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NUCLEAR REACTIONS IN THE STARS AND IN THE LABORATORY *

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The paper discusses the reaction rates at low energies, needed for the description of nucleosynthesis processes. In contrast to the stellar environment, the laboratory measurements are complicated by the coulomb potential screening caused by bound electrons. The consequences of recent ^{7}Be+p reaction measurements on solar modelling are presented. The new high-energy laser facilities will open new possibilities for measurements of stellar reaction rates.
Abstract provided by the editors.

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1. Introduction

Astrophysicists want to describe the physics involved in the various sites where nucleosynthesis takes place, and accordingly the nuclear parameters governing these processes have to be determined as well as possible. Actually the modeling of the various sites needs the use of reactions networks, including all nuclear reactions and decays that can play a role in energy generation or chemical transformation of the material. For instance is shown (figure 1) the reaction network we used for big bang nucleosynthesis studies. For any computation one must know the rates of all these reactions (symbolised by lines connecting the nuclei) in the range of relevant temperatures.

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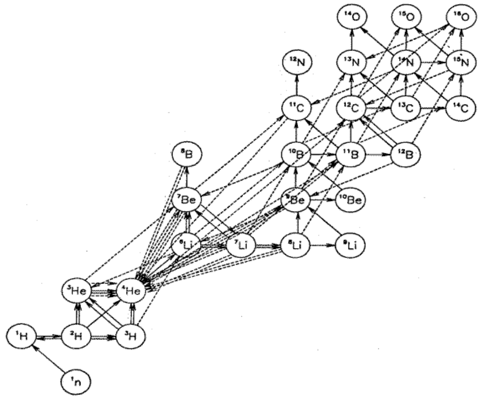

Fig. 1. Reaction network used for Big Bang nucleosynthesis calculations [1].

1.1. Nuclear reaction rates

Due to the exponential increase of the tunnelling probability with increasing energies, non resonant nuclear reactions usually occur at higher energies than the mean energy of particles (corresponding to the site temperature), in the energy range of the so called "Gamow peak" (in case of resonances in the cross section, this may be slightly modified). In the sun core, the temperature is 15 millions degrees, that corresponds to a mean kinetic energy of 1–2 keV. For the ^{7}Be+p reaction the Gamow peak energy is 15–20 keV, however still much smaller than the coulomb barrier. Cross sec-

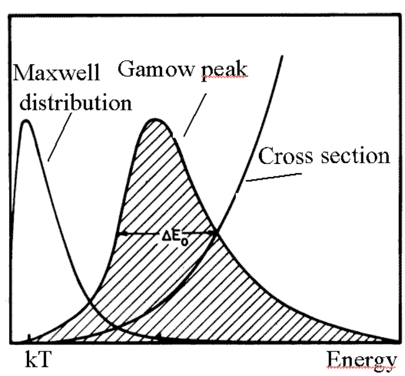

Fig. 2. The convolution of the Maxwell Boltzmann distribution and the tunneling function through the barrier results in a peak (the Gamow peak) giving a sufficiently high probability to allow a significant number of reaction to occur (from [2]).

tion determination of these reactions leads to large experimental problems connected either with the low cross section or with activity of the target or the beam for explosive nucleosynthesis studies. For the ^{7}Be+p reaction, the cross section at the Gamow peak energy ranges 10^{-15} barn! It should be stressed that each reaction with light nuclei represents a specific problem, and that no general computation as Hauser–Feschbach type analysis is valid.

1.2. Nuclear reaction cross sections at low energy

It is clear that nuclear reaction studies become very difficult at low energy because of the coulomb barrier. So far cross sections in the range of picobarn were measured for some particular reactions like ^{3}He(^{3}He,2p)^{4}He using current technology (high intensity beam, underground experiment to reduce the background in the detectors, multidetectors ...). By chance it corresponds to the Gamow peak energy in the sun (see Fig. 3). But in all other cases the cross sections to be measured are smaller than picobarn by orders of magnitudes. Then the procedure is the following: the cross section is measured at higher energies and then extrapolated to astrophysical energies using theoretical calculations that must fit the experimental data.

