Nuclear Physics A478 (1988) 355c–363c
North-Holland, Amsterdam

OBSERVATIONAL PARTICLE PHYSICS

M. KOSHIBA

Universität Hamburg, II. Institut für Experimentalphysik and DESY, Hamburg, F.R. Germany

Abstract: A review is given of the detection of neutrinos from the supernova SN1987a and of neutrinos from the sun. Searches for monopoles, dark matter candidates and supersymmetric particles are described, and an outlook on future experiments given.

Observational particle physics is meant to imply particle physics without using artificial accelerators. Namely it covers the studies of:

1) baryon number non-conservation processes like proton decay, n-n oscillation, etc.,
2) lepton number non-conservation processes like neutrino-less double β decay,
3) observation of elementary particles from celestial objects like ν_e from the sun, high energy ν's from Cyg-X-3, ν's from supernova explosion, etc.,
4) relic elementary particles from the big-bang, like monopoles, supersymmetric particles etc.,
5) astrophysical dark matter,
6) ν mass, ν oscillations in vacuum and in matter,
7) possible 5th force,
8) gravity waves and gravitons, and so forth.

In view of the first observation of a neutrino burst from the supernova explosion SN 1987a in LMC by KAMIOKANDE-II [1,2]) and its immediate corroboration by IMB [3]), I shall mainly discuss item 3 above, which might be called neutrino astrophysics.

Modern astronomy was founded by Galilei in the early 17th century. The development of radar technology during the last world war opened the way for radio astronomy. In the 1960's the X-ray astronomy was born and infrared astronomy is now making a steady growth. These astronomies have given and are giving a great variety of information regarding celestial objects. The signals are, however, all electromagnetic waves and as such they interact with matter rather strongly. This on one hand facilitates detection, but on the other hand electromagnetic waves give information pertaining only to the thin surface of celestial bodies. In order to obtain information on the core of celestial objects, one needs to detect particles which are produced in the core and come out to the surface intact. The required very small interaction implies now the severe difficulty of detecting such particles. The kind of particle we should look for is obviously the neutrino.

The observation of a neutrino burst from the supernova explosion implies thus the birth of an entirely new astrophysics different from the well established electromagnetic astrophysics. The detectors of the above two experiments used for the detection of supernova neutrinos are both of the water Cherenkov type in which the charged particles produced by neutrinos are detected by the Cherenkov light they produce in the water. The hit pattern and the signal arrival time of the photomultipliers installed over the surrounding surface give the information on the production vertex, the direction of motion, and the energy of the particle. The distinction between (γ, $e^{\pm}$) and ($\pi^{\pm}$, $\mu^{\pm}$) is done with better than 90% confidence. Both experiments were originally designed for search of energy liberated in proton decay (1 GeV), and during the last years they both accumulated hundreds of cosmic ray neutrino events. The KAMIOKANDE experiment decided in late 1983 to aim for the observation of ^{8}B decay neutrinos ($\leq$14 MeV) from the sun, and a 4π anti-counter, also of the water Cherenkov type, was installed. Furthermore, with the help of their new collaborators from the US, they installed new multihit electronics (ADC+TCD) (see fig. 1). The upgraded experiment, KAMIOKANDE-II, has began data-taking of solar ^{8}B neutrinos in January 1986. The difficult task of observing low energy electrons elastically scattered by ν_e of energy 10 MeV was well on its way by lowering the effective threshold down to 7.5 MeV [refs. [2,4])].

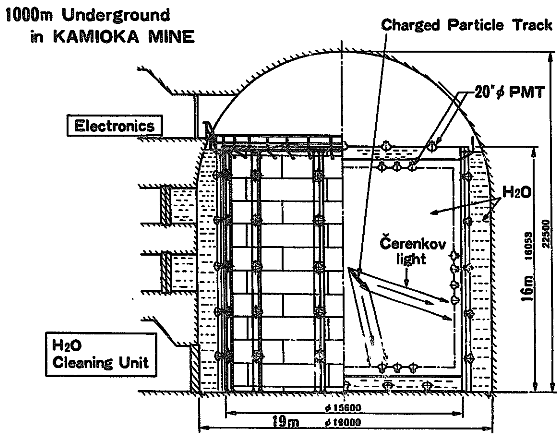

Fig. 1. The detector of KAMIOKANDE-II. The numbers give the dimensions in millimeters.

