Nuclear astrophysics and neutrinos

G. Fiorentini$^{1,2}$

1 Dipartimento di Fisica, Università di Ferrara, Via Paradiso 12, I-44100 Ferrara, Italy
2 Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara, Via Paradiso 12, I-44100 Ferrara, Italy

Talk presented at “VII Convegno su Problemi di Fisica Nucleare Teorica”, Cortona (Italy), 19-21 October 1998

Abstract. In this report, centered on the activities within the MURST-PRIN project “Fisica teorica del nucleo e dei sistemi a più corpi” we discuss recent advances on the following items: i) neutrinos as probes of the solar interior and of other astrophysical objects; ii) neutrinos as probes of physics beyond the Standard Model of electroweak interactions; iii) the role of nuclear physics in i) and ii); iv) who is doing what within the Italian network; v) future projects.

1 Introduction

After the results of solar neutrino experiments in the last few years (see for reviews [1, 2]) and the recent impressive data reported by Superkamiokande [3, 4] on both solar and atmospheric neutrinos, we are living a really exciting phase of neutrino physics. Nuclear physics is deeply involved in it, since neutrinos are produced as a result of nuclear reactions and are detected in the laboratory generally by means of nuclear interactions.

In this report, centered on the activities within the MURST-PRIN project “Fisica teorica del nucleo e dei sistemi a più corpi” we discuss recent advances on the following items:

i) neutrinos as probes of the solar interior, and of other astrophysical objects;

ii) neutrinos as probes of physics beyond the Standard Model of electroweak interactions;

iii) the role of nuclear physics in i) and ii);

iv) who is doing what within the Italian network;

v) future projects.

With respect to the last item, we concentrate on the calculation of hep and other rare neutrinos, we outline the interesting problems posed by a recent experimental proposal, LENS [5], and the physics potential of a new underground
apparatus for nuclear astrophysics, LUNA2 [6], which will be installed at Gran Sasso in the next few years.

2 Neutrino as probes of astrophysical objects

Due to their extremely long mean free path, neutrinos are ideal probes of stellar interiors. As an example, the heat and light we get from the sun correspond to photons generated in the outermost layer of the solar atmosphere whereas neutrinos directly emerge from the solar core and can probe the innermost part of the star, a region otherwise inaccessible to observations. In this section we briefly discuss just a few topics, so as to outline the potential of neutrinos as probes of stellar interiors. Actually, the structure of other astrophysical objects can also be determined by exploiting the long mean free path of neutrinos. As an example, we shall present a neutrino map of the Galaxy at the end of this section.

2.1 Nuclear energy production in stars

Since the pioneer papers in the thirties by Bethe [7], Bethe and Critchfield [8], concerning the role of the pp chain and the CNO cycle, theoretical calculations of nuclear energy production in stars have greatly advanced and have reached a high degree of complexity and sophistication. On the other hand, for the succeeding fifty years there was no real observation of the fact that stellar energy is generated by means of nuclear fusion.

In fact, no matter which is the detailed mechanism, Hydrogen burning requires neutrino emission due to (global) lepton number conservation:

\[ 4p + 2e \rightarrow ^4He + 2\nu + \text{heat} , \]  

(1)

and neutrinos are the only product of nuclear reactions which can escape, undisturbed, from the solar energy generating core.

In the early nineties Gallex [9] and Sage [10], two experiments sensitive to pp neutrinos (i.e. those from \( p + p \rightarrow d + e + \nu_e \)) have shown that the neutrino signal agrees, within a factor two, with the assumption that Eq. (1) is the source of solar power.

Conceptually this result, i.e. the observational proof that the sun is powered by nuclear fusion, is at least as important as the missing factor two, the so called solar neutrino puzzle.

Neutrinos from the different branches of Eq. (1), see Figs. 1, 2 and 3, can be discriminated due to the different energies. As an example, pp neutrinos have a continuous spectrum up to \( E_\nu = 0.420 \text{ MeV} \), whereas \(^7\text{Be} \) neutrinos are monochromatic with \( E_\nu = 0.861 \text{ MeV} \).

According to Standard Solar Model (SSM) calculations, pp neutrinos are produced at distance \( r \) from the center such that \( r/r_\odot < 0.3 \), whereas \(^7\text{Be} \)
production is peaked much closer to the solar center, at $r/r_\odot \approx 1/20$, so that different neutrinos probe different portions of the solar interior.

The next generation of solar neutrino experiments (e.g. Hellaz, Borexino and Lens) points toward a neutrino spectroscopy, which will elucidate the detailed mechanism of energy production in the sun.

![Diagram of the pp chain]  

**Fig. 1.** The pp chain

### 2.2 Neutrinos as solar thermometers

The central temperature $T$ of the sun is a nice example of a physical quantity which can be determined by means of solar neutrino detection, provided that the relevant nuclear physics is known (and neutrino properties are also known).
SSM calculations predict $T$ with an accuracy of 1% or even better. In order to appreciate such a result, let us remind that the central temperature of Earth is known with an accuracy of about 20%. However, let us remind that this is a theoretical prediction which, as any result in physics, demands observational evidence.

The fluxes of $^8\text{B}$ and $^7\text{Be}$ neutrinos are given by:

$$\Phi(B) = c_B S_{17} \frac{S_{34}}{\sqrt{S_{33}}} T^{-20}$$  \hspace{1cm} (2)

$$\Phi(\text{Be}) = c_{\text{Be}} S_{34} \frac{S_{34}}{\sqrt{S_{33}}} T^{-10}$$  \hspace{1cm} (3)

where $S_{ij}$ are the low energy astrophysical factors for nuclear reactions between nuclei with atomic mass numbers $i$ and $j$, $c_B$ and $c_{\text{Be}}$ are well determined constants.

