# EXPERIMENTAL SEARCH FOR NEUTRINO BURSTS FROM COLLAPSING STARS: POSSIBILITIES AND PLANS*

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## I . Introduction

Existence of stars with their matter density of the order of nuclear one, so called neutron stars, may be considered now as a real fact established from studying pulsars. Less definitely but with some certainty we can speak about an experimental discovery of black holes. Both, neutron stars and black holes must appear as a result of gravitational collapse of stars at the last stage of their evolution.

Up to now only after-effects of supposed gravitational collapse of a star were possible to observe but not the collapse itself. Association of a gravitational collapse with a supernova explosion is not inevitable though it is attractive from energy considerations. For instance, one can imagine a gravitational collapse without envelope explosion and, consequently, without an observed supernova outburst, but on the other hand one can not exclude the possibility that some supernovas are not associated with gravitational collapse at all.

The most direct observation of a gravitational collapse of a star could apparently be an observation of neutrino bursts accompanying the collapse. Neutrino radiation of a collapsing star is not a collateral process but it determines the dynamics of a gravitational collapse. In process of a collapse the main portion of gravitational energy release must turn into a neutrino radiation. An experimental observation of neutrino bursts could obviously be of importance for a wide range of problems associated with the last stage of evolution of massive stars and black holes and also for the gravitational collapse itself .

## II. Neutrino burst characteristics and necessary parameters of the detector

To discuss the experiment the following characteristics of a neutrino burst are essential:

1. Total energy flux carried by different neutrinos in the process of gravitational collapse of a star.
2. Energy spectrum of neutrinos.
3. Time distribution of neutrino radiation.
4. Expected frequency of bursts.

Calculations made in recent years (D. K. Nadyozhin, 1975; J. R. Wilson, 1975) advanced to some extent the problem of prediction of neutrino bursts characteristics, at least comparing to the state of the problem in 1965 when Domogatsky and Zatsepin proposed an experiment based on conceptions of that time (Ya. B. Zel'dovich, 1965). Now it is clear that a gravitational collapse is rather complex phenomenon and depends

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on composition and state of a star before collapse. Great difficulties arise when taking into account rotation of a star. For further discussions we shall take, according to paper (G. V. Domogatsky, 1977), the following parameters of a $\nu$-burst.

1. The energy flux of all neutrinos - $5 \cdot 10^{53}$ *erg* ( for collapsing mass 2 $M_{\odot}$). (Apparently, the total energy flux does not strongly depend on the mass of a star if collapse is possible). The energy is approximately equally distributed between different types of neutrino, and for electron antineutrinos it amounts to $1.3 \cdot 10^{53}$ *erg*.

2. The energy spectrum of neutrinos is practically thermal with $T \approx 5 \cdot 10^{10}$ $K$, $< E_{\nu} > = 12$ *MeV*.

3. The burst duration turns out to be expanded up to - 20 *sec* due to neutrino non-transparency of a star. (This duration, perhaps, will be reduced for 10 $M_{\odot}$), but on the other hand it can increase when taking into account a star rotation). After reaching the maximum at 0.03 *sec* after the beginning of the collapse neutrino flux decreases as ~ $t^{-2/3}$ and falls to zero at $t$ ~ 25 *sec*.

If fluxes of electron neutrinos and antineutrinos have similar values and the mean energy $< E_{\nu} > \approx 12$ *MeV* then the reaction

$$\tilde{\nu}_e + p \rightarrow n + e^+ \qquad (1)$$

is the most important for recording a neutrino burst by electronic methods. Either water or $CH_2$ - scintillator is used as a hydrogenous target in the experiments being under way. For neutrino energy spectrum

$$\frac{dN}{dE_{\nu}} \propto \frac{E_{\nu}^2}{1 + e^{E_{\nu}/kT}} \ , \qquad T \sim 5 \cdot 10^{10} \ K \qquad (2)$$

and for equal numbers of neutrinos and antineutrinos the contribution of $\nu_e + {}^{12}C$ or $\nu_e + {}^{16}O$ reactions is less than 1%. It is also possible to neglect excitation reactions of ${}^{12}C$ or ${}^{16}O$ atoms (neutral currents) and neutrino-electron scattering ($\nu_e e$).

