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Search for stellar gravitational collapses with the MACRO detector

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Abstract. We present the final results of the search for stellar gravitational collapses obtained by the MACRO experiment. The detector was active for a stellar collapse search for more than 11 years and it was sensitive to collapses occurring all over in our galaxy for 8.6 years. A real time system for a prompt recognition of neutrino bursts was developed and was operating on-line for almost the whole life of the experiment. No signal compatible with a neutrino burst from a galactic supernova was observed.

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1 Introduction

The ending stage of massive stars ($M \gtrsim 8\ M_{\odot}$) is the gravitational collapse (GC) of their iron cores. The collapse of the stellar core stops when its central density becomes larger than that of nuclear matter; the elastic bounce of the core is thought to produce a shock wave, which expels the external layers of the star into space, generating a supernova explosion. Detailed reviews of the mechanism of gravitational collapse have been published by many authors [1–3].

The core collapse supernovæ (type II and Ib) are powerful sources of neutrinos of tens of MeV energy. The detection of neutrinos from SN1987A by the Kamiokande II and IMB [4,5] and probably by the Mt. Blanc and Baksan detectors [6,7] confirmed the main features of supernova models, showed that supernova neutrino astronomy is a practical possibility and gave an indication of the amount of information which could be extracted from a galactic stellar collapse.

MACRO was a multipurpose underground detector [8, 9] located in Hall B of the Gran Sasso National Laboratory and optimized for the search for heavy magnetic monopoles [10] and other rare particles [11]. It had also very good capabilities for studying atmospheric neutrino oscillations [12] and cosmic rays [13], to search for astrophysical point sources (neutrino astronomy) [14], for neutrinos from stellar gravitational collapses [15,16] and others [17]. The apparatus was assembled in a modular structure; it had overall dimensions $76.5 \times 12 \times 9.3$ m^3 and was made of three sub-detectors: liquid scintillation counters, limited streamer tubes and nuclear track detectors. The detector capabilities for GC neutrino physics, the first results of the supernova search and the description of the real time alert system were published in [15, 16]. The MACRO detector became active as a supernova observatory in November 1989 and reached sensitivity to the entire galaxy at the end of 1992; it was turned off in December 2000.

In this paper we present the results of the search for GC neutrino bursts during the period from February 1st, 1992 to December 19th, 2000 (the end of the data taking) and we summarize such results for the whole operational life of the experiment.

2 Neutrino bursts from stellar gravitational collapses

Many numerical models have been developed over more than 30 years (see for instance [3,18–21]) to derive the main properties, like energy spectra and luminosity profiles, of the supernova neutrinos. During the collapse, almost all the binding energy of the star ($2 \div 4 \times 10^{53}$erg) is radiated away in form of neutrinos. The neutrino emission can be divided into three stages: neutronization, matter accretion and neutron star cooling. The first phase produces a pure ν_e burst, of few ms duration, with a total energy $\sim 2 \times 10^{51}$ erg. In the second and third phase neutrinos and antineutrinos of all flavours are emitted, with a time scale of ~ 10 s. About 99 % of the total energy of the star is released in these two last stages, approximately equipartitioned between all neutrino flavours. Note that, as predicted by most SN models and confirmed by the SN1987A neutrino signal, about 70 % of the neutrinos are emitted during the first 2 s after the core bounce.

Neutrinos of different flavours have a different coupling with stellar matter: ν_μ, ν_τ and their antineutrinos (collectively indicated by ν_x) interact via neutral current reactions only, while ν_e and $\bar{\nu}_e$ interact via charged and neutral current processes; then, the non electron neutrinos and antineutrinos decouple first, deeper within the core, and emerge with higher energy. Moreover, since the neutronization stage makes the stellar core richer in neutrons than in protons, the charged current reaction rate is lower for $\bar{\nu}_e$ than for ν_e. As a result, the ν_e's have the lowest mean energy and the ν_x's the highest; some indicative values are [22,23]:

$$\langle E_{\nu_e} \rangle \approx 12 \text{ MeV} \tag{1}$$

$$\langle E_{\bar{\nu}_e} \rangle \approx 15 \text{ MeV} \tag{2}$$

$$\langle E_{\nu_x} \rangle \approx 25 \text{ MeV} \tag{3}$$

The observation of neutrinos from SN1987A confirmed some of the general predictions of the supernova neutrino models, like the total energy emitted in $\bar{\nu}_e$ and the average $\bar{\nu}_e$ energy. A simplified modeling of SN1987A can be found in [24].