The high powers of $T$ in the above equations imply that the measured neutrino fluxes are strongly sensitive to $T$, i.e. $^7\text{Be}$ and $^8\text{B}$ neutrinos in principle are good thermometers for the innermost part of the sun. On the other hand, the relevant
nuclear physics has to be known, which justifies the present theoretical and experimental efforts for better determinations of the $S_{ij}$.

The result of Superkamiokande [3] can be used for determining a lower limit to $T$. In fact, the observed flux $\Phi(B)_{\text{obs}} = 2.44 \pm 0.10 \cdot 10^6$ cm$^{-2}$ s$^{-1}$ is a lower limit to the produced flux $\Phi(B)$, since some of the produced $\nu_e$ can transform into other neutrinos ($\nu_\mu, \nu_\tau$) with a much smaller detection cross section (by definition this latter vanishes for oscillation into sterile neutrinos). By using $\Phi(B)_{\text{obs}} \leq \Phi(B)$ together with eq. (2) and for the largest (smallest) values of $S_{17}$ and $S_{34}$ ($S_{33}$) one gets: $T \geq 1.49 \cdot 10^7$ K, a value within five percent from the most recent SSM estimate, $T_{SSM} = 1.57 \cdot 10^7$ K [11].

We consider this as one of the successes of the SSM. Let us observe however that this approach cannot lead to a measurement of $T$, unless the fate of $\nu_e$ is known, i.e. the oscillation parameters are determined.

One can conceive a measurement of the central temperature which is independent on the oscillation mechanism. In this direction, Bahcall [12] has proposed to measure the difference in average energy between the neutrino line produced by $^7$Be electron capture in the solar interior and the corresponding neutrino line.
produced in terrestrial laboratory. The high temperatures in the center of the sun cause an average energy shift of 1.3 KeV and broaden the line asymmetrically (FWHM=1.6 KeV).

Experimentally this is an extremely difficult task, in particular if one aims at a few percent accuracy on $T$. It shows however one of the aspects why detection of $^7$Be neutrinos is particularly interesting. In fact there is a big effort to measure the $^7$Be neutrino flux with Borexino, a detector which is being built by an international collaboration at Laboratori Nazionali del Gran Sasso [14].

### 2.3 Neutrinos from Stellar collapse

As well known, in a stellar collapse leading to Supernova-II explosion most of the energy, $E_{SN} \approx 5 \times 10^{46} \text{ J}$, is carried out by neutrinos, with average energy of about 12 MeV, in a few seconds. In fact, the detection of a few (anti)neutrinos from SN-1987A in the Large Magellan Cloud by Kamiokande and IMB detectors [15] opened a completely new field of neutrino astronomy.

The number of detected neutrinos, as well as their energy, was enough to show, at a semiquantitative level, that stellar collapse is essentially understood, see e.g. [16]. On the other hand, the mechanism leading to the explosion after collapse is still a mistery, see e.g. [17].

In this respect it is worth observing that detectors have advanced substantially. As an example, for a Supernova-II at the center of the Galaxy Superkamiokande will collect some 5000 events, of which 1000 already in the first second after collapse [18, 19]. This clearly implies that neutrino emission can be followed quite accurately. In particular, processes with a few millisecond time scale, i.e. the typical scale of neutron stars ($t = 1/\sqrt{G\rho}$) can be studied. In addition, a detailed neutrino energy spectrum can be determined. All this should allow for a basic understanding of the process, and also clarify between different types of remnants (e.g. neutron stars, quark stars, black holes and other exotic objects). This really will open, from the observational point of view, a completely new field of physics, where nuclear physics is deeply involved, see e.g. the contributions to this workshop by Drago and Alberico.

### 2.4 A neutrino map of the Galaxy

It is interesting to compare the energy $E$ and neutrinos $N$ released from a stellar collapse and from all stars in our galaxy. For a Supernova one has:

$$E_{SN} \approx 5 \times 10^{46} \text{ J}, \quad N_{SN} \approx 3 \times 10^{58}$$

The luminosity of the Galaxy is about $10^{11} L_\odot = 4 \times 10^{37} \text{ J/s}$. Most of the energy is carried out by photons (not by neutrinos) and it is produced through $4p + 2e^+ \rightarrow ^4He + 2\nu + 27 \text{ MeV}$, i.e. a neutrino is produced for each 13 MeV of electromagnetic energy, so that the neutrino production rate is about $2 \times 10^{49}/\text{s}$.
Roughly, one estimates that there is a Supernova every 30 years in the Galaxy, see [20]. In the same time all stars in the Galaxy have produced:

\[ E_{\text{stars}} \approx 4 \cdot 10^{46} \text{J} \quad , \quad N_{\text{stars}} = 2 \cdot 10^{58} \quad (5) \]

There are two curious aspects when comparing eq. (4) and eq. (5):

i) on the average, the contribution of supernovae to galactic energy production equals that from all other stars.

ii) again on the average, the contribution of supernovae to neutrino production in the universe equals that from all other stars.

The detection of stellar neutrinos in our galaxy is beyond present experimental possibility. It is however very interesting since, due to the long neutrino mean free path, it could provide an unobscured map of the galaxy, see fig. 4 [32].

**Fig. 4.** The Galaxy seen in neutrinos (top) and in the visible light (bottom)
3 Neutrinos as probes of physics beyond the standard model of electroweak interactions

In the Minimal Standard Model of Electroweak interactions ($MSM_{EW}$) neutrinos are massless, thus stable and with vanishing electro-magnetic moments.