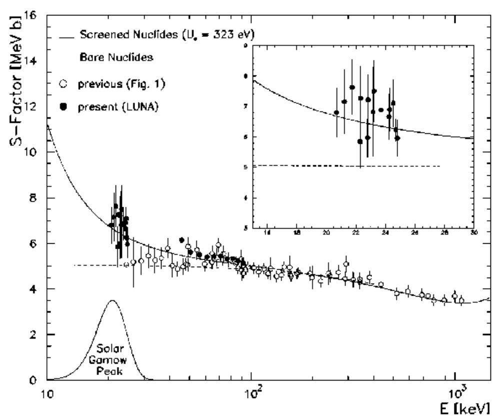

Fig. 3. The ^{3}He(^{3}He,2p)^{4}He S-factor measurements from [3].

1.3. Electron screening effect in laboratory

At very low energy the extrapolation procedure may be complicated by the fact that cross sections measured in the laboratory are enhanced by the coulomb potential screening effect arising from bound electrons present in the target (and the projectile). This screening effect has already been seen in many experiments involving light nuclei (like ^{3}He(^{3}He,2p)^{4}He; see Fig. 3). Roughly the screening effect has a notable influence for energies smaller than 10 to 100 times the U_e value given by the difference in binding energy of the unified atom and the sum of the projectile and target atoms. However some observed enhancement are found larger than predicted, and this discrepancy make the screened experimental data quite useless for bare nucleus cross section determination. These discrepancies could have their origin in the energy loss data [4].

1.4. Screening in the stellar plasma

In laboratory experiments electrons are bound to the nucleus while in stellar plasmas they occupy (mainly) continuum states. Therefore the screening effects are different in the laboratory and in the stellar plasmas. In the sun core for most reactions the screening is expected to be weak and the Salpeter formula may be used which takes into account the Debye radius (that depends on the density, on the temperature and composition of the plasma). This calculation is usually corrected for second order effects and it is believed that the accuracy of the correction is better than a few percents for all reactions [4]. However no one experiment was ever made to measure the screening effect in a solar like plasma.

2. The ^{7}Be+p reaction and solar neutrinos

2.1. Solar modeling for the determination of the neutrino properties

In the sun core the hydrogen nuclei are burned into helium through three reaction chains (figure 4) and this transformation gives rise to various neutrinos. To mention briefly the experimental results, one can say that the neutrino flux detected on the Earth was always found appreciably smaller than predicted by the so called Standard Model. The ^{7}Be+p cross section governs the flux of ^{8}B neutrinos that plays a critical role in the solar neutrino puzzle: the neutrinos from ^{8}B decays are very energetic and the most easily detected on the Earth. Furthermore the ^{8}B neutrino flux is very sensitive to the sun temperature (Φ is proportional to T^{24} and a lower ^{8}B neutrino flux could have its origin in a lower core temperature). After the Gallex and Sage experiment, the set of neutrinos data rules out any explanation of the observed deficit by only solar modeling (*i.e.* with a cooler sun core) or nuclear reactions rates (decreasing the flux of material processed by this reaction). So the experimental results on solar (and atmospheric) neutrinos are considered strong evidence for neutrino oscillation scenarios, in which the still uncertain mass differences and mixing angles may be related to the solar modeling and nuclear cross sections. For the neutrino properties

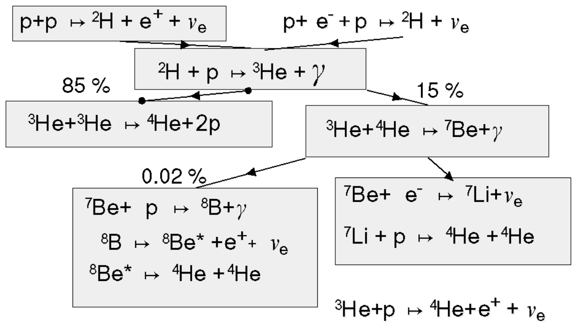

Fig. 4. The main nuclear reactions in the sun.