The result of reaction (1) is a fast positron with energy practically equal to that of neutrino. For the great detector mass, which is the case to be considered, a positron is completely absorbed by the scintillator and the light signal amplitude is proportional to a neutrino energy. The same situation in the first approximation is for Cherenkov flash in water, only the absolute value of the light signal is by an order of magnitude less. A single pulse corresponding to an energy release $10 \div 20$ *MeV* by no means can be attributed to neutrinos in the presence of real cosmic ray and local radioactivity background. The idea of the experiment (Domogatsky, 1965) lies in observation of a group of pulses and that requires several (preferably many) pulses to be recorded over time period corresponding to a burst duration. This requirement determines the basic parameters of the detector - mass, energy sensitivity, and acceptable background.

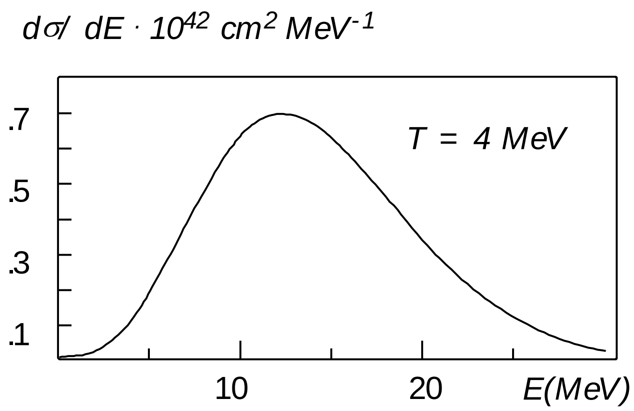


Fig. 1 Pulse amplitude distribution in detector due to the reaction $\tilde{\nu} + p \to n + e^{+}$.

Fig. 1 shows the expected energy release distribution in the detector due to reaction (1) for incident neutrino spectrum (2) which is corrected by a factor $exp\left(-0.04\left(E_{\nu}/kT\right)^{2}\right)$ ; this cut off term was obtained in calculations of the process of neutrino escaping from the collapsing star. The plot corresponds to the temperature *kT* = 4 *MeV* (Domogatsky, 1977).

It can be seen from fig. 1 that the most significant amplitudes lie in the range 10 ÷ 20 *MeV*.

If the detector has an energy threshold $E_0$ and contains *N* hydrogen atoms the total number of pulses produced in the detector by a neutrino burst at the distance *R* from the Earth will be

$$K = \frac{1.3 \cdot 10^{53} \cdot 0.6 \cdot 10^{6} MeV}{< E_{\nu} > MeV} \cdot \frac{N_p}{4\pi R^2} \int_{E_0}^{\infty} \frac{d\sigma}{dE} dE \qquad (3)$$

where $< E_{\nu} >$ is the mean energy of the neutrino spectrum and *R* is the distance to a star in *cm*.

The total number of counts *K* must have a time distribution proportional to a temporal behaviour of neutrino radiation.

An expected number of counts in a hypothetical detector (mass - 100 tons of $CH_2$, threshold $E_0$) over time $\tau$ after the beginning of a burst from the Galaxy centre is presented in table 1. In the model used the time interval 25 *sec* corresponds to the total neutrino flux.

Table 1

| $E_0$ | $\tau$ *(sec)* | | | | |
|---|---|---|---|---|---|
| *(MeV)* | 0.01 | 0.1 | 1 | 10 | 25 |
| 5 | 0.23 | 4.0 | 14.5 | 38 | 55 |
| 10 | 0.17 | 3.0 | 10.9 | 29 | 41 |
| 15 | 0.09 | 1.6 | 5.7 | 15 | 22 |
| 20 | 0.04 | 0.6 | 2.2 | 6 | 8.5 |

