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The nuclear processes relevant to the synthesis of the γ rays emitters ^{26}Al and ^{60}Fe

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Abstract. Long-lived γ rays emitter isotopes constitute a unique opportunity to shed light on the sites where Nucleosynthesis is presently ongoing and on the evolutionary properties of the stars that emit such nuclei. In fact, their half life is long enough to expect them to be present in an appreciable amount in the Galaxy but short enough to decay quite close to the stars responsible for their production. In this paper we will focus on two specific long-lived γ rays emitters, namely ^{26}Al and ^{60}Fe. In particular, we will examine which nuclear processes are relevant for their production and hence point out the importance of (re)measuring their nuclear cross sections in order to improve the theoretical yields of both these nuclei produced by the massive stars.

Key words. Stars: evolution – Stars: supernovae – Stars: massive stars – Nucleosynthesis – Nuclear reactions

1. Introduction

In this talk we'll briefly review the nuclear processes that are relevant for the synthesis of two important long-lived gamma ray emitters, ^{26}Al and ^{60}Fe. The importance of these nuclei has been pointed out many times over the last three decades and will not be repeated. Here it suffices to remind that both nuclei are mainly produced by stars more massive than, say, 12-15 $M_{\odot}$. While ^{60}Fe has always been associated to the massive stars, the origin of the bulk of ^{26}Al has been debated for a long time. Quite recently a comparison between the ^{26}Al all sky map produced by COMPTEL and other all sky maps in different energetic bands (Knödlseder et al. 1999; Knödlseder 1999) revealed that the ^{26}Al shares exactly the same angular distribution of the 53 GHz free free emission that maps the regions of strongly ionized gas. Since only stars more massive than 12-15 $M_{\odot}$ produce a sufficiently strong ionizing flux, it follows that the ^{26}Al all sky map superimposes to the distribution of the massive stars. A comprehensive review of all aspects of the astrophysical importance of both ^{26}Al and ^{60}Fe has been given

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by Limongi & Chieffi (2006). In the following we'll address each nucleus separately.

2. ^{26}Al

^{26}Al is produced in three distinct evolutionary stages: the central H burning, the C convective shell just prior the core collapse and the explosive Ne burning.

The synthesis of this nucleus in H burning is controlled by the simple balance between the ^{25}Mg(p, γ) and the β^+ decay. There is no addition of ^{25}Mg by any process so that the total amount of available fuel is just the initial abundance of ^{25}Mg (that amounts to 7.1 10^{-5} by mass fraction in the solar system composition). The most recent determination of the cross section for the ^{25}Mg(p, γ)^{26}Al has been provided by Iliadis et al. (2001) and the uncertainty quoted for this process at the relevant temperatures (30-50 Million K) is significantly less than a factor of 2. Hence one could imagine that the synthesis of the ^{26}Al by the H burning does not deserve any special attention (from the point of view of the nuclear cross sections, of course). This is not the case since the ^{26}Al(p,γ)^{27}Si process, that presently does not compete significantly with the β^+ decay, may be presently underestimated by a factor as large as one hundred (Iliadis et al. 2001). It could even be overestimated by many orders of magnitudes but this is of no relevance in this context because already the recommended rate is low enough that the β^+ decay dominates the ^{26}Al destruction. The ^{26}Al(p, γ)^{27}Si and the β^+ decay rates intersect at a temperature of the order of 46 MK for a typical central density of 10 gr/cm^3 and central H abundance equal to 0.35 by mass fraction. Though the β^+ decay overcomes the ^{26}Al(p, γ) over the whole range of the massive stars, in many cases its rate is not smaller than a factor of 2-3 with respect to the β^+ decay rate. Since the ^{26}Al(p, γ)^{27}Si cross section is uncertain by a much larger factor, it is clear that a better determination of this cross section is mandatory to constrain the theoretical estimate of the ^{26}Al produced by the H burning and (partly) ejected by the stellar wind.