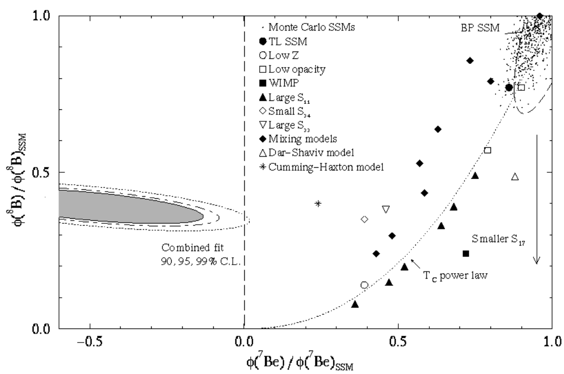

Fig. 5. 90% CL combined fit for the ^{7}Be and ^{8}B fluxes. The best fit occurs at $\Phi(^7\mathrm{Be})< 0$ and around half the ^{8}B Standard Model value (from http://dept.physics.upenn.edu/ www/neutrino/ by N. Hata and P. Langacker).

determination, it is important to know accurately all reactions rates like ^{3}He(^{3}He,2p)^{4}He and ^{7}Be(p,γ)^{8}B with an accuracy better than 5% as shown in details by Bahcall *et al.* [5].

2.2. The ^{7}Be+p reaction cross section recent measurements

During years the cross section of ^{7}Be+p cross section was calculated by averaging the world data which were in disagreement by more than 30% due to systematic errors that were not understood. Many experiments are now running around the world (at Seattle, Rehovot, Naples, Bochum ...) to obtain more accurate results and remove any doubt on the value of the cross section. Most recent measurement [6, 7] give results compatible with those of Filippone *et al.* [8] (see figure 6).

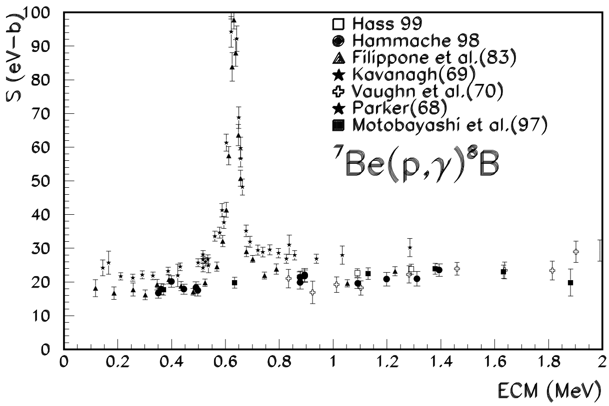

Fig. 6. S factor world data for the ^{7}Be(p,γ) reaction.

2.3. Extrapolation at solar energy

The ^{7}Be(p,γ) reaction is measured at energies higher than 110 keV, while it takes place at around 20 keV in the sun. Due to the small binding energy of ^{8}B (Q = 137.5 keV), the ^{7}Be+p reaction at low energy is an external direct capture process (see [9] for the most recent calculation, within the frame of the shell model, and references herein) which takes place at large distances (greater than 7 fm). At such distances the E1 capture probes the Whittaker asymptotics of the ground state and the Coulomb functions describing the ^{7}Be+p scattering states. Consequently below 300 or 400 keV the cross section behaviour should be almost model independent. At higher energies theoretical calculations disagree for the energy dependence of the cross section because above 400 keV the reaction becomes sensitive to nuclear structure (the capture process probes the internal wave functions). For an accurate extrapolation (model independent) only low energy data could in principle be used. Extrapolation of the most recent data leads to a value near 19 eV b, 15 % below the previously adopted value of 22.4 eV b obtained by averaging the world data. This implies a reduction by the same factor of the neutrino flux. However, some theoretical calculations do predict levels in ^{8}B that have not been seen, but could exist above the particle threshold [10]. The tails of such resonances could have an influence on the cross section at low energy. So due to the accuracy needed in the case of this reaction involved in the solar modeling and neutrino generation in the sun, both careful theoretical and experimental studies should still be made.