Actually, the deficit of neutrinos reported by all five solar neutrino experiments performed so far strongly points towards some neutrino property beyond the $MSM_{EW}$. More importantly, the experiments look in contradiction among themselves unless some non-standard neutrino property is advocated, see e.g. refs. [21, 22]. Furthermore, the recent results of Superkamiokande on atmospheric neutrinos, confirming with much higher statistics and better particle discrimination the indications of previous experiments, provide additional evidence towards some non standard neutrino property.

The simplest (although not unique) solution of the solar and atmospheric neutrino puzzles is in terms of oscillations due to a mass difference $\Delta m$ among the mass eigenstates, which are superposition of weak-flavour eigenstates. If this mechanism is correct, the real problem now is to determine the neutrino mass matrix. This of course is essential for extending the $MSM_{EW}$ and it is also important for understanding the mass generation of matter fields. More generally this study is also significant to understand which contribution, if any, to the dark matter in the universe is due to neutrinos.

In the near future neutrino oscillations will be studied with a variety of approaches. Long baseline (e.g. CERN to Gran Sasso) accelerator experiments are planned and a new generation of refined solar neutrino detectors is advancing. All these experiments, however, are sensitive to mass difference and cannot determine the absolute mass scale.

In this respect measurements of neutrino masses, e.g. by Tritium beta decay and $\beta\beta_{0}\nu$ decay (this latter for Majorana neutrino only) are extremely important. We recall that if neutrino oscillations really occur, these experiments are sensitive to all the neutrino masses, and not only to the lightest one [23].

4 The role of nuclear physics

Nuclear physics has an important role in the program outlined above, and the theoretical as well as the experimental approach are both important. Roughly, one has three kind of problems:

4.1 Determination of the production cross sections

As an example, the reaction which is at the starting point of the pp chain:

$$p + p \rightarrow d + e^{+} + \nu_{e}$$

has a cross section so small that it cannot be measured in the laboratory and it has to be determined theoretically.
The calculated cross section should now be accurate to the percent level [25, 26], the most recent and possibly precise determination [29] being produced by a large international collaboration which includes members of the MURST project.

The value of the cross section is clearly relevant for determining the solar temperature in the energy production zone. The observed solar luminosity essentially fixes the pp reaction rate in the sun, which depends both on the cross section and on the energy distribution of the colliding protons. From numerical simulations, see e.g. [1], one has $T \propto S_{11}^{-0.1}$, so that a 1% error on $S_{11}$ translates into a 0.1% error on the temperature, a small however non negligible contribution to the present total uncertainty of $T$.

We remark that there are reactions which are important for neutrino production, although neutrinos are not directly involved. As an example, let us mention the $^3\text{He} + \ ^3\text{He} \rightarrow ^4\text{He} + 2p$ and $^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma$ reactions. As clear from Fig. 1 and from Eqs. (2,3), the competition between the two rates determines the flux of $^7\text{Be}$ and $^8\text{B}$ neutrinos. This is why these reactions are being extensively studied, both theoretically and experimentally, see [25, 26].

### 4.2 Determination of the absorption cross section

So far, all but one solar neutrino experiments use nuclear targets for neutrino detection. With respect to $\nu - e$ scattering, one loses the directionality of the process, however the much larger neutrino-nucleus cross sections allow for larger statistics, a point which is always relevant in solar neutrino physics where one typically collects a few hundred events in several years of data taking. Among future projects, let us remind the following reactions, as a couple of examples:

\[ \nu_e + ^{40}\text{Ar} \rightarrow ^{40}\text{K} + e^- \quad \text{(Icarus)[13]} \]
\[ \nu_e + ^{160}\text{Gd} \rightarrow ^{160}\text{Tb} + e^- \quad \text{(Lens)[5]} \]

The relevant nuclear cross sections are needed, firstly in order to fix the size of the apparatus and later in order to interpret the data.

As shown by Gallex and Sage, the apparatus can be calibrated by using a suitable neutrino source and thus the detection cross section can be determined \textit{a posteriori} [30]. However, it has to be known reliably in advance in order that the size of the apparatus can be correctly determined, i.e. one cannot built a multi million dollar solar neutrino experiment and finally discover that the cross section is too small for solar neutrino detection!

### 4.3 Determination of the nuclear matrix elements relevant for the measurement of neutrino mass

Neutrinoless double beta decay ($\beta\beta0\nu$) is presently the best tool for determining Majorana neutrino masses. Actually the upper bound derived by this approach, $m \lesssim 0.5$ eV, is an order of magnitude smaller that that from Tritium beta decay experiments [31]. The interpretation of $\beta\beta0\nu$ results, however, relies on the calculated nuclear matrix elements, see [33].
5 Activity within the network

The network is active on all the items mentioned in the previous section. Recent activity is exemplified in the four boxes, each containing information on selected papers pertinent to this field of physics.

The Milan node, coordinated by R Broglia, has been working in close connection with the experimental groups in the same university, which has a very important tradition in experimental neutrino physics. In fact, Broglia et al [34] provided the first estimate of the neutrino cross section for $^{23}$Na, which is a crucial ingredient for a planned solar neutrino experiment by Fiorini et al. [35]. They also produced a more accurate estimate for the neutrino cross section on $^{40}$Ar, a result important for Icarus [36]. The new calculation of electron capture of $^{123}$Te [37] helped resolve a discrepancy between the experimental results of Fiorini et al. [38] and the previous ones by another group.

The Pisa group, coordinated by S. Rosati, has developed over the years more and more refined calculation methods for few body systems, see [27, 28], which are becoming important for applications to nuclear astrophysics, a field where the activity of the group will concentrate in the near future. In this respect, it is worth mentioning the contribution [29] of this group to the study of the weak capture of protons by protons, a process which importance has been previously mentioned.