The synthesis of ^{26}Al in the C convective shell occurs in the final rapid contraction of the CO core just prior the core collapse and it is once again the result of the balance between the ^{25}Mg(p, γ)^{26}Al and the β^+ decay. In this case, however, the ^{25}Mg comes from the conversion of the initial global abundance of the CNO nuclei into ^{22}Ne first and into ^{25}Mg later. The protons, vice versa, come from the balance between the ^{12}C(^{12}C,p)^{23}Na and the ^{23}Na(p,α)^{20}Ne, i.e. between the unique proton producer and the main proton poison. While the cross sections of the ^{25}Mg(p, γ)^{26}Al and the ^{23}Na(p,α)^{20}Ne seem to be reasonably well known (Iliadis et al. 2001), the determination of the ^{12}C(^{12}C,p)^{23}Na dates back to Caughlan & Fowler (1988), and hence we think it would be important to readdress the ^{12}C^{12}C rates as soon as possible. As for its destruction, let us remind that the ^{26}Al half life dramatically reduces as the temperature increases above 500 MK. Since such a shortening of the half life is purely theoretical, we could only check the stability, if not the reliability, of this rate by comparing the rates provided by three different papers: Fuller, Fowler & Newman (1982), Rauscher & Thielemann (2000) and Oda et al. (1994). Such a comparison shows that at the relevant temperatures (1-1.4 GK) the three estimates agree well within a factor of two. Other two processes marginally contribute to the ^{26}Al destruction, i.e. the ^{26}Al(n,p)^{26}Mg and the ^{26}Al(n,α)^{23}Na. The adopted rate for the first of the two is still the Caughlan & Fowler (1988) one while the second one has been redetermined by the NACRE team (Angulo et al. 1999). The uncertainty quoted for this last process is much smaller than a factor of two at the relevant energies. Two other processes that are important for the synthesis of the ^{26}Al are the ^{25}Mg(n, γ)^{26}Mg and the ^{25}Mg(α, n)^{28}Si since they may act as ^{25}Mg poisons. The first of these two rates is simply the one provided by Rauscher & Thielemann (2000) shifted in order to match the Bao et al. (2000) rate at 100 KeV (Limongi & Chieffi 2003); the second one comes from the NACRE compilation and for this process the NACRE team quotes an uncertainty of roughly a factor of two at a temperature of the order of 1 GK. On the basis of this analysis, it seems that the most uncertain nuclear cross section is, in this case, the

^{12}C(^{12}C,p)^{23}Na. Before going further on, we think to be important to remind that the process that really plays a major role in the synthesis of the ^{26}Al in the C convective shell is the ^{12}C(α,γ)^{16}O because it directly determines both the physical and chemical properties of the C burning.

The third episode of ^{26}Al production occurs in Ne explosive burning. Once again it is produced by the ^{25}Mg(p, γ)^{26}Al while its destruction is now mainly controlled by ^{26}Al(n,p)^{26}Mg and the ^{26}Al(n,a)^{23}Na processes. At variance with the two other episodes of production, this time there is a strong contribution to the abundance of the ^{25}Mg, and hence to that of the ^{26}Al, from the ^{24}Mg(n,γ)^{25}Mg. The relevant temperature is now of the order of 2.2-2.5 BK and at this temperature both the ^{25}Mg(p, γ)^{26}Al (Iliadis et al. 2001) and the ^{26}Al(n,α)^{23}Na (NACRE) seem to be quite well determined. We are not aware of the uncertainty connected with the ^{26}Al(n,p)^{26}Mg since, as far as we know, the only published rate is still the Caughlan & Fowler (1988) one. It is also quite difficult to determine, at least for us, the uncertainty of the ^{24}Mg(n,γ)^{25}Mg since also in this case we rely on the theoretical one provided by Rauscher & Thielemann (2000) shifted in order to match the Bao et al. (2000) rate at 100 KeV. All the processes involved in the synthesis of the ^{26}Al require the presence of the protons and neutrons and therefore one could question about the reliability of their abundances. Quite fortunately the equilibrium abundances of both protons and neutrons are determined by a rather conspicuous number of processes so that, even if one of them would be particularly uncertain, it should not affect their equilibrium abundance too seriously. Unfortunately, however, the fuel that really powers the production of protons and neutrons are the α particles provided by the photo disintegration of Ne. Since the Ne abundance totally depends on the amount of C left by the He burning, it turn out that also in this case the efficiency of the ^{12}C(α,γ)^{16}O severely influences the ^{26}Al production.

3. ^{60}Fe

^{60}Fe is an unstable nucleus that lies slightly out of the stability valley. The main processes that are directly involved in its synthesis are: ^{59}Fe(n,γ)^{60}Fe, ^{59}Fe(β^-)^{59}Co, ^{60}Fe(n,γ)^{61}Fe and ^{60}Fe(β^-)^{60}Co. The competition between the first two processes determines which fraction of the ^{59}Fe produced by the ^{58}Fe(n,γ)^{59}Fe can capture an additional neutron instead of decaying β^-. The second two processes both contribute to the destruction of ^{60}Fe. Since the neutron density plays a pivotal role in the synthesis of the ^{60}Fe, it goes without saying that also the main processes that determine the equilibrium abundance of neutrons are crucial for the production of this nucleus.

There are essentially three evolutionary phases in which ^{60}Fe may be produced: the He convective shell of stars more massive than, $\simeq$40M$_\odot$, the C convective shell and the Ne explosive burning.