2.4. Influence of new reaction rates on the solar modeling

Recently the cross sections of solar reactions have been scrutinized and critically reviewed by two independent groups of physicists. The first compilation was made for sun modelisation purpose [4]. The second has more ambitious goal and provide reaction rates for most nuclear processes involving nuclei with mass<40 [11]. In a recent paper both compilations are used as input in the same solar standard model [12]. Calculations are made for the global structure of the sun, expected neutrinos fluxes, chemical composition, and sound speed profiles.

Table I [12] shows the expected fluxes for the three neutrino experiments (chlorine, gallium and Kamiokande) compared with the observed values. In the last line are shown the expected fluxes in events per day while in SNU for the two first lines. The Kamiokande (chlorine) experiment is sensible only (respectively partly) to the ^{8}B neutrinos. The difference between the expected fluxes is mainly due to the difference in the ^{7}Be+p cross section values adopted by both compilations, namely 21 [11] and 19 eV b [4].

TABLE I

Observed neutrinos fluxes compared with calculations

	N99	A98	Observed values
Φ_{Gallex}	130.1	128.4	77.75 SNU
Φ_{Chlore}	8.31	7.71	2.55 SNU
Φ_{Ka}	0.61	0.55	0.29evts/day

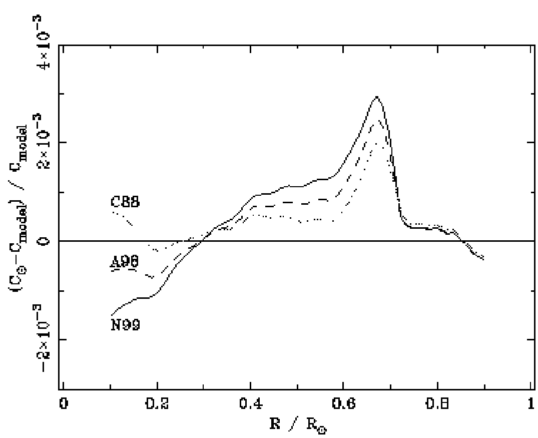

Fig. 7. Relative difference in sound velocities between the sun and the calibrated models from [12]; C88, A98 N99 refer to [4, 11, 13] respectively.

The sound speed calculated using both sets of data are compared to each other and to the sound speed deduced from helioseismology measurements made by the SOHO satellite. The results for the sound speed disagree by around 30% in the region above the core and below the convective zone (R <0.7 R_{sun}) due to a small 5% difference in the $p+p$ reaction rate (which was never measured). This reaction governs the rate of the hydrogen fusion into helium and then the actual core size and the temperature and density profile inside the sun. One sees that a much better accuracy in nuclear cross sections is needed to take profit of the helioseismology measurements.

3. High energy lasers

The development of high energy laser facilities in US (NIF) and France (MegaJoule) is opening many new fields for the experimentalists. The high energy high density plasmas produced by laser shots are close to those found in the stars, and astrophysics should provide strong motivations to studying theses plasmas: among these are radiative opacities, the equation of state, plasma instabilities, *etc.*

3.1. Plasmas for nuclear astrophysics studies

There are two motivations for nuclear reaction studies with plasmas: the first is a fundamental motivation to study the influence of the plasmas characteristics on the nuclear reactions: the screening of the nucleus coulomb potential could be studied for the first time in stellar conditions. The second is that this tool is expected to be more powerfull that accelerators-based experiments due to the huge amount of reactions produced in the heated plasmas with mm or cm sizes. In addition, nuclear reactions occur in a very short time, and no background events should mask the true events in detectors!

Figure 8 describes the temperature density parameter space relevant for high energy laser plasmas. The NIF and MJ conditions overlap various stellar burning phases. Even without ignition of a D+T bullet, hydrogen and helium burning temperatures are obtainable at corresponding density regimes. It seems possible that using appropriate target design one may be able to nearly reproduce these stellar conditions during a very short time (ns).