The same process has been studied by the Ferrara group, coordinated by G. Fiorentini, within a completely different approach. We already remarked that it is impossible to measure the cross section in the laboratory. However one can get observational constraints on its value by exploiting helioseismic data [39].

Nuclear reaction rates in stars are also investigated by the group of “Torino-Politecnico”, coordinated by P. Quarati. In particular, they have considered the possible modification of reaction rates, due to deviations from the Boltzmann statistics, in the framework of the extended Tsallis statistics [40, 41]. This hypothesis cannot be discarded a priori, in the presence of long range forces. In a paper coauthored with the Ferrara group [42], again by exploiting helioseismic constraints, it has been shown that such deviations, if they exist, are extremely tiny.

Clearly there is a strong overlap of scientific interests among the different groups and similar problems, e.g. the pp reaction, are approached with complementary methods. There is more joint work than the number of coauthored papers would suggest. We are confident that several presently informal collaborations will bring in joint papers in the near future, see the next section.
The solar neutrino capture cross section for $^{23}$Na

W.E. Ormand, P.M. Pizzochero, P.F. Bortignon, and R.A. Broglia.

Phys. Lett. B308 (1993) 207

A coincidence (electron, gamma-ray) experiment designed to identify one or more components of the solar neutrino spectrum has been proposed based on a large array of NaBr detectors. In support of the design of this detector, we calculate the solar neutrino absorption rate for $n + ^{23}\text{Na} \rightarrow ^{23}\text{Mg} + e$ within the Standard Solar Model making use of both experimental and theoretical data for the structure of the two nuclei involved. It is found that the inclusion of excited states in $^{23}\text{Mg}$ enhances the absorption cross section by $\approx 30\%$, with approximately one third of this enhancement coming from excited states for which experimental data does not exist. The solar neutrino absorption rate is calculated to be $3.5 \pm 1.3$ SNU, which amounts to about one count every six days for the proposed detector.

Neutrino Capture Cross Sections for $^{40}$Ar and beta-decay of $^{40}$Ti

W.E. Ormand, P.M. Pizzochero, P.F. Bortignon, and R.A. Broglia.

Phys. Lett. B345 (1995) 343

Shell-model calculations of solar neutrino absorption cross sections for $^{40}$Ar, the proposed component of the ICARUS detector, are presented. It is found that low-lying Gamow-Teller transitions lead to a significant enhancement of the absorption rate over that expected from the Fermi transition between the isobaric analog states, leading to an overall absorption rate of 6.7 SNU. We also note that the pertinent Gamow-Teller transitions in $^{40}$Ar are experimentally accessible from the $\beta$-decay of the mirror nucleus $^{40}$Ti. Predictions for the branching ratios to states in $^{40}$Sc are presented, and the theoretical half-life of 53 ms is found to be in good agreement with the experimental value of $56^{+18}_{-12}$ ms.

Competition Between Particle-Hole and Particle-Particle Correlations in Forbidden Electron Capture: the Case of $^{123}$Te

M. Bianchetti, M. R. Quaglia, G. Colo, P.M. Pizzochero, R.A. Broglia and P.F. Bortignon

Phys. Rev. C 56 (1997) R1676

The K-electron capture half-life of $^{123}$Te has been recently measured to be $K_{\exp} = 2.4 \cdot 10^{19}$ yr, and constitutes the longest half-life ever measured in a single $b$ transition of any nuclear species. We have calculated this second unique forbidden transition within the framework of the proton-neutron quasi-particle random phase approximation, making use of Skyrme-type effective interactions. A strong cancellation effect between particle-hole and particle-particle correlations is found. The model, without any renormalization of the force, provides a lower limit for the K-electron capture half-life of $\approx 10^{17}$ yr, which unambiguously rules out the old experimental values of $10^{13} - 10^{14}$ yr. A few percent increase of the particle-particle matrix elements of the Skyrme interaction allows to reproduce the experimental findings.

Box 1: Milan results
Weak capture of protons by protons
R. Schiavilla, V. G. J. Stoks, W. Gloeckle, H. Kamada, A. Nogga, J. Carlson, R. Machleidt, V. R. Pandharipande, R. B. Wiringa, A. Kievsky, S. Rosati, M. Viviani
Phys.Rev. C58 (1998) 1263
The cross section for the proton weak capture reaction $^1\text{H}(p,e^+ + \nu_e)^2\text{H}$ is calculated with wave functions obtained from a number of modern, realistic high-precision interactions. To minimize the uncertainty in the axial two-body current operator, its matrix element has been adjusted to reproduce the measured Gamow-Teller matrix element of tritium $\beta$ decay in model calculations using trinucleon wave functions from these interactions. A thorough analysis of the ambiguities that this procedure introduces in evaluating the two-body current contribution to the pp capture is given. Its inherent model dependence is in fact found to be very weak. The overlap integral $L_2(E=0)$ for the pp capture is predicted to be in the range 7.05–7.06, including the axial two-body current contribution, for all interactions considered.

Neutron-$^3\text{H}$ and Proton-$^3\text{He}$ Zero Energy Scattering
M. Viviani, S. Rosati, A. Kievsky
Phys.Rev.Lett. 81 (1998) 1580-1583
The Kohn variational principle and the (correlated) Hyperspherical Harmonics technique are applied to study the n-$^3\text{H}$ and p-$^3\text{He}$ scattering at zero energy. Predictions for the singlet and triplet scattering lengths are obtained for non-relativistic nuclear Hamiltonians including two- and three-body potentials. The calculated n-$^3\text{H}$ total cross section agrees well with the measured value, while some small discrepancy is found for the coherent scattering length. For the p-$^3\text{He}$ channel, the calculated scattering lengths are in reasonable agreement with the values extrapolated from the measurements made above 1 MeV.