3 GC neutrino detection in MACRO

MACRO was able to detect low energy neutrinos through their interactions with liquid scintillator. The dominant reaction is $\bar{\nu}_e + \mathrm{p} \;\rightarrow\; \mathrm{n} + e^+$. The emitted neutron, after being moderated in the scintillator, is captured by a proton, forming a deuterium nucleus: $\mathrm{n} + \mathrm{p} \rightarrow \gamma + \mathrm{d}$. The average capture time is $180\,\mu$s and the γ energy is 2.2 MeV. The photon detection could provide a further signature for a GC $\bar{\nu}_e$ induced event. The capability of the MACRO counters to detect the neutron capture on proton was experimentally demonstrated by means of an Am/Be source [25]. The neutron capture signature was not used in this analysis.

The expected signal from a GC at the galactic center (8.5 kpc) is ~ 200 $\bar{\nu}_e\,\mathrm{p}$ interactions in the 570 ton of the MACRO liquid scintillator, for a threshold on the detected positron energy of ≈ 7 MeV. Less significant, but still detectable, are the neutrino elastic scattering on electrons, $\nu_x + \mathrm{e}^- \rightarrow\; \nu_x + \mathrm{e}^-$, and the neutral current reactions on carbon, $\nu_x + {}^{12}\mathrm{C} \;\rightarrow\; {}^{12}\mathrm{C}^* + \nu_x$, followed by the electromagnetic ${}^{12}\mathrm{C}^*$ de-excitation, with a 15.1 MeV γ emission. The additional contribution from the above two processes is of

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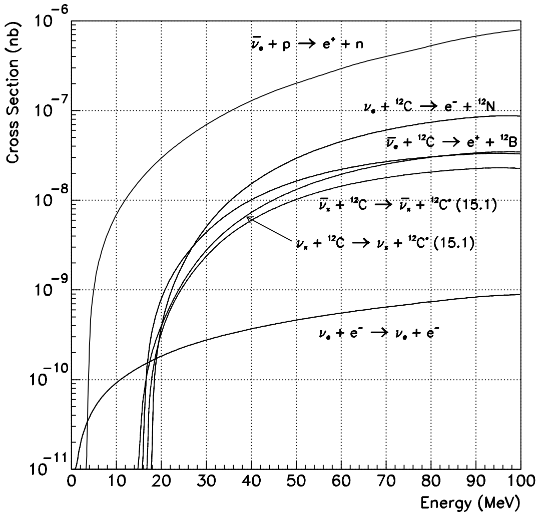

Fig. 1. Neutrino and antineutrino cross-sections on carbon nuclei [26], protons [27] and electrons [27]

the order of $10 \div 15$ events. An almost negligible contribution comes from the charged current reactions on carbon nuclei: $\nu_e +^{12}\mathrm{C} \rightarrow \mathrm{e}^- +^{12}\mathrm{N}$ and $\bar{\nu}_e +^{12}\mathrm{C} \rightarrow \mathrm{e}^+ +^{12}\mathrm{B}$; even if very rare, because of the high energy threshold ($\sim$ 15 MeV), these reactions have a very clean signature, since the primary process is followed, within $\sim$ 20 ms, by the β decay of the product nuclei.

The cross sections for all processes discussed here are shown in Fig. 1.

A summary of the total number of events expected in MACRO from a supernova at the Galactic Center is presented in Table 1 for the gravitational collapse model of ref. [23]. In this calculation the response of the liquid scintillation counters to low energy neutrinos was completely simulated. The expected signal has been evaluated by using the final scintillator mass of 570 ton and two energy thresholds: the 7 MeV hardware energy threshold and the 10 MeV software analysis threshold. Using different models (for instance [18]) one obtains predictions on the number of events which differ from that of Table 1 by $\sim$ 10 % for the dominant reaction $\bar{\nu}_e$ p and up to $\sim$ 30 % for the neutral current process ν_x ^{12}C.

Recently, several solar [28,29], reactor [30], atmospheric [31,12] and accelerator [32] neutrino experiments have definitively confirmed the existence of the neutrino oscillations and have restricted the allowed regions of the oscillation parameters space. The effects of the neutrino oscillations on the GC neutrino detection are currently under evaluation by several authors [33]. Their results indicate that the number of expected $\bar{\nu}_e$interactions and the e$^+$ energy spectrum are affected by the neutrino oscillations in the star and in the earth with respect to the non oscillation case. However, even under pessimistic assumptions, the experiment sensitivity in detecting a galactic supernova neutrino burst remains essentially unchanged.