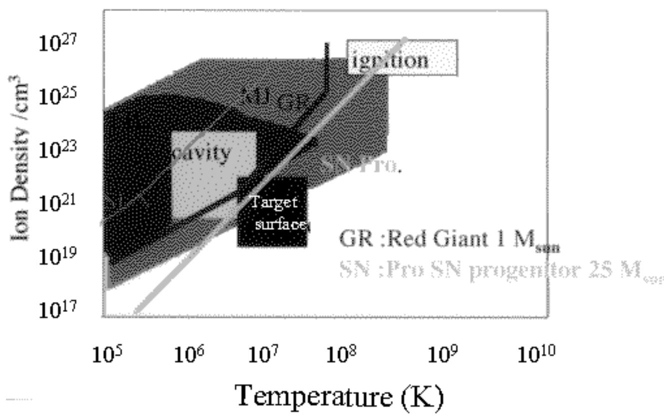

Fig. 8. Comparison of the regimes of temperature and density that will be attained on the MJ with typical conditions found for various stars [14].

3.2. An example: the d(p,γ)^{3}He reaction

This reaction could be studied as a test case [15] using the gas bag technique (a direct shot on a bullet filled with protonium and deuterium) that is expected to guarantee homogeneous conditions during nanosecond periods of time. Table II shows the number of expected counts for various temperatures and for a 0.6 cm^3 gas bag. One sees that at 3.1 keV the expected count is the same as for an accelerator-based measurement at 10 keV during 5000 hours!

TABLE II

Expected number of events in a plasma at various temperatures compared with accelerator-based measurements for the d(p,γ)^{3}He reaction.

T	$E_{\rm Gamow}$	$\Gamma_{\rm Gamow}$	rate/ns	etvs/time	facility
kelvin			/cm^3	cm^3/3bars	
1 E6	1.1	0.9	1.E-7		LIL
5 E6	3.1	2.7	0.2	100/s	LIL
100 E6	23	32	40000	2E7/s	MJ
$E_{\rm cm}$=10keV	10			100/5000h	accelerator

The detection system should have both a high efficiency for 5.5 MeV γ rays and a very efficient neutron rejection because the $D+D$ reaction is expected to produce a huge amount of 2.5 MeV neutrons (more than 500 times the gamma flux). Neutrons gamma discrimination could be based on time of flight technique, provided the detectors are at a distance larger than 1 meter. The gamma induced signal should then be integrated in 10 to 20 ns. High dynamics (factor 1000) is required due to high sensitivity of the reaction rate with the temperature. Finally a TAPS like detector appears well suited for the study of this reaction in the MJ chamber. With a few tens to a few hundred of thousands of events in the range 10^7 to 10^9 K, the needed statistics could be reached with a single shot, or with a few shots for low temperature regimes.

4. Conclusion

From the early times when Davis and Bahcall wanted to detect solar neutrinos to check that nuclear reactions are the sun's fuel, to the present day, no agreement has ever been found between the measured neutrino flux and the theoretical predictions. In order to reduce the uncertainties in solar modeling all the key reactions have been investigated many times with increasingly sophisticated methods and techniques. Despite these efforts too large uncertainties still remain for some important reactions like ^{7}Be(p,γ)^{8}B, ^{3}He(^{4}He,γ)^{7}Be, ^{3}He($p, e^+\nu_e$)^{4}He, and even the $p+p$ one. The accuracy requirement is found in others areas: the ^{12}C(α,γ)^{16}O reaction should be mentioned as the most important reaction for large mass star evolution and also a few reactions for Big Bang nucleosynthesis calculations with too large uncertainties when compared with the accuracy of the determination of the light element abundances. For a few years now nuclear astrophysics has entered the precision era ... . For this precision are also needed data on stellar screening, and for the first time new facilities will create sample plasmas similar to those found in astronomical bodies and will provide a laboratory environment for the study of various plasma properties.

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