Stars more massive than $\simeq$40M$_\odot$ lose all their H rich envelope plus a fraction of the He core through a strong wind: the progressive shrinking of the He convective core that follows the reduction of the He core mass leaves behind a He profile in which a "hot" He convective shell forms. By hot we mean that the temperature at its base reaches values even larger than 400 MK. At these temperatures the half lives of both ^{59}Fe and ^{60}Fe are still the terrestrial values and hence they may be assumed to be quite well known. As for the neutron captures on both nuclei we must rely on theoretical predictions (Rauscher & Thielemann 2000) and hence we cannot reliably evaluate their uncertainty. The adoption of these rates implies that only neutron densities larger than a threshold value of $\simeq 3\times10^{10}$ n/cm^3 may lead to a significant production of ^{60}Fe. The actual neutron density reached in the He convective shell is determined by the balance between the ^{22}Ne(α,n)^{25}Mg and the main poisons ^{16}O and ^{25}Mg; note that ^{12}C is a false poison in this case since the rate of the ^{12}C(n,γ)^{13}C is fully balanced by the ^{13}C(α,n)^{16}O. The latest measures for the ^{22}Ne(α,n)^{25}Mg reaction rate (Jaeger et al. 2001) seem to indicate a rather small uncertainty at the temperature of interest. Also the cross sections of neutron captures on ^{16}O and ^{25}Mg seem to have quite a small uncertainty (Bao et al. 2000).

The typical temperature at the base of the C convective shell is of the order of 1-1.5 BK and at this temperature the half lives of both ^{59}Fe and ^{60}Fe drop dramatically. Two theoretical estimates are available at present for the temperature dependence of the ^{59}Fe half life: a first one by Fuller, Fowler & Newman (1982) and a second one by Langanke & Martínez-Pinedo (2000). The two computations differ by more than an order of magnitude at the relevant temperatures and though the more recent theoretical determination is certainly much more accurate than the older one, it is not clear how much room still exists for a further significant change. As for the ^{60}Fe decay rate, we have adopted the Fuller, Fowler & Newman (1982) decay rate. The neutron capture cross sections on both ^{59}Fe and ^{60}Fe are obviously once again the Rauscher & Thielemann (2000) ones. The adoption of these rates leads to a critical neutron density for the synthesis of the ^{60}Fe of the order of $\simeq 10^{12}$ n/cm^3. The equilibrium abundance of neutrons is determined on one side by the ^{22}Ne(α,n)^{25}Mg and on the other side by the ^{25}Mg(n,γ)^{26}Mg, the ^{16}O(n,γ)^{17}O and the ^{20}Ne(n,γ)^{21}Ne even if the poisoning action of the last two processes is partly mitigated by the additional processes ^{17}O(α,n)^{20}Ne and ^{21}Ne(α,n)^{24}Mg. The latest determination of the ^{22}Ne(α,n)^{25}Mg cross section (Jaeger et al. 2001) quotes a quite small error bar for this process but it must be noticed that data are provided only up to 1 BK, just at the lowest end of the temperature range of interest. The cross sections adopted for the ^{25}Mg(n,γ)^{26}Mg and the ^{20}Ne(n,γ)^{21}Ne are the Rauscher & Thielemann (2000) theoretical ones shifted to fit the Bao et al. (2000) at 100 KeV; the cross section for the ^{16}O(n,γ)^{17}O is vice versa just the value quoted by Bao et al. (2000). The ones adopted for both the ^{17}O(α,n)^{20}Ne and the ^{21}Ne(α,n)^{24}Mg come from the NACRE compilation and for both of them a quite small error bar is quoted at the temperatures of interest.

The last episode of production of ^{60}Fe occurs in the Ne explosive burning when the peak temperature of the shock wave is of the order of 2.2 BK. Such a peak temperature is reached in almost all stellar models within the C convective shell and hence the processes and related uncertainties are again the ones discussed above for the C convective shell.

4. Conclusions

In this paper we have analyzed in some detail the processes that are important for the synthesis of both the ^{26}Al and ^{60}Fe. Only in the case of the ^{26}Al produced by the H burning and ejected later by the wind it has been possible to clearly identify one specific process whose better knowledge would really improve the theoretical estimate, i.e. the ^{26}Al(p,γ)^{27}Si. In all other cases the situation is much more confused: first of all the lack of a firm determination of the amount of C left by the He burning, which depends also on the ^{12}C(α,γ)^{16}O, does not allow a reliable computation of the C burning that is the cradle for the synthesis of both these gamma ray emitters in both the advanced and explosive burnings; second, most of the processes involved in the synthesis of the ^{16}O are purely theoretical and hence no real meaningful progress will be really possible until the cross sections of these processes will not be experimentally determined. We refer the interested reader to our paper (Limongi & Chieffi 2006) for a recent fully comprehensive discussion of the theoretical ^{26}Al and ^{60}Fe yields produced by a generation of massive stars ($11 \leq M(M_{\odot}) \leq 120$) of solar metallicity and their comparison with the available observational counterparts.

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