Possible three-nucleon force effects in D-P scattering at low energies
C. R. Brune, W. H. Geist, H. J. Karwowski, E. J. Ludwig, K. D. Veal, M. H. Wood, A. Kievsky, S. Rosati, M. Viviani
Phys.Lett. B428 (1998) 13-17
We present measurements of the analyzing powers $A_y$ and $iT_{11}$ for proton-deuteron scattering at $E_{cm}=432$ keV. Calculations using a realistic nucleon-nucleon potential (Argonne V18) are found to underpredict both analyzing powers by 40. The inclusion of the Urbana three-nucleon interaction does not significantly modify the calculated analyzing powers. Due to its short range, it is difficult for this three-nucleon interaction to affect $A_y$ and $iT_{11}$ at this low energy. The origin of the discrepancy remains an open question.

Box 2: Pisa results
Superkamiokande and solar antineutrinos
G. Fiorentini, M. Moretti, F. L. Villante
Phys. Lett. B413 (1997) 378-381.

We propose to exploit the angular distribution of the positrons emitted in the inverse beta decay to extract a possible antineutrino signal from the Superkamiokande background. From the statistics collected in just 101.9 days one obtains a model independent upper bound on the antineutrino flux (for energy greater than 8.3 MeV) $\Phi < 9 \times 10^4$ cm$^{-2}$ s$^{-1}$ at the 95% C.L. By assuming the same energy spectrum as for the $^8$B neutrinos, the 95% C.L. bound is $\Phi < 6 \times 10^4$ cm$^{-2}$ s$^{-1}$. Within three years of data taking the sensitivity to neutrino-antineutrino transition probability will reach the 1% level, thus providing a stringent test of hybrid oscillation models.

Helioseismology and $p+p \rightarrow d + e^+ + \nu_e$ in the sun
S. Degl’Innocenti, G. Fiorentini, B. Ricci
Phys. Lett. B416 (1998) 365-368

By using a phenomenological field theory of nucleon-nucleon interactions, Oberhummer et al. found a cross section of $p+p \rightarrow d + e^+ + \nu_e$ about 2.9 times that given by the potential approach and adopted in Standard Solar Model calculations. We show that a solar model with $S = 2.9 S_{SSM}$ is inconsistent with helioseismic data, the difference between model predictions and helioseismic determinations being typically a factor ten larger than estimated uncertainties. We also show that, according to helioseismology, $S$ cannot differ from $S_{SSM}$ by more than 15%.

Bounds on hep neutrinos
G. Fiorentini, V. Berezinsky, S. Degl’Innocenti, B. Ricci
astro-ph/9810083, to appear on Phys. Lett. B (1998)

The excess of highest energy solar-neutrino events recently observed by Superkamiokande can be in principle explained by anomalously high hep-neutrino flux $\Phi_\nu(hep)$. Without using SSM calculations, from the solar luminosity constraint we derive that $\Phi_\nu(hep)/S_{13}$ cannot exceed the SSM estimate by more than a factor three. If one makes the additional hypothesis that hep neutrino production occurs where the $^3$He concentration is at equilibrium, helioseismology gives an upper bound which is (less then) two times the SSM prediction. We argue that the anomalous hep-neutrino flux of order of that observed by Superkamiokande cannot be explained by astrophysics, but rather by a large production cross-section.

Box 2: Ferrara results
Anomalous diffusion modifies solar neutrino fluxes
G. Kaniadakis, A. Lavagno, M. Lissia, P. Quarati
astro-ph/9710173, to appear on Physica A (1998)

Density and temperature conditions in the solar core suggest that the microscopic diffusion of electrons and ions could be nonstandard: Diffusion and friction coefficients are energy dependent, collisions are not two-body processes and retain memory beyond the single scattering event. A direct consequence of nonstandard diffusion is that the equilibrium energy distribution of particles departs from the Maxwellian one (tails go to zero more slowly or faster than exponentially) modifying the reaction rates. This effect is qualitatively different from temperature and/or composition modification: Small changes in the number of particles in the distribution tails can strongly modify the rates without affecting bulk properties, such as the sound speed or hydrostatic equilibrium, which depend on the mean values from the distribution. This mechanism can considerably increase the range of predictions for the neutrino fluxes allowed by the current experimental values (cross sections and solar properties) and can be used to reduce the discrepancy between these predictions and the solar neutrino experiments.

Helioseismology can test the Maxwell-Boltzmann distribution
S. Degl’Innocenti, G. Fiorentini, M. Lissia, P. Quarati, B. Ricci
astro-ph/9807078, to appear on Phys. Lett. B

Nuclear reactions in stars occur between nuclei in the high-energy tail of the energy distribution and are sensitive to possible deviations from the standard equilibrium thermal-energy distribution. We are able to derive strong constraints on such deviations by using the detailed helioseismic information of the solar structure. If a small deviation is parameterized with a factor $\exp(-\delta(E/kT)^2)$, we find that $\delta$ should lie between $-0.005$ and $+0.002$. However, even values of $\delta$ as small as $0.003$ would still give important effects on the neutrino fluxes.