From table 1 we can conclude that the detector mass 100 tons is rather characteristic for recording of gravitational collapses in our Galaxy. Choice of an optimal energy threshold is largely determined by background conditions which depend on mine depth, radioactivity level of the detector itself and its environment, and on the detector energy resolution. For a scintillation detector with a moderate shield and mass of 100 *t* one can probably recommend $E_0$ = 10 *MeV* and in this case the number of background counts is expected to be $n \leq 0.1$ per second. If we consider the last column of table 1, i. e. adopt *K* = 41 and $\tau$ = 25 *sec* then obviously an imitation of such an event by Poisson fluctuations is practically impossible. If the detector characteristics are worse and the threshold is chosen to be, say, 15 *MeV*, $K = 22$, then with the background level $N = 0.1$ the imitation probability is still small, ~ $10^{-3}$ per year. It is interesting that despite a sharp fall of the adopted time dependence of $\nu$-radiation the optimal integration time proves to be large, ~ 20 *sec* which is close to the total time 25 *sec* (Domogatsky, 1977). However, it should be noted that if the burst is reliably recorded within the time interval 20 *sec* then "a posteriori" one can determine its beginning moment with better accuracy, ~ 0.l *sec*. It can be seen from table 1 that in order to reach an accuracy 0.01 *sec*, i. e. to obtain significant delay at the distance of the order of the Earth radius, it is necessary to increase the detector mass by one or two orders of magnitude . Though sharp spikes are unlikely to be present within a neutrino burst and consequently it is difficult to determine the direction of the burst from delay at a distance available on the Earth we should emphasize the absolute necessity of synchronous measurements by completely independent installations. The fact is that the method of recording of extremely rare events in the form of a group of pulses can not completely eliminate an imitation of the signal by an electronic instrumentation effects. Only simultaneous observation by 2, or even better 3, independent detectors will be rather convincing.

4. Expected frequency of neutrino bursts.

In the first approximation this value should be estimated from frequency of supernova explosions. The frequency of "soundless" collapses can apparently be of the same order of magnitude (Zel'dovich, 1971). According to recent estimates (Tammann, 1976) the frequency of supernova explosions in our Galaxy is ( $0.07^{+0.06}_{-0.04}$ ) per year. Sufficient increase in the number of supernova outbursts can be expected only if we increase the radius of observation by almost 1000 times. But in case of neutrino burst recording this would mean an increase of the detector mass by more than million times. "More" means that together with the detector mass the background will also increase. Fig. 2 shows the expected frequency of recorded neutrino bursts as a function of the detector mass. The threshold energy was taken to be $E_0 = 10$ *MeV* and the necessary number of counts in a series $K = 20$. It can be seen from the figure that even for such unlikely parameters, for the case of great mass, an increase of expected frequency of $\nu$ - burst by recording them from the outside of the Galaxy is unrealistic. Thus, the range of observation of gravitational collapses of stars is practically restricted by limits of our Galaxy. In this case the experiment will take very much time, may be decades of years will be necessary for acquiring essential experimental data, but mass of the detectors will be in reasonable range, 100 ÷ 1000 tons. As we have mentioned above, it is absolutely necessary a simultaneous operation of independent detectors with rather high sensitivity. Taking into account that it is

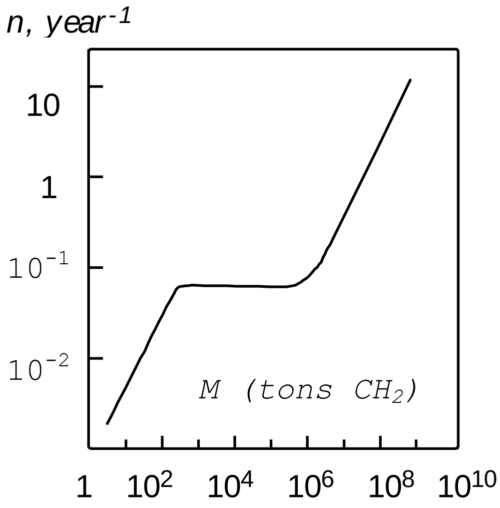


Fig. 2 Expected frequency of neutrino bursts with size bigger than 20 pulses in the detector versus detector mass

desirable to locate detectors in remote points of the globe it is expedient to organize this observation in different countries in frames of international cooperation. Now the work on design of Cherenkov detectors is under way in Pennsylvania University (USA) and scintillation detectors are now being designed in the Institute for Nuclear Research of the Academy of Sciences of the USSR. Cooperation is also taking place with Cosmogeophysics Laboratory in Turin (experiments in tunnel under Mont Blanc); possibilities of performing experiments in deep mines in India and Brazil are now being discussed. In the following paragraph we shall present a description of some detectors, both already operating and to be put into operation in the nearest future.