The KAMIOKANDE-II was thus ready to detect the supernova neutrinos because the expected energy range is about twice that of solar ^{8}B neutrinos and they will be bunched in a time interval of seconds. Furthermore, the expected presence in the supernova of anti-neutrinos will enhance the detection probability by its interaction with protons in the water, which has a cross section 100 times that of ν_e elastic scattering on electrons.

The long waited for signal from a not too distant supernova explosion, after 384 years since Kepler's supernova, did come on February 23, 07:35:35 UT from SN 1987a in the Large Magellanic Cloud (see fig. 2). The signal was immediately confirmed by IMB at 07:35:41 UT and we should take this time as the first signal arrival time because their clock was better calibrated and they detected higher energy events.

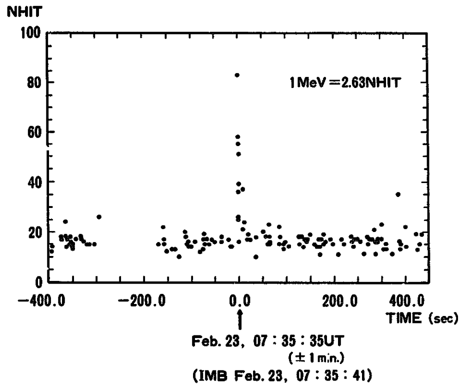

Fig. 2. The supernova signal of the KAMIOKANDE-II experiment. It is a part of the laser printer output of the low energy raw data. Nhit is the number of hit photomultipliers.

The impact of this observation on elementary particle physics and on astrophysics was tremendous and within two weeks more than two dozen preprints of theoretical papers were flowing in. In fig. 3 are shown the claims on the mass of neutrinos some of them deduced from the KAMIOKANDE-II data.

One can see that most of them claim an upper limit for the mass lower than the mass range of the Russian experiment. The situation however is still far from settled and requires further scrutiny before reaching an equivocal conclusion on the mass limit or mass value of the electron neutrino.

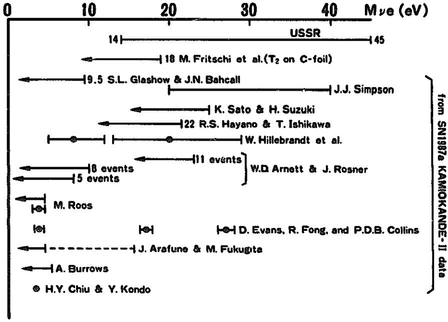

Fig. 3. The estimates of neutrino mass from the KAMIOKANDE-II supernova neutrino data made by various authors. Included also are the two tritium beta-data results at left of the figure.

I will skip solar ^{8}B results because Y. Totsuka [2]) nicely covered the subject in this conference, but I wish to point out that this is the first directional spectral and real-time observation of ^{8}B neutrinos, despite the existence of the pioneering work of R. Davies for which I have the greatest respect.

We then go on to the search for relic elementary particles from the big bang. The searches for monopoles have been done also by large underground detectors and they give the most stringent upper limits to the monopole flux. Fig. 4a shows the present upper limits for the flux as obtained from KAMIOKANDE, IMB, and BAKSAN experiments. They were obtained from the search in their respective detectors for the Rubakov effect, i.e. the catalysis of nucleon decay by a monopole. The search for the Rubakov effect in the sun can be done by looking for neutrinos of energy 35 MeV from the direction of the sun resulting from $\pi^{\pm} \to \mu^{\pm} \to e^{\pm}$ decay of nucleon decays. This way KAMIOKANDE produced orders of magnitude more stringent upper limits for the monopole flux, as shown in fig. 4b. The searches for dark matter candidates and for super symmetric particles were done along a similar approach. Namely we look for the high energy neutrinos from the direction of the sun which is expected if such heavy particles were trapped and annihilated in the sun.

The preliminary results, as of April 1987, of KAMIOKANDE from the analysis of the contained neutrino events, 1.5 to ~15 GeV, from the direction of the sun are:

The mass range 4.5 GeV to 25 GeV is excluded for a Dirac neutrino, the mass range 15 GeV to 27 GeV is excluded for a Majorana neutrino, and the mass range 3 GeV to 15 GeV is excluded for a scalar neutrino. Similar and more stringent restrictions were obtained by the FREJUS experiment, a fine grained calorimeter type detector under the Alps. Namely, for a Dirac neutrino the mass ranges 4 to

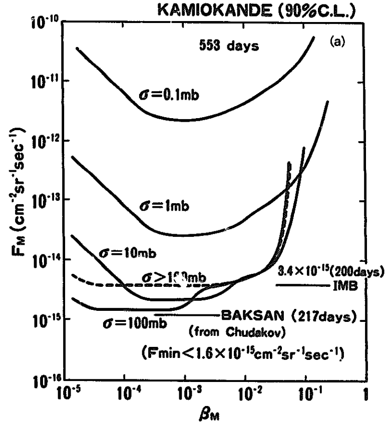

Fig. 4a. The upper limits of Monopole flux obtained by various experiments. The method of search is the Rubakov-effect in the respective detectors.