Table 1. Number of events from a stellar collapse at the Galactic Center (8.5 kpc) expected in MACRO; ν_x indicates the sum of all ν and $\bar{\nu}$ flavours. The model [23] was used

	Reaction				
Threshold (MeV)	$\bar{\nu}_e$ p	ν_x ^{12}C	ν_x e	ν_e ^{12}C	$\bar{\nu}_e$ ^{12}C
7	210	10	4	< 1	< 1
10	195	9	2	< 1	< 1

The expected rate of stellar gravitational collapses in the Milky Way varies from only 2 up to 10 collapses per century [34–36]. For such a rare event the detector should be kept always active, well calibrated and highly efficient. In the following sections we describe the methods that we selected to operate the detector over a period of more than 10 years. Furthermore the environmental conditions, like temperature, ventilation and power lines, were kept stable and continuously monitored.

3.1 The background reduction

The two main sources of background in the MACRO liquid scintillator were cosmic ray muons and natural radioactivity.

In the Gran Sasso National Laboratory, with an average rock overburden corresponding to 3700 m of water equivalent, the cosmic ray flux is reduced by a factor 10^6 with respect to the sea-level external one. The surviving cosmic ray muons usually crossed at least two counters within a few hundreds of ns; they were effectively rejected by looking for coincidences (within 320 ns) among scintillation counters or by requiring a temporal and spatial matching with a track of the streamer tube system. The remaining events released energy within a single box and were therefore named “single events”. The effect of the cosmic ray μ's rejection is shown in Fig. 2. Some very few atmospheric muons escaped identification because of the dead zones in the apparatus, like the support structure between detector modules. They are seen in the energy spectrum in Fig. 2 C) as a broad peak centered around 40 MeV. The residual background rate induced by non-recognized muons was $\sim$ 0.020 s^{-1} for a released energy $\geq$ 20 MeV.

The natural radioactivity background originates primarily from the decay of radioactive isotopes present in the experimental hall environment and in the materials used within the detector. The neutrons emitted by ^{238}U and ^{232}Th (present in small traces in the Gran Sasso rock and concrete) or produced by cosmic ray interactions are a further source of $>$ 5 MeV γ's. In a single scintillation counter the background rate was $\sim 5 \times 10^3\,\mathrm{s}^{-1}$ for an energy deposit larger than 1 MeV and it fell rapidly down to $\sim 1\,\mathrm{s}^{-1}$ for an energy deposit larger than 4 MeV. The acquisition rate of single events was $\sim 4\,\mathrm{s}^{-1}$ for the total active mass and a hardware acquisition threshold of $\sim$ 7 MeV. The radioactive background can be further suppressed by selecting events with large energy deposition. The residual rate in the energy interval $10 \div 20$ MeV was $\sim$ 0.025 s^{-1}.

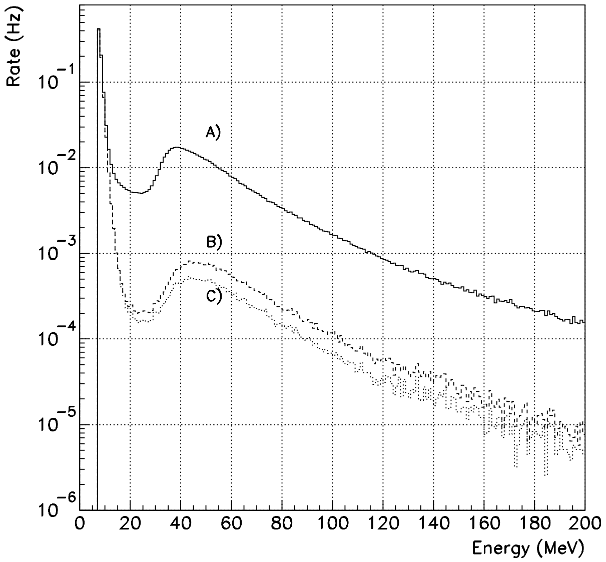

Fig. 2. The energy distributions of events collected in scintillation counters. A) all events, B) after rejection of coincidences among counters (scintillator muon veto) and C) after rejection of coincidences with the tracking system

The total rate of single events with an energy release larger than 10 MeV was $\approx 0.044\,\mathrm{s}^{-1}$.