## III. Cherenkov detectors of Pennsylvania University

By these detectors observations have been performed since 1972 (K. Lande, 1974), though the total mass of the target was not great, of the order of tens of tons. The detectors consist of standard modules containing 2 $m^3$ of water each. Into preliminary refined water a redshifter is introduced which increases the photomultiplier signal amplitude by a factor of 4. But still the signal is rather small and one has to use a coincidence method at the one-electron-pulse level. For this purpose each module is viewed by 8 photomultipliers. The threshold signal is taken as that corresponding to 5-fold coincidence of this group of photomultipliers. In this case an estimated threshold sensitivity is 15 *MeV*. Five of these Cherenkov detectors are mounted in the chamber under Mont Blanc. Similar detector groups are operating at a comparable depth of 4000 m. w. e. in two places in the USA: in mines in states S. Dakota and Ohio.

The main shortcoming of Cherenkov detectors - relatively high energy threshold and low energy resolution. The latter may lead to an inadmissible background increase due to local radioactivity when energy threshold is reduced. If it is not possible to reduce the energy threshold of the detectors of this type then a required sensitivity can be achieved by increasing the total mass of a target. In case of the neutrino spectrum form under discussion this increase, according to table 1, should be by a factor of 5 for energy threshold 20 MeV as compared to the threshold of 10 MeV. The main advantage of Cherenkov detectors as compared to scintillators is their fire safety which simplifies and makes easier their operation in mines. The team of Pennsylvania University plans to increase in 1977 the total mass of the target up to 500 tons.

## IV. 2 $m^3$ scintillation detectors of INR. Mont Blanc

Liquid scintillator on the basis of "white-spirit" with an admixture

of 1 *g/litre* of PPO and 0.03 *g/litre* of POPOP is placed in a stainless

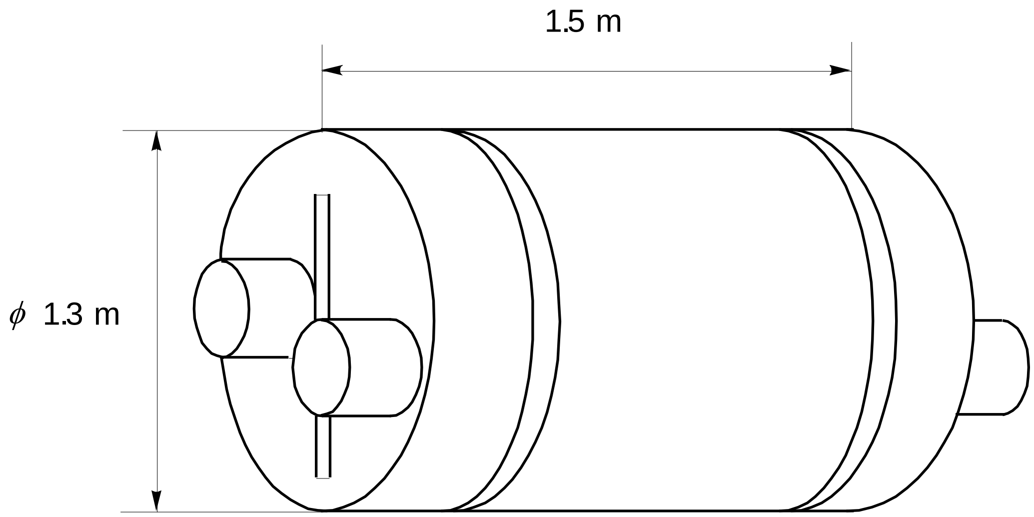


Fig. 3   2 $m^3$ scintillation detector

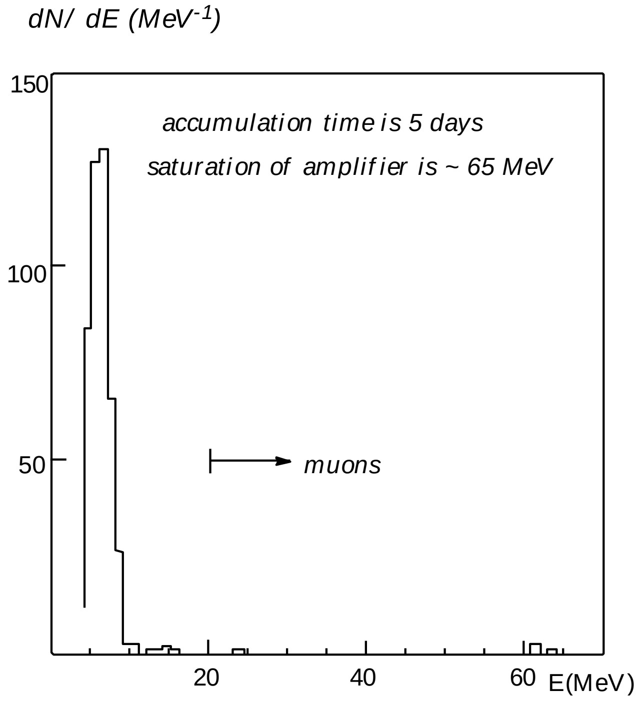


Fig. 4 Differential energy spectrum from one detector measured during 5 days. Threshold is about 6 *MeV*