~32 GeV and >65 GeV are excluded, for a Majorana neutrino the mass ranges 6 to ~32 GeV and >75 GeV are excluded, for a scalar neutrino the mass range >4 GeV is excluded. They give also the excluded mass range of 4 to ~12 GeV for the photino.

Now that the observational neutrino astrophysics is born and the observational particle physics is well on its way, our next task is to develop this new branch of experimental science in the most cost-effective manner. Here we consider two complementary lines of approach; one is to pursue the line of KAMIOKANDE-II and build a much larger detector with a still lower threshold and the other one is to forget about the low-energy events and aim for high-energy neutrino astronomy, and for search of new particles, by building a detector of a really large sensitive area, $>10^4$ m^2, and of detecting mass, 500 000 tonnes.

In both lines of approach, the advantage of the imaging water Cherenkov detector, a large mass of clear water surrounded by large photomultipliers, is obvious and it is at present the only feasible way, technically and economically, to build the next generation detectors of mass ranging in tens of thousands of tonnes.

The first line of approach was first made public in January 1984 in the form of Super KAMIOKANDE [5]). Fig. 5 shows a schematic drawing of Super-KAMIOKANDE. With twice the surface density of phototubes and with a factor of 25 larger fiducial mass as compared with the present KAMIOKANDE-II, the expected performance of Super-KAMIOKANDE is summarized in table 1. Note

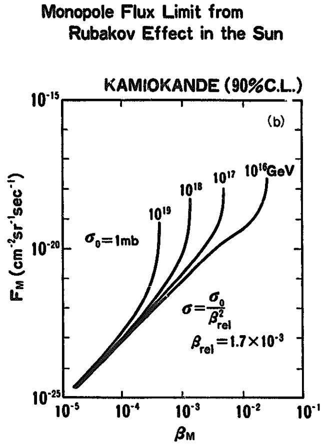

Fig. 4b. the Monopole flux limit obtained by KAMIOKANDE. The method of search here is to look for the neutrinos of energy around 35 MeV from the direction of the Sun; Rubakov-effect in the Sun.

that the expected number of solar ^{8}B neutrino events will allow the monitoring of the solar core temperature with an accuracy of better than 1% every week, because the yield of ^{8}B is very strongly temperature dependent, T^{19}. The cost of this detector is estimated at 40 M$ US plus the excavation cost of 15 M$ US at the KAMIOKA Mine. If such detectors are installed at a number of suitable locations in the world, Super-AMERIKANDE, Super-EUROPEANDE, Super AUSTRALIANDE etc., with a good timing accuracy of say 10 μ sec, any supernova explosion within a million light years will be detected in real-time with an angular accuracy of a minute of arc and thus an advance notice can be given to the astronomical observations at least several hours ahead of any optical activities.

The second line of approach is schematically shown in fig. 6 and is called LENA [6]), lake experiment on neutrino astronomy. The upward going μ's produced by high energy neutrinos in the underlying rock will be detected at a rate of 4000 per year and with an angular resolution better than 1°. It can also observe, with an angular accuracy well below 1°, the high-energy γ-ray showers very clearly and well separated from the large background of cosmic ray hadronic showers. This is possible because the lower detector covering almost the entire sensitive area can detect all the muons contained in the shower. The Monte Carlo simulation of γ-proton separation is shown in fig. 7. The simultaneous observation of high energy γ-rays and high energy

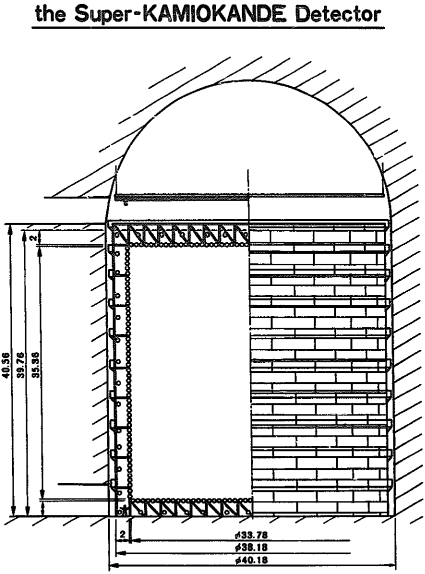

Fig. 5. The Super-KAMIOKANDE detector. The dimensions are given in meters. Compare the size with a human figure at the left lower corner of the detector.