Non-Markovian effects in the solar neutrino problem
G. Gervino, G. Kaniadakis, A. Lavagno, M. Lissia, P. Quarati
physics/9809001, to appear in the Proceedings of Nuclei in the Cosmos V (1998)

The solar core, because of its density and temperature, is not a weakly-interacting or a high-temperature plasma. Collective effects have time scales comparable to the average time between collisions, and the microfield distribution influences the particle dynamics. In this conditions ion and electron diffusion is a non-Markovian process, memory effects are present and the equilibrium statistical distribution function differs from the Maxwellian one. We show that, even if the deviations from the standard velocity distribution that are compatible with our present knowledge of the solar interior are small, they are sufficient to sensibly modify the sub-barrier nuclear reaction rates. The consequent changes of the neutrino fluxes are comparable to the flux deficits that constitute the solar neutrino problem.
6 Hot topics

In this section we consider a few points, which look presently as particularly interesting and which will be investigated by our collaboration, in the near future.

6.1 hep neutrinos

They are produced by means of the reaction,

\[ p + ^{3}\text{He} \rightarrow ^{4}\text{He} + e^+ + \nu_e \]  

(7)
a very marginal branch of the pp-chain, \(\Phi(\text{hep})/\Phi(\text{tot}) \approx 10^{-8}\), which gives the highest energy solar neutrinos (\(E_{\text{max}} = 18.8 \text{ MeV}\)). In the last few months, these rare neutrinos have become particularly interesting in view of the surprising result of Superkamiokande [3], which reported an excess of events near and beyond the end point of the \(^8\text{B}\) spectrum. This result might be explained [43] by an anomalously high hep flux,

\[ \Phi(\text{hep}) \approx 30\Phi(\text{hep})_{\text{SSM}} \]  

(8)

where \(\Phi(\text{hep})_{\text{SSM}} = 2.1 \cdot 10^3 \text{cm}^{-2} \text{s}^{-1}\) is the SSM prediction [11].

This result has to be taken with some reservation. The experimental indication is not that strong, and actually needs confirmation. Within one year Superkamiokande will have collected enough data to establish beyond any statistical doubt if the excess of high energy events is there. Furthermore, more or less in the same time data from SNO should be available. These are particularly interesting, since the neutrino detection is based on a completely different method.

Let us observe that for the first time we have an excess, and not a deficit, of solar neutrinos! Beyond this possibly amusing point, one has to remark the substantial progress of our experimental colleagues. Solar neutrino physics has really advanced to a stage such that even the rarest branch of the pp chain has possibly been detected.

The measurement of \(\Phi(\text{hep})\) is really a benchmark for testing our present knowledge of stellar interiors, if the zero energy astrophysical S-factor of reaction (7) has been correctly calculated.

In fact one can derive on very general grounds upper bounds on the ratio \(\Phi(\text{hep})/S_{13}\) [24]:

i) From the luminosity constraint, i.e. the fact that the presently observed solar luminosity equals the nuclear power presently generated in the solar interior, one has:

\[ \Phi(\text{hep})/S_{13} \leq 3\Phi(\text{hep})_{\text{SSM}}/S_{13,\text{SSM}} \]  

(9)

ii) If one assumes that hep neutrinos are produced in a region where \(^3\text{He}\) abundance has reached local equilibrium – an assumption which is actually a result in
many standard and non standard solar model calculations – one gets a stronger bound by using helioseismology:

$$\Phi(\text{hep})/S_{13} \leq 1.7\Phi(\text{hep})_{\text{SSM}}/S_{13\text{SSM}}.$$  \hspace{1cm} (10)

In other words, if $\Phi(\text{hep}) \simeq 30\Phi(\text{hep})_{\text{SSM}}$ is confirmed and the present value $S_{13\text{SSM}} = (2.3\pm0.9) \cdot 10^{-20}$ KeVb \cite{45,25} is confirmed, then one should abandon the common view of the solar interior, which should be in a state dramatically out of equilibrium conditions.

All this shows the relevance of an accurate calculation of $S_{13}$, a rather difficult task indeed. With respect to the intitial estimate by Salpeter \cite{44}, the presently accepted value is smaller by two orders of magnitude. This results from selection rules as well as from subtle cancellations, as emphasized in \cite{45}. The authors of \cite{45} are very careful in estimating an uncertainty of at least a factor two in the recommended value. In view of the present situation, a more refined examination, including fully state-of-the art methods of few body physics is clearly needed, and the Pisa group has all the technology which is needed for this difficult goal.

### 6.2 Be-e-p neutrinos

In addition to neutrinos from $^8B$ beta decay, a few neutrinos can also result from electron capture, $e^- + ^8B \rightarrow \alpha + \alpha + \nu_e$. Their energy is clearly $2m_e$ above the end point of the $^8B$ decay, so that they are in the region of the event excess reported by Superkamiokande. Evaluation of the flux of these neutrinos is thus clearly interesting. One has to remind that in the calculation one has to take into account the full reaction which yields these neutrinos:

$$^7\text{Be} + e^- + p \rightarrow \alpha + \alpha + \nu_e \hspace{1cm} (11)$$

which justifies the nickname “Be-e-p”. The calculation is in progress, within a collaboration between Milan and Ferrara.

### 6.3 p-e-p neutrinos

These too are (relatively) rare neutrinos, from:

$$p + e + p \rightarrow d + \nu_e \hspace{1cm} (12)$$

the estimated flux being about one percent of the total neutrino flux.

The ratio $R = \Phi(\text{pep})/\Phi(\text{pp})$ is an important quantity, for discriminating among several proposed solutions of the solar neutrino puzzle. The point is that $R$ should be predicted very accurately, since several uncertainties, originating from both nuclear physics and astrophysics, cancel in the ratio. On the other hand, there are oscillation mechanisms which predict strongly different oscillation probabilities for pp and pep neutrinos \cite{46}. Furthermore, the ratio $R$ will be measured in future generation solar neutrino experiments, e.g. Hellaz.
So far, $R$ has been calculated many years ago only in [47], using several approximations. On the other hand, such a few body problem is within the possibility of an “ab initio” calculation. Due to the importance of this quantity, the Pisa and Ferrara nodes are planning to produce a new estimate in the near future.