3.2 The electronic systems

The detector was equipped with two independent trigger and digitizing electronic systems to detect GC neutrino bursts.

The main requirement of the GC electronics was the capability of generating triggers on low energy events contained in a single counter. The light transmission properties of the scintillation counters were hardware compensated in the GC trigger systems in such a way that the events could be selected on the basis of the deposited energy alone. The energy threshold of both systems was set at $\sim$ 7 MeV to collect possible $\bar{\nu}_e\,\mathrm{p}$ interactions at the acceptable background level of a few events s^{-1}. The trigger thresholds of the two systems were rather sharp so that both triggers were fully efficient on the whole counter length at $\sim$ 9 MeV. The systems were able to measure the time of the energy release and to digitise and record the corresponding PMT pulses, making possible a fast reconstruction of the event position along the counter and of the energy deposit.

A double energy threshold trigger was implemented in one of the two electronic systems. After each event with an energy release larger than 7 MeV, the circuit lowered the threshold to $\approx$ 1 MeV for 850 μs. This feature was intended to exploit the correlation between an $\bar{\nu}_e$ interaction and the subsequent neutron capture on the liquid scintillator. It also provided low energy events that were used to calibrate the detector response.

The presence of two independent triggers improved the continuity of on-line monitoring, enhanced the detector live-time and reduced the possibility of fake signals. These systems are described in detail in [8,15,16].

3.3 The energy scale calibration

The cosmic ray muons and the natural radioactivity provided two independent energy calibration references.

The Gran Sasso rock contains ^{208}Tl which emits a 2.61 MeV γ-line. The low energy spectrum of radioactive background is shown in the left plot of Fig. 3. The energy resolution of the MACRO counters was good enough to allow the identification of the thallium γ-line. The fit to the energy distribution was obtained by adding a Gaussian line to a phenomenological exponential background and folding it with the electronic trigger efficiency profile (visible in the spectrum behaviour below 1 MeV). The measured energy of the Tl-line is slightly shifted (by $\approx 10\,\%$) with respect to the nominal value because of the energy leakage from the counters and the saturation of the liquid scintillator response for particles at the end of their range [37].

The most probable energy loss of vertical muons was $\sim$ 34 MeV. The energy distribution, shown in the right plot of Fig. 3, is in good agreement with the expected Landau deposited energy fluctuations. By using cosmic ray muons, two weeks of data were needed to calibrate the detector with a 5 % accuracy. The use of the thallium reference required a comparable amount of data taking and the calibration accuracy was nearly as good: $< 10\,\%$. Although both calibration points were studied, the Tl reference was normally used, because it was closer to the hardware energy threshold and because the analysis chain was faster and did not require streamer tube information. When the Tl calibration reference was used, the spread of the most probable muon energy loss remained within 10 % of the nominal value.

The energy resolution was directly measured with the Tl-line and with the cosmic ray muons. It was interpolated between the two references and extrapolated at higher energies with the laser calibration system of the experiment. The energy resolution at the analysis threshold of 10 MeV was 8 %. Further details can be found in [38].

4 The search for GC neutrino bursts

The energy of the $\bar{\nu}_e$ induced positron is released in a very small volume, of a few cm radius, around the interaction point; therefore, the $\bar{\nu}_e$ events were searched for in the "single event" category defined in Sect. 3.1. The problem of detecting a GC neutrino burst is simplified by the pulsed character of the supernova neutrino signal. Therefore, the search for GC neutrino bursts was performed by looking for low-probability temporal clusters of single events.

The single event cluster generated by a GC might be faked by a statistical fluctuation of the residual background above the average single event rate. The analysis