cylindrical container and viewed through end faces by 4 photomultipliers. The inner surface of the container is covered with a white enamel deposited on aluminium foil. Two detectors are now being tested in the tunnel under Mont Blanc (Fig. 3). The whole arrangement will contain 60 such detectors with the total mass of $CH_2$ 100 tons (1978 - 79). The energy resolution of one module is rather good which enables with the threshold of 10 *MeV* practically completely to eliminate the radioactive background. 60 electrons from a photocathode of one PM-tube and 240 electrons from 4 ones correspond to an energy release 10 *MeV* in a detector. Fig. 4 shows the differential amplitude spectrum of one detector measured over 120 hours with the threshold equivalent to an energy release of 6 *MeV*. All the pulses with energy exceeding 20 *MeV* are due to cosmic ray muons (at a depth of 600 m. w. e. muon intensity is very low and ~ 1 muon per 24 hours passes through the detector). Let us also note that only 5 events with energy higher than 8 *MeV* are observed over 24 hours time. On the basis of this plot one can conclude that for 60 similar detectors an expected count rate of events with energy higher than the 6 *MeV* threshold will not exceed 0.1 *pulse/sec*.

**V. 100-tons scintillation detector of INR. Artyomovsk**

That is a big stationary detector the design of which differs from that just described only by dimensions and number of photomultipliers; in this case their number is 128 and they are arranged on the circular

