies with underground muons and an all-sky survey for muon point sources with the MACRO detector;
- Search for astrophysical point sources of muons with the MACRO detector;
 - Arrival time distributions of very high energy cosmic ray muons in MACRO.
- [20] P.D. Acton et al., (OPAL Collab.), (Search for free gluons in hadronic Z^0 decays) Phys. Lett. **B278** (1992) 485.
- [21] G. Auriemma, et al. (1984).
- [22] V.S. Berezinsky, et al. (1988).
- [23] T.C. Weekes, Nature **233** (1971) 129.
- [24] G. Badino et al., Nuovo Cimento **28** (1980) 93.
- C. Morello et al., Nuovo Cimento **7C** (1984) 682.
- [25] M. De Vincenzi et al., MACRO Collaboration (Effect of the geomagnetic field on the separation of underground muons) this symposium.
- [26] C. Forti et al., Phys. Rev. **D42** (1990) 3668.
- J.A. Goodman et al., Phys. Rev. Lett. **42** (1979) 854.
- C. Fichtel and J. Linsley, Astrophys. **300** (1986) 474.
- [27] S. Ahlen et al. (Search for neutrino bursts from collapsing stars with the MACRO detector) LNGS 92/93 (1992).
- M. Aglietta et al. (limits on low energy neutrino fluxes with Mont Blanc liquid scintillator detector) ICGF 269-22 (1992).
- [28] V.S. Berezinsky, High energy neutrino sources, Neutrino Telescopes Conf., 1991 and High energy neutrinos from astrophysical sources, this symposium.
- [29] M. Mori et al., Search for neutralino dark matter in Kamiokande, KEK Preprint 91-62 (1991).
- N. Sato et al., Mass limits for dark-matter particles derived from high energy neutrinos from the sun, KEK Preprint 90-166 (1990).
- A. Bottino et al., Direct versus indirect searches for neutralino dark matter, DFTT 35/91 (1991).
- [30] M. Mori et al., (A limit on massive neutrino dark matter from Kamiokande) KEK Preprint 92-44 (1992).
- [31] M. Mori (Upward going muons in Kamiokande) KEK Preprint 92-29 (1992).
- [32] E. W Beier et al., Kamiokande collaboration (Survey of atmospheric neutrino data and implications for neutrino mass and mixing) Phys. Lett **283** (1992) 446.
- [33] R. Bellotti et al., MACRO Collab., Cosmic ray search for nuclearites with the MACRO detector, TAUP conf., Toledo (1991).