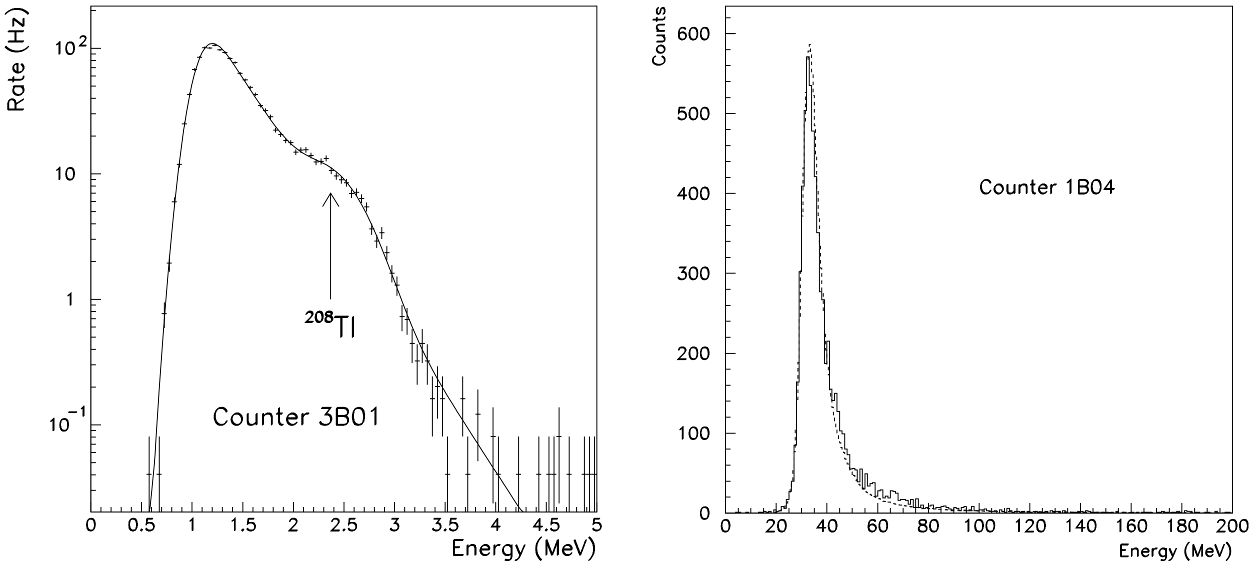

Fig. 3. The two energy calibration points. Left plot: the ^{208}Tl line as seen in a MACRO liquid scintillation counter. The energy spectrum is interpolated by the superimposition of an exponential background and a Gaussian line (at the energy of ^{208}Tl), folded with the electronic efficiency profile. Right plot: the energy loss distribution of cosmic ray muons vertically crossing a counter, compared with the expectation computed using the Landau formula

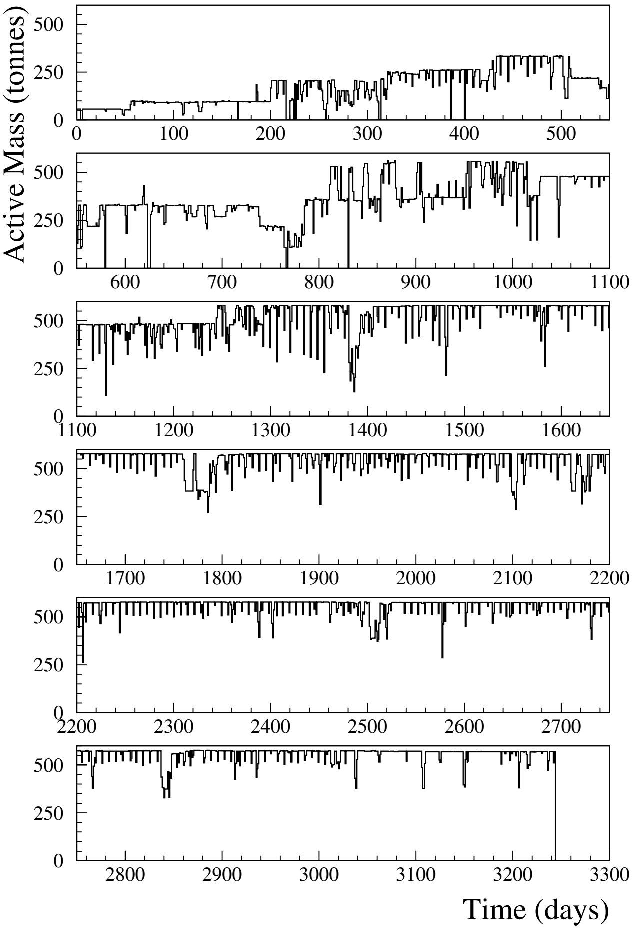

Fig. 4. The detector active mass for the 3245 days from February, 1^{st}, 1992 to December, 19^{th}, 2000

threshold of 10 MeV was introduced to reduce the background rate. The counting rate, averaged over the time interval from February, 1^{st}, 1992 to December, 19^{th}, 2000, was $\approx 0.044\,\mathrm{s}^{-1}$. The scintillator mass, active for detecting possible GC neutrino bursts during the acquisition time, is shown in Fig. 4 on a day by day basis. Over the first ~ 1000 days of data taking, the apparatus assembly was in progress; the detector active mass increased almost regularly from ≈ 45 to 570 ton. The negative spikes present during the whole history of the experiment were due to periodical calibrations and hardware maintenance operations (e.g. PMT gain setting) and to sporadic malfunctions of some hardware equipment. In all these cases a fraction of the apparatus was temporarily excluded from the data taking.