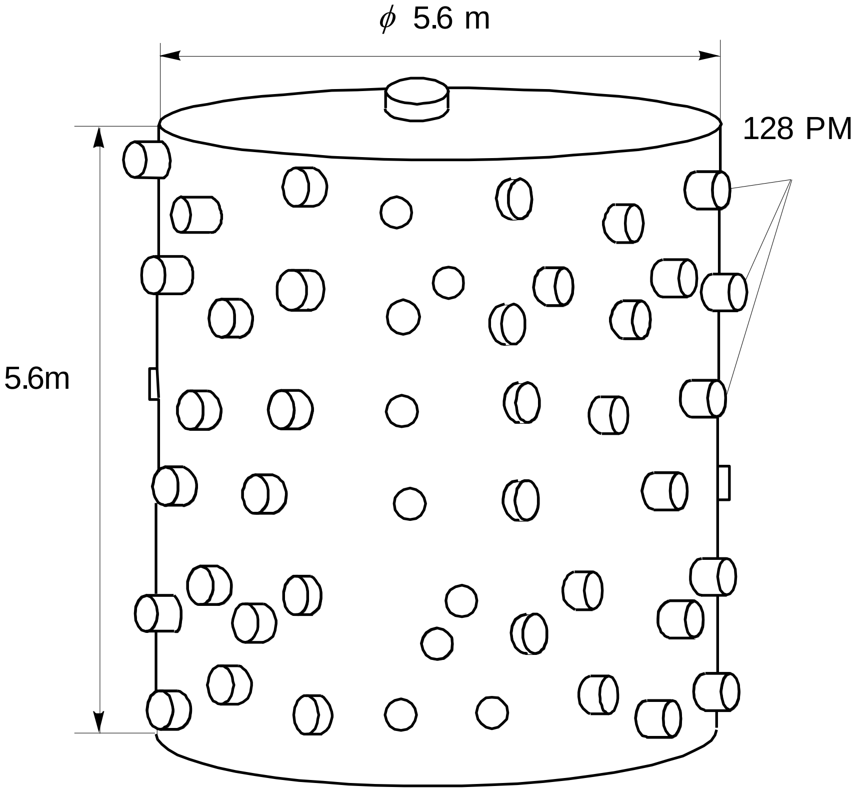


Fig. 5 100 tons scintillation detector

vertical surface of the cylinder (Chudakov, 1973). The detector is mounted in a salt mine with a low level of radioactive background but at a small depth of 600 m. w. e., so that muon background is rather high, ~ 5 $sec^{-1}$. The main portion of this background can be eliminated by an upper level amplitude discrimination of the signal. Discrimination in the energy range 5 $MeV < E < 30$ $MeV$ will result in the expected background from traversing muons less than 0.1 $sec^{-1}$. The detector (Fig. 5) is to be put into operation in 1977. For amplitude discrimination in both small detectors and a big one the method is used in which the signal summed over several photomultipliers is fed into a discriminator to pass to the output only when a coincidence between several photomultipliers occurs. In case of the big scintillation detector phototubes are arranged in four groups with 32 each. Signals from photomultipliers of each group are summed, amplified and fed into a 4-fold coincidence circuit the signal from which is a "permission" for an amplitude measurement. This allows to obtain a high energy resolution and eliminate cases when a low energy-release near one of the photocathodes produces a big signal in a given photomultiplier. An energy release of 10 *MeV* corresponds to 3-4 photoelectrons in one photomultiplier or 450 electrons in all of them. For better identification of antineutrino events there is a hope to realize a recording of neutrons produced by antineutrino - hydrogen interaction. A neutron diffusing in a scintillator is trapped by hydrogen with $\tau = 170$ $\mu sec$ and 2.2 *MeV* $\gamma$-quantum is emitted. For recording of such $\gamma$-quanta the threshold was reduced down to 1 *MeV* over 680 *μsec* after an arrival of the pulse corresponding to an energy release greater than 5 *MeV*.

The recording system incorporates a memory which allows to record an amplitude and time of arrival of 270 pulses. With the background level of 0.1 *pulse/sec* this memory can operate over 40 minutes. The information received is fed into a teletype or a tape-recorder. The reduction of time intervals in a pulse series as compared to the Poisson distribution is assumed to be a control signal. Now the control signal is the presence of 3 pulses within 0.3 sec interval. After such an event the information concerning all the pulses arriving during 1 min after the control pulse is recorded and then output of all the information stored over 40 minutes is performed.

**VI. Scintillation telescope. INR. Baksan**

This apparatus unlike the aforementioned, is not specially destined for search of neutrino bursts but can be used for this purpose together with the basic program of investigation of high energy muons and neutrinos in cosmic rays (A. E. Chudakov, 1977). The scintillation telescope is placed in a big chamber under a mountain slope at a depth corresponding to 850 m. w. e. The chamber is covered from inside with a

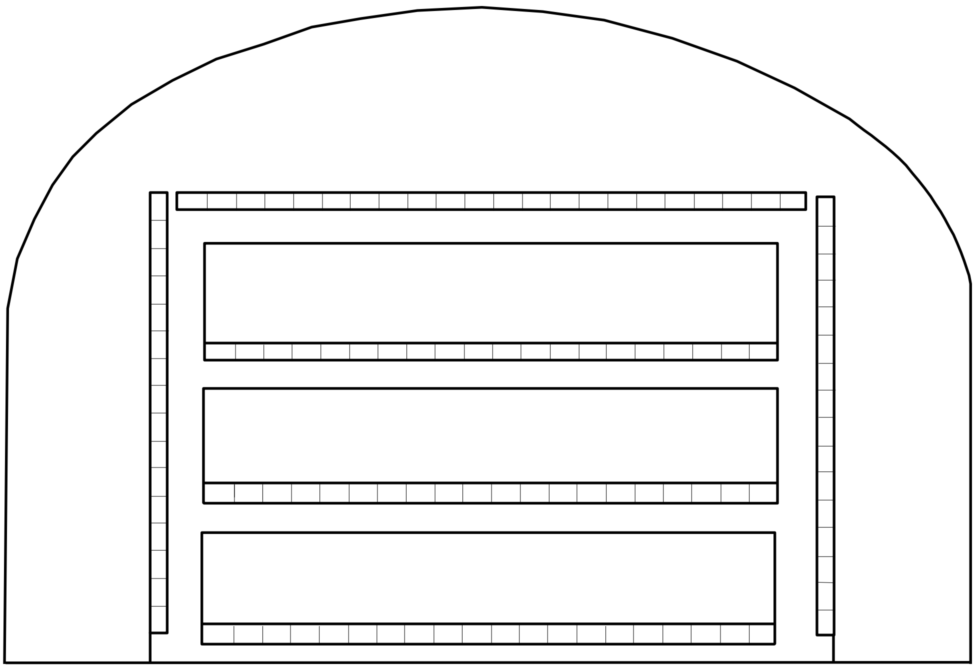

Fig. 6 Section view of the scintillation telescope at Baksan Neutrino Observatory, INR