ν by the same detector is of crucial importance in observing, for instance the radio-outburst period of Cyg-X-3.

The cost of such a detector is 4 M$ US plus the cost of a water reservoir of 150 m diameter and of <35 m depth. This type of experiment seems quite appropriate in training young graduate students, even undergraduates, in countries where the access to a present day gigantic accelerator complex is not easy, geographically and/or economically. The experiment is not too expensive, can be installed in the neighborhood, is simple in structure with one type of sensor, and does not require a large number of collaborators. Still younger people can get trained in particle physics, nuclear physics, astrophysics, cosmology, and in fast electronics as well as in data-taking/data-analysis by computer. The installation of LENA's at various locations over the world would be nice because each would look at a different part of the sky.

TABLE 1
Expected performance of the Super-KAMIOKANDE detector

	Sensitivity
Test of GUTs	
nucleon decay	$\tau/B \leq 10^{33} \sim 10^{34}$ y
n-n̄ oscillation	$T_{n\bar{n}} \leq 10^{33}$ y
magnetic monopoles	$F_M \geq 10^{-23}$ cm^{-2} s^{-1} sr^{-1}
neutrino oscillation	$\delta m^2 \geq 10^{-4} \sim 10^{-11}$ eV^2 $\sin^2(2\vartheta) \geq 0.2$
Neutrino astronomy	
ν's from stellar collapse	$\sim 10^4$ eV/10 kpc
ν's accumulated from the past stellar collapse	≥ 50 cm^{-2} s^{-1}
solar ^{8}B νe	~ 2900 eV/y
ultra-high energy ν from point sources	$\geq 10^{-9}\ E_{\mathrm{TeV}}^{-2.1}$ cm^{-2} s^{-1} TeV^{-1}

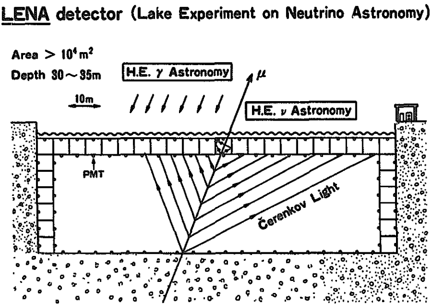

Fig. 6. The LENA detector.

The improvement of the 20″∅ photomultiplier is also on its way. As of March 1987, the following improvements are seen: (i) time jitter at 1 photoelectron level measured to be 4.67 nsec FWHM, (ii) a good single photo-electron peak is expected because photo-electron collection efficiency is improved from 43% to 80%; (iii) tube length shorter by about 20 cm, and (iv) production rate can be increased from the present 200 tubes per month to 500 tubes per month.

In conclusion, observational neutrino astrophysics is born and observational particle physics is well on its way. Let us build the world network of Super-Neutrino Detecting Experiments and of LENA and proceed into the 21st century.

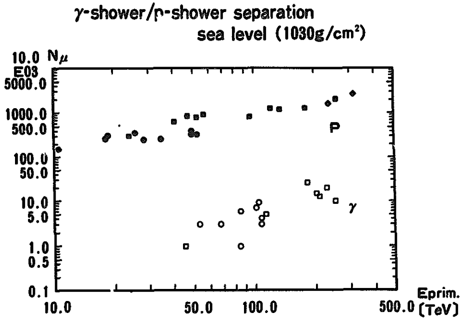

Fig. 7.

The author acknowledges his thanks to Profs. Fiorini, R. Barlouteaud and A.E. Chudakov for communicating to him the latest results of their respective experiments.

References

1) K. Hirata *et al.*, Phys. Rev. Lett., 58 (1987) 1490
2) Y. Totsuka's talk in this conference
3) R.M. Bionta *et al.*, Phys. Rev. Lett. 58 (1987) 1494
4) A. Suzuki, Proc. of Neutrino'86, Sendai, June (1986);
T. Kajita, Moriond Conf. March (1987);
N. Nakahata, 8th Workshop on Grand unification, Syracuse, April (1987)
5) M. Koshiba, Talk at ICOBAN'84, Park City, Utah, January (1984);
Y. Totsuka, Proc. of Workshop on Future Plans, KEK Report 85-6;
M. Koshiba and S. Orito, KEK Workshop, August (1986)