### 6.4 LENS

A new solar neutrino experiment has been proposed recently by Raghavan [5]. The experimental aim is really a Low Energy Solar Neutrino Spectroscopy - hence the acronym LENS - of unprecedented quality, see Fig 5. The experiment should clearly discriminate between pp and Be neutrinos, a feature which is very important again in connection with the predictions of different oscillation mechanisms. Concerning Be neutrinos, one has to remark the complementarity between this experiment and Borexino. Since LENS is sensitive only to $\nu_e$, whereas the signal in Borexino gets contribution from any active neutrino species, the comparison between the results of the two experiments should allow to extract the signature of active neutrinos other than $\nu_e$, i.e. one can exploit the conjunction between the two experiments so as to realize an “appearance” experiment. We remark also that LENS should be able to detect neutrinos from the CNO cycle.

The reaction to be used in Lens is

$$\nu_e + ^{160}\text{Gd} \rightarrow ^{160}\text{Tb}^* + e^- \quad (13)$$

The electron is detected in (delayed) coincidence with the gammas resulting, a few nanoseconds after neutrino capture, from $^{160}\text{Tb}^*$ decay, so as to reduce background to acceptable levels.

Of course, the cross section of (13) will have to be measured “a posteriori” with the same detector used for solar neutrinos, by irradiating the target with an artificial neutrino source, e.g. the $^{51}\text{Cr}$ source used by Gallex or a similar and possibly more powerful one. However, a knowledge, as good as possible, of the cross section is important “a priori” for planning the detector and determine its size. Some indirect experimental data is available, by means of a recent study of the Gd($^3\text{He},^3\text{H})\text{Tb}$ reaction at Osaka. A significant theoretical effort however is needed in order to understand the complicated excitation pattern and the strength of the transitions to different excited states, an activity which looks well on the research lines of the Milan group.

### 6.5 LUNA2 at LNGS

Some years ago Rolfs and Fiorentini proposed that INFN exploits the underground facilities at Laboratori Nazionali del Gran Sasso to measure nuclear cross sections at the low energies of astrophysical interest, in an environment naturally shielded against the cosmic radiation, so that even very low reaction rates can be discriminated from background, see box 5.
To the President of INFN  
Prof. Nicola Cabibbo  
cc:  
To the Director of The Gran Sasso Lab  
Prof. Enrico Bellotti  
Ferrara 7 January 1991  

Dear President,

We believe that the Gran Sasso Laboratory offers a unique possibility for progress in the measurement of low energy nuclear cross sections, which are relevant for nucleosynthesis in stars and in the early universe, as well as for the evaluation of the solar neutrino flux.

In this context, hydrogen burning processes operating in the p-p chain (low-mass stars, such as the sun) and in the CNO-cycles (high-mass stars) are of particular interest. Experimental studies of these processes have been carried out to energies \( \frac{E}{E_c} \) far below the respective Coulomb barriers \( E_c \). However, experiments have been performed so far typically at energies \( \frac{E}{E_c} \) greater than \( 1/20 \), whereas the stellar burning occurs at \( \frac{E}{E_c} \approx 1/100 \). Thus, the available data have always to be extrapolated.

Fig. 5. Spectrum of expected events in LENS experiment.
INFN answered quickly, actually on the phone. A small 30 kV accelerator was installed at LNGS and in this way the first Laboratory for Underground Nuclear Astrophysics (LUNA) was born. LUNA has been successful [48, 49]. As an example, for the first time a nuclear reaction, $^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p$, was measured at the energies relevant for burning in the sun [49]. Corvisiero et al. [6] are now planning LUNA2, a second generation apparatus involving a 200 kV accelerator, which should be capable of measuring several other cross sections relevant to H burning in the sun via the pp-chain and the CNO cycle, see Table. Furthermore, the experiment can also measure other few body reactions at very low energies, so that, e.g., electron screening of nuclear reactions can be elucidated. This will offer a unique opportunity to test the most accurate calculation methods of few body nuclear physics, so that one can again expect a strong collaboration between the experimental group and our theoretical network.

| Year | Reaction          |
|------|------------------|
| 1999 | Installation and testing of a new 200KV accelerator |
| 2000 | $^3\text{He}(\alpha, \gamma)^7\text{Be}$ |
| 2001 | $^7\text{Be}(p + \gamma)^8\text{B}$ |
| 2002 | $^{14}\text{N}(p, \gamma)^{16}\text{O}$ |

**Acknowledgments**

I would like thank particularly Giovanni Corbelli and Barbara Ricci for their help in preparing this compuscript. I am grateful to Pierfrancesco Bortignon, Sergio Rosati and Pierino Quarati, for fruitful discussion about the activity within the network. This work was supported by Ministero dell’ Universita’ e della Ricerca Scientifica e Tecnologica (MURST).