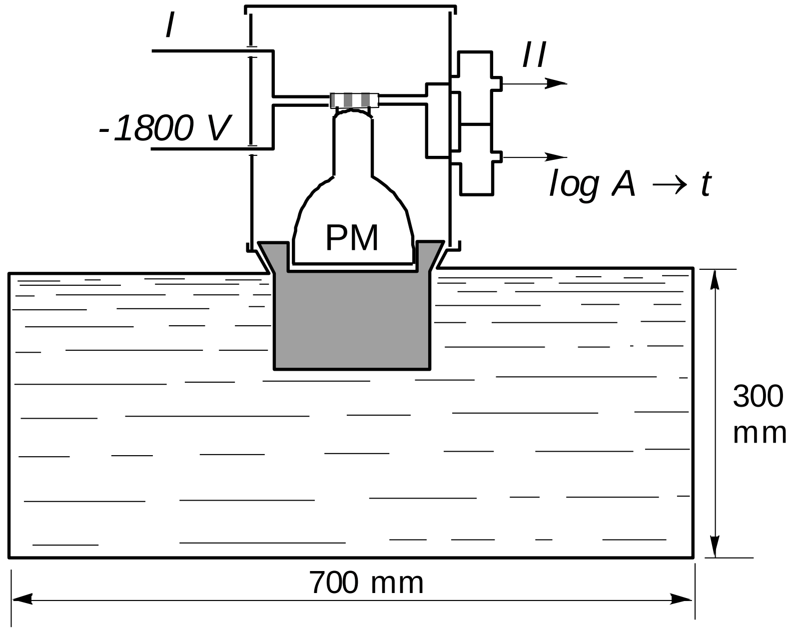


Fig. 7. The standard detector of the 3150 channel telescope

low radioactivity concrete which reduces the radioactive background from rocks by a factor of 20. The telescope itself consists of 8 recording layers each composed of standard 0.7 x 0.7 x 0.3 m detectors filled with a liquid scintillator similar to that used in previous experiments. Recording layers form a parallelepiped with dimensions 16 x 16 m and 11 m high with two horizontal planes inside the parallelepiped.. The section of this apparatus is shown in Fig. 6. The total number of standard detectors is 3150 and the total scintillator mass exceeds 300 tons. The scheme of the standard detector is shown in Fig. 7. It comprises one photomultiplier, 105 kg of liquid scintillator $CH_2$ and can provide an information over three channels:

1) linear output from a photomultiplier anode, the signal from which is then summed over the whole layer (400 detectors) and also over the whole telescope,

2) an individual signal from the last photomultiplier dynode with a discrimination level 10 *MeV*,

3) logarithmic amplitude-time converter (the signal from the 5th dynode) for measuring high energy release. The first and second channels can be used for detection of neutrino bursts, whereas the third one with a high threshold has nothing to do with $\nu$-bursts recording.

This detector has a high energy resolution. An energy release of 10 *MeV* produces 500 photoelectrons. The background created by cosmic-ray muons is rather high, 15 $sec^{-1}$ (for the whole apparatus) which is absolutely inadmissible, but it can be discriminated by at least three methods:

1) an upper level amplitude discrimination (1st channel, linear output);

2) a veto when coincidence between different layers occurs (channel 1);

3) an exclusion of detectors placed along edges of the parallelepiped (channel 2). The last method reduces the total number of detectors by 236 or 7% but excludes the possibility of a small energy release, produced by a penetrating particle, imitating a neutrino signal. An assumed amplitude "gate", according to table 1, is chosen to be from 10 to 50 *MeV*. A lower level discrimination is possible in both the 1st and 2nd channels. In the latter case the threshold is specified and is equal to 10 *MeV*. With such

discrimination a requirement is valid that in a given moment one and only one standard detector must operate. The use of above mentioned methods will allow to reduce the background from muons traversing the apparatus by approximately 3 orders of magnitude. Then other sources of background will become more essential: radioactivity and $\delta$-electrons from muons not traversing the apparatus (for outer layers only). Preliminary estimates enable to expect the total not-eliminated background of the apparatus in the range 10 - 50 *MeV* to be ~ 0.1 $sec^{-1}$. Recording of events which are candidates for neutrino bursts is assumed to be performed in the following way. A group of pulses left after aforementioned