In the examined period the GC electronics, the calibration procedures and the real time analysis software were properly working; the total down time of the complete detector was $\approx 7.8\,\%$. If we consider the data taking period from 1995 (after the MACRO completion) to the end of the operation, the down time becomes $4.1\,\%$, mainly attributable to power supply failures and acquisition crashes.

The observed multiplicity distributions of all single event clusters, at fixed cluster durations of 2, 10, 20 and 40 s, are shown in Fig. 5 and the cluster duration distributions at fixed multiplicities of 1, 5, 10, 15 and 20 in Fig. 6. The experimental distributions were obtained excluding sporadic misbehaviours of some counters or general failures of the entire apparatus. The expected distributions were computed by considering the statistical fluctuations of the counting rate measured in each individual run. The background rate varied during the experiment lifetime from $\sim 0.015\,\mathrm{s}^{-1}$ to $\sim 0.075\,\mathrm{s}^{-1}$ depending on the total active mass and on the efficiency of the muon rejec-

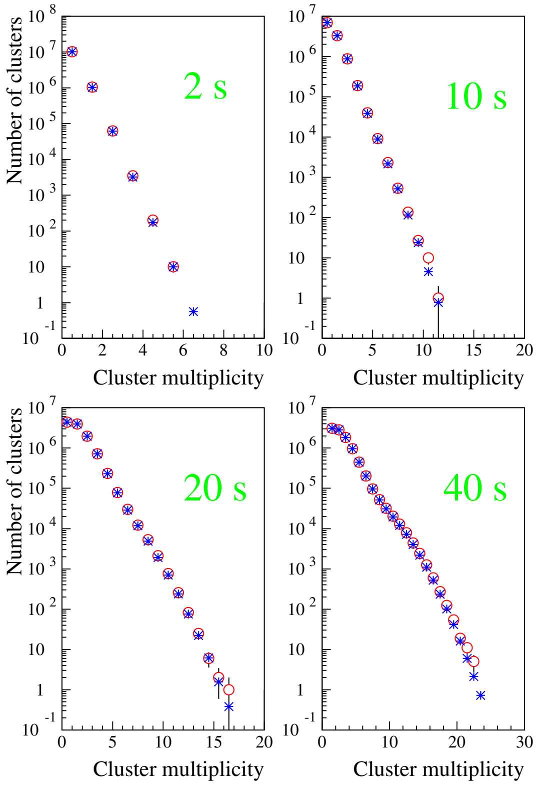

Fig. 5. Number of event clusters vs. cluster multiplicity for fixed time intervals of 2, 10, 20 and 40 s. The open circles indicate the experimental points and the asterisks the expectations due to statistical background fluctuations

tion (related to the geometrical configuration of the active detector). These rate variations produced the structure clearly visible (both in the measured and in the predicted number of clusters) in Fig. 5 for the 40 s time interval at multiplicity about ten. The agreement between the measured number of single events clusters and the expected number, evaluated only by using the Poissonian fluctuation of the average counting rate, is very good for all time intervals explored. There is no evidence of abnormal cluster of events.

To compare the measured background clusters with the expected signal we note that a GC like SN1987A at a distance of 20 kpc would have produced in MACRO $\approx 15\div20\ \bar{\nu}_e$ interactions in 2 s. Such event would generate a cluster that should fall outside of the scale of Fig. 5.

5 The real time GC burst detection

The astrophysical models predict, as experimentally confirmed by the SN1987A observations [4,5,39,40], that the neutrino signal precedes the supernova optical flare by a few hours. The observation of the onset of the optical signal is of great interest for the astrophysical community. The first light carries information on the supernova progenitor and its immediate surroundings and the delay between the neutrino burst and the light signal is a further test of the simulations of the explosion mechanism [41, 42]. Several experimental collaborations (MACRO, Super-Kamiokande, SNO, LVD, AMANDA ...) were motivated by these arguments to develop systems for prompt recognitions of neutrino bursts from supernovæ.