**References**

1. V. Castellani, S. Degl’Innocenti, G. Fiorentini, M. Lissia and B. Ricci, Phy. Rep. 281 (1997) 309.
2. J. N. Bahcall, P.I. Krastev and A.Yu. Smirnov, hep-ph/9807216, to appear on Phys. Rev. D (1998)
3. Superkamiokande collaboration, XVII International Conference on Neutrino Physics and Astrophysics (Neutrino '98), Takayama, Japan, June 1998, to appear on Nucl. Phys. B (Proc. Suppl.),
4. Superkamiokande collaboration, Phys. Rev. Lett. 81 (1998) 1562.
5. R.S. Raghavan, Phys. Rev. Lett. 78 (1997) 3618.
6. LUNA collaboration, proposal of LUNA2, preprint 1998.
7. H.A. Bethe, Phys. Rev 55 (1939) 434.
8. H.A. Bethe and C.L. Critchfield, Phys. Rev. 54 (1938) 248.
9. GALLEX collaboration, Phys. Lett. B 327 (1994) 377; GALLEX collaboration, Nucl. Phys. B (Proc. Suppl.) 70 (1999) 284 and Refs. therein.
10. A. I. Abazov et al., Phys. Rev. Lett. 67 (1991) 3332;
11. J.N. Bahcall, S. Basu and M.H. Pinsoneault, Phys. Lett. B 433 (1998) 1.
12. J.N. Bahcall, Phys. Rev. Lett. 71 (1993) 2369; J.N. Bahcall, Phys. Rev. D 49 (1994) 3293.
13. P. Cennini et al., Icarus Proposal vol 1 & 2, LNGS-94/99.
14. C. Arpesella et al., “Borexino at Gran Sasso: proposal for a real time detector for low energy solar neutrinos”, internal report INFN, Milano, 1992.
15. K.S. Hirata et. al. Phys. Rev. Lett. 58 (1987) 1490.
16. T.J. Loredo and D.Q. Lamb, in Proc 14th Texas Symp. on Relativistic Astrophysics, Ann. N.Y. Ac. Sc. (1988) 601.
17. M. Koshiba, Phys. Rep. 220 (1992) 231.
18. A. Barrows, D. Klein adn R. Gandhi, Phys. Rev. D 45 (1992) 3361.
19. G. Fiorentini and C. Acerbi, Astr. Phys. 7 (1997) 245.
20. S. van den Bergh and G.A. Tammann, Ann. Rev. Astron. Astroph. 29 (1991) 363.
21. J.N. Bahcall, Phys. Lett. B 338 (1994) 276.
22. S. Degl’Innocenti, G. Fiorentini and M. Lissia, Nucl. Phys. B (Proc. Suppl.) 43 (1995) 66.
23. V. Barger, T.J. Weiler and K. Whisnant, hep-ph/9808367
24. S. Degl’Innocenti, G. Fiorentini and B. Ricci, astro-ph/9810083, to appear on Phys. Lett. B.
25. E. G. Adelberger et al., astro-ph/9805121, to appear on Rev. Mod. Phys. (1998)
26. Nacre Collaboration, to appear on Nucl. Phys. A (1998).
27. M. Viviani, S. Rosati, A. Kievsky, Phys.Rev.Lett. 81 (1998) 1580.
28. C. R. Brune, W. H. Geist, H. J. Karwowski, E. J. Ludwig, K. D. Veal, M. H. Wood, A. Kievsky, S. Rosati, M. Viviani, Phys. Lett. B 428 (1998) 13.
29. R. Schiavilla, V. G. J. Stoks, W. Gloeckle, H. Kamada, A. Nogga, J. Carlson, R.Machleidt, V. R. Pandharipande, R. B. Wiringa, A. Kievsky, S. Rosati, M. Viviani, Phys.Rev. C58 (1998) 1263.
30. GALLEX Collaboration, Phys. Lett. B 342 (1995) 440;
31. Review of Particle Physic, Europ. Phys. J. C 3 (1998) 1, and refs. therein.
32. E. Brocato, V. Castellani, S. Degl’Innocenti, G. Fiorentini, and G. Raimondo, Astron. Astroph. 333 (1998) 910.
33. K. Grotz and H.V. Klapdor, “The weak interaction in nuclear particle and astrophysics”, Adam Hilger Publishing, Bristol 1990.
34. W.E. Ormand, P.M. Pizzochero, P.F. Bortignon, and R.A. Broglia, Phys. Lett. B308 (1993) 207.
35. A. Alessandrello et al., preprint INFN/AE-92/25 (1992).
36. W.E.Ormand, P.M. Pizzochero, P.F. Bortignon, and R.A. Broglia, Phys. Lett. B345 (1995) 343.
37. M. Bianchetti, M. R. Quaglia, G. Colog, P.M. Pizzochero, R.A. Broglia and P.F. Bortignon, Phys. Rev. C 56 (1997) R1676.
38. A. Alessandrello et al., Phys. Rev. Lett. 77 (1996) 3319.
39. S. Degl’Innocenti, G. Fiorentini, B. Ricci, Phys. Lett. B416 (1998) 365.
40. G. Kaniadakis, A. Lavagno, M. Lissia, P. Quarati, astro-ph/9710173.
41. G. Gervino, G. Kaniadakis, A. Lavagno, M. Lissia, P. Quarati, physics/9809001, to appear in the Proceedings of Nuclei in the Cosmos 1998.
42. S. Degl’Innocenti, G. Fiorentini, M. Lissia, P. Quarati, B. Ricci astro-ph/9807078, to appear on Phys. Lett. B.
43. J.N. Bahcall and P.I. Krastev, hep-ph/9807525 (1998).
44. E.E. Salpeter, Phys. Rev. 88 (1952) 547.
45. R. Schiavilla, R.B. wirings, V.R. Pandharipande, J. Carlson, Phys. Rev. C 45 (1992) 2628.
46. E. Calabresu, N. Ferrari, G. Fiorentini and M. Lissia, Astropart. Phys. 4 (1995) 159.
47. J.N. Bahcall and R.M. May, Ap. J. (1969) 501.
48. LUNA collaboration, Nucl. Ins. Meth. A 350 (1994) 327.
   LUNA collaboration, Nucl. Ins. Meth. A 360 (1995) 607.
   LUNA collaboration, Phys. Lett. B 389 (1996) 452.
49. LUNA collaboration, Phys. Rev. C 57 (1998) 2700.