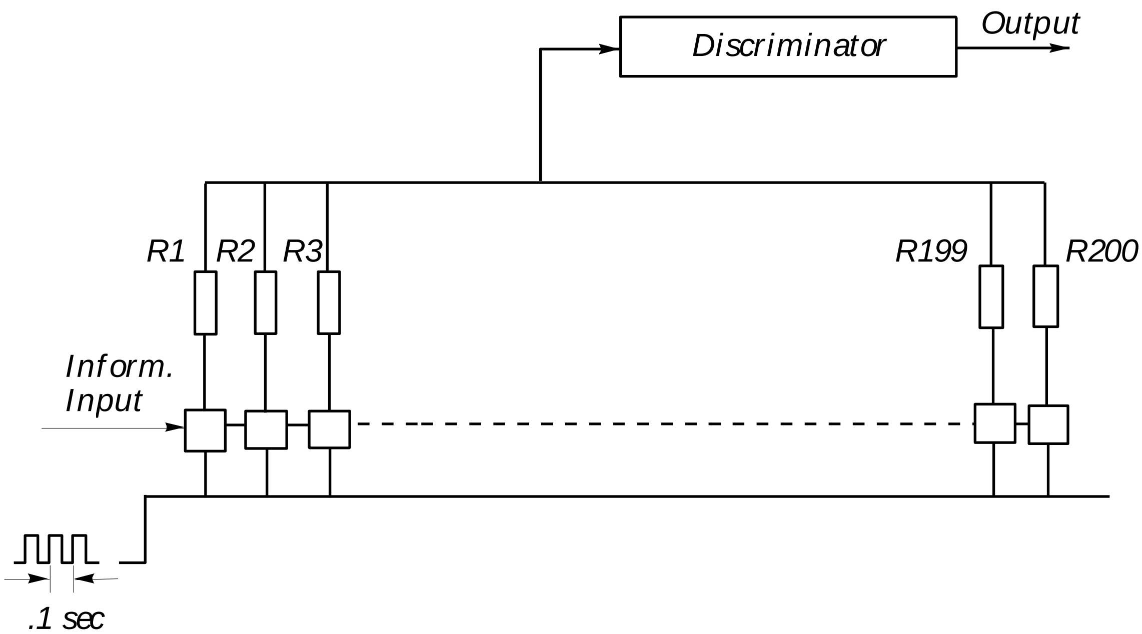


Fig. 8. Circuit of the sliding time gate

discrimination is fed into a shift register which shifts the information to the right with a tact frequency 10 *Hz*. The register consists of 200 cells and in a given time stores the information obtained during 20 *sec*. If the resistors *R1* - *R200* in Fig. 8 are equal a definite number of units held in a given moment in the shift register will correspond to a certain discrimination level of the summator signal. In other words we obtain a "sliding" time gate. It is interesting to note that by this method we can obtain not only a rectangular time gate, but the gate of an arbitrary shape. To get an optimal filter in our case when an expected intensity of bursts drops sharply within 25 sec the resistors values must monotonously decay from the beginning of the register to its end. This shift register is only a trigger for storage (by computer) more complete information "in the region" of a given moment. Depending on the real background, a discrimination level for a storage command is convenient to be adjusted in such a way that several imitations per 24 hours due to Poisson fluctuations will be recorded. Search for true events must, as it was mentioned above, be done by investigation of the correlation between independent apparatuses.

The programme of observing neutrino bursts by the scintillation telescope is to begin in 1978.

In conclusion we would like to note that none of the apparatuses described is optimal from the point of view of long-term observation, of gravitational collapses in our Galaxy. An optimal detector must, to our mind, have the following characteristics:

1. Mass ($CH_2$ or $H_2O$) - 300 *tons*.
2. Energy sensitivity with a 90% efficiency - 10 *MeV*.
3. Background level - 0.01 $sec^{-1}$.
4. Number of photomultipliers - 300.

To realize these characteristics one has evidently to choose:

a) target material - liquid scintillator ($CH_2$),
b) depth - 4000 m. w. e.,
c) shielding from local radioactivity of rocks,
d) mass of a single module - 2-20 *tons*.

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