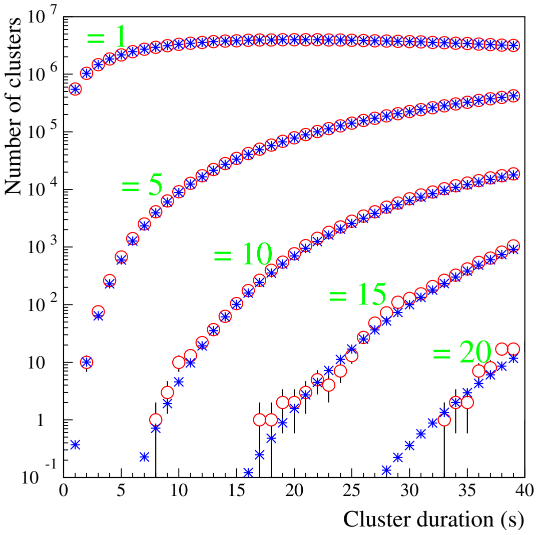

Fig. 6. Number of event clusters vs. cluster time duration for fixed cluster multiplicities of 1, 5, 10, 15 and 20. The open circles indicate the experimental points and the asterisks the expectations due to statistical background fluctuations

The MACRO collaboration started a real time analysis procedure of its data in 1991, and since then was able, in case of a signal, to rapidly distribute an "alarm". MACRO's redundant neutrino burst detection capability allowed us to operate dual on-line monitors. These monitors [16] were integrated into a single GC alarm protocol, tailored to maintain the amount of non-sensitive mass, the down-time and the false alarm rate at smaller levels than would be possible with only one of the two electronic systems alone. The total time required for recognizing a GC candidate, including the time needed to satisfy our validation protocol [16], was less than one hour.

The MACRO early warning system was adopted as a model for an integrated and coordinated network of supernova observatories (the **SNEWS**, **S**uper**N**ova **E**arly **W**arning **S**ystem), whose goal is to provide a fast and reliable alert to the astronomical observatories around the world [43].

The real time search for GCs was performed by computing the Poissonian probability of the measured single-event clusters multiplicity in several time windows ending on the last event acquired. If one of these probabilities was lower than a preset warning threshold P_w, an alert to the collaboration was generated. The P_w threshold was chosen to keep the alert rate at a manageable level, of the order of one alert per week, and to ensure the full efficiency on genuine GC event cluster. The chosen P_w was 10^{-5}. This threshold corresponds to 5 events within 2 s at the measured background rate of $0.044\,\mathrm{s}^{-1}$. During the analyzed 8.9 years, one of the real time monitors generated a total of 396 alerts for all examined time windows. Among these,

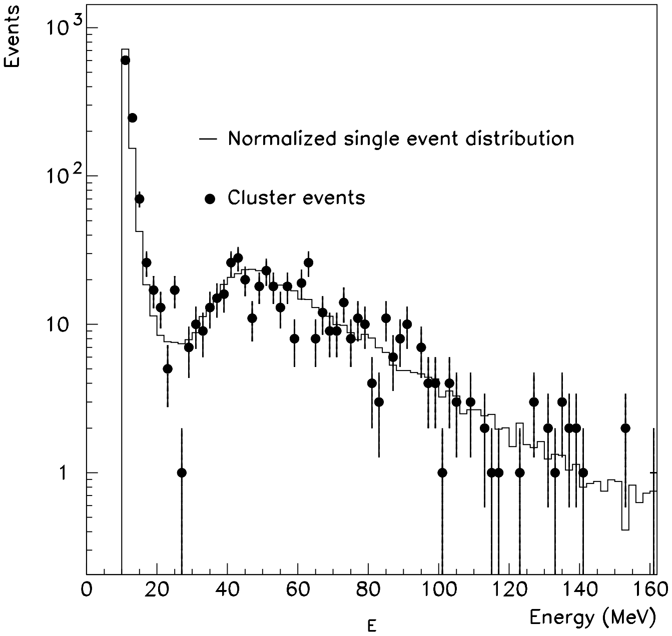

Fig. 7. The energy distribution of the events contained in clusters classified as "background fluctuation" (black points) compared with the normalized single event background energy distribution (histogram)

180 clusters were associated to apparatus misbehaviours, like sparking counters, calibration events and power supply failures. The remaining 216 clusters were classified as "background fluctuations". The energy distribution of the cluster events for this group is shown in Fig. 7; the normalized energy distribution of background events, already illustrated in Fig. 2 curve C), is superimposed. The hypothesis of genuine low-probability background fluctuations is confirmed by the good agreement between the two. Furthermore, these clusters populate the high multiplicity tails of the distributions shown in Fig. 5, and the number of alerts agrees with what is expected from background fluctuations. None of them can be associated with a GC neutrino burst.

6 Final result

The single event clusters observed during the operation of the MACRO detector are compatible with statistical fluctuations of the background counting rate. This observation can be quantified in a total integrated exposure of the detector to GC signals.

An intuitive and extra-conservative detector exposure can be obtained as follows. We selected the simplified and conservative SN model given in [24], tailored on SN1987A, to compute the expected neutrino signal. The knowledge of the active scintillator mass and the measured background rate in each run are used to calculate the maximum distance D_{run} at which a SN has a negligible probability (10^{-5} in 10 years) to be simulated by a background fluctuation and a very large probability ($> 99\%$) of being detected. These two probabilities were arbitrarily chosen.

More precisely, for every run and for a fixed cluster time duration T, we defined a cluster size N_{clu} that has a less than 10^{-5} probability to be generated by a background fluctuation in 10 years of running. For instance, at the average experimental rate of $0.044\ \mathrm{s}^{-1}$ and for $T = 2$ s, we have $N_{\mathrm{clu}} = 9$. The efficiency for detecting a SN at a distance D is:

$$\epsilon_{\mathrm{run}} = 1 - \sum_{N<N_{\mathrm{clu}}} P\left[N; N_B\left(T\right) + N_S\left(D,T\right)\right] \qquad (4)$$

where N_B and N_S are respectively the expected background and the signal events in a time window T and P is the Poissonian probability of observing N events when $N_B + N_S$ are expected. The requirement $\epsilon_{\mathrm{run}} \geq 0.99$ defined the distance D_{run}.

Using the Bahcall-Soneira model [44] of the distribution of the stars in our galaxy, we finally calculated the fraction of galaxy $f^{\mathrm{gal}}\left(D_{\mathrm{run}}\right)$ we could explore in a given acquisition run. Since November 1989, the overall time exposure of the detector to GC signals was:

$$T_{Tot} = \sum_{\mathrm{run}} T_{\mathrm{run}} = 10.3 \text{ years} \qquad (5)$$

where T_{run} is the live-time of a given run. The total exposure sensitive to a GC occurring anywhere in the galaxy can be expressed by the form:

$$E_S = \sum_{\mathrm{run}} f^{\mathrm{gal}}\left(D_{\mathrm{run}}\right) \times T_{\mathrm{run}} \times \epsilon_{\mathrm{run}} \qquad (6)$$

For a cluster time duration $T = 2$ s, which maximized the signal-to-noise ratio in the case of SN1987A, we obtained $E_S = 8.6$ galaxy × years. The difference between T_{Tot} and E_S is due to the fact that the MACRO active scintillator mass varied from ≈ 45 ton to 570 ton; therefore, the factor $f^{\mathrm{gal}}\left(D_{\mathrm{run}}\right)$ in (6) was lower than one during the apparatus construction.

An unbiased detector exposure can be obtained by weighting the differential density of stars in our galaxy with the collapse detection efficiency. The exposure resulted

$$E_U = \sum_{\mathrm{run}} T_{\mathrm{run}} \int_0^1 \epsilon_{\mathrm{run}}\left(X\right) \times \frac{df^{\mathrm{gal}}\left(X\right)}{dX} dX \qquad (7)$$

where the star distance X is given in fraction of 30 kpc (corresponding to the full extension of our galaxy), the detection efficiency, defined in equation (4), is a function of the run and the integrated density of stars in the galaxy, $f^{\mathrm{gal}}\left(X\right)$, is normalized to the stars within 30 kpc. For a cluster time duration $T = 2$ s we obtained $E_U = 9.2$ galaxy × years.

7 Conclusions

The MACRO experiment was active for the search of stellar gravitational collapses for more than 11 years, from November 1989 to December 2000. The experiment reached the sensitivity to the whole galaxy in 1994, at the end of detector construction.

A real time system for the prompt recognition of neutrino bursts from stellar collapses was developed by the collaboration and operated since 1991.

The low energy event clusters observed during the detector operation were compatible with statistical fluctuations of the background counting rate, and therefore we can conclude that we did not observe any signal of a galactic stellar collapse. This observation can be summarized in an unbiased detector exposure to the whole galaxy of $E_U = 9.2$ galaxy × years and in an extra-conservative exposure of $E_S = 8.6$ galaxy × years.

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