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Roles of nuclear physics on the final evolution of degenerate cores

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Abstract. Electron-capture and β-decay rates in stellar environments are evaluated for p-shell, sd-shell and pf-shell nuclei as well as for nuclei in the island of inversion with the use of new shell-model Hamiltonians. Important roles of the nuclear weak rates on the final evolution of the degenerate cores in stars are presented. The weak rates for sd-shell are applied to study nuclear Urca processes in O-Ne-Mg cores of stars with 8-10 solar masses, as well as the role of the rates on the final evolution and fate of the cores. The weak rates for pf-shell are used to study nucleosynthesis of iron-group elements in Type Ia supernova explosions. Overproduction problem of neutron-rich iron-group isotopes compared to the solar abundances is shown to be nearly solved with the use of the new rates. Electron-capture rates in $p$shell, especially for ^{13}N (e^{-}, ν) ^{13}C, which is important for neutraliztion of white dwarfs prior to the onset of the exlosions, are evaluated with a new interaction that can reproduce well the Gamow-Teller (GT) strengths in p-shell nuclei. Evaluation of the weak rates is extended to the nuclear region such as the island of inversion, where two major shells contribute to their configurations.

Key words. nuclear reactions, nucleosynthesis, abundances – Stars: AGB and post-AGB – Stars: evolution – Supernovae: general

1. Introduction

Roles of nuclear weak rates on the final evolution of electron-degenerate cores of stars are investigated. Standard electron-capture and β-decay rates of nuclei presented in a recent literature (Sullivan et al. 2016) are those for (1) sd-shell nuclei by Oda et al. (2002), (2) pf-shell of LMP (Langanke & Martinez-Pinedo 2001), (3) $pf-g$-shell of LMSH (Langanke, Kolbe, & Dean 2001), and (4) Fuller-Fowler-Newman (FFN) rates (Fuller, Fowler, & Newman 1982). Besides them, an approximate two-parameter formula for the rates is obtained (Langanke & Martinez-Pinedo 2003) to be used for nuclei which have no available data tables.

Here, we study nuclear Urca processes in stars with O-Ne-Mg cores with the use of new weak rates of sd-shell obtained for USDB (Brown & Richter 2006). Evaluations of new weak rates for pf-shell are carried out by using a new Hamiltonian GXPF1J (Honma et al. 2005), and nucleosynthesis of iron-group nuclei in Type Ia supernova explosions (SNe) is discussed. We also study the weak rates for nuclei in the island of inversion, where sd-shell

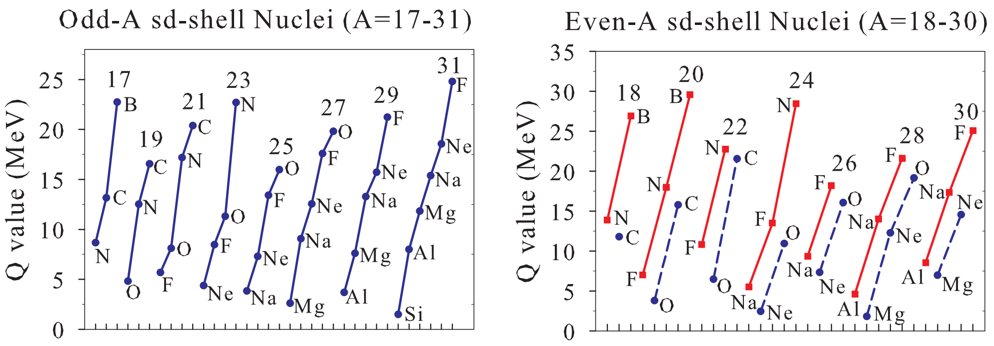

Fig. 1. β-decay Q-values in odd and even-mass *sd*-shell nuclei (Wang et al. 2012). Figures taken from Suzuki et al., ApJ, 817, 163 (2016).

and *pf*-shell components are considerably admixed. The weak rates for *p*-shell nuclei are studied with a new shell-model Hamiltonian (Yuan et al. 2012).

2. Weak rates in *sd*-shell and nuclear Urca processes in O-Ne-Mg cores

In stars with 8-10 solar masses, O-Ne-Mg cores are formed after carbon burning, and the stars may end up in various ways such as O-Ne-Mg white dwarfs (WD), e-capture (EC) SNe or core-collapse (CC) SNe. The fate of the stars is sensitive to their masses and nuclear e-capture and β-decay rates. Cooling of the O-Ne-Mg core by nuclear Urca processes determines whether the star ends up with ECSNe or CCSNe (Toki et al. 2013; Jones et al. 2013).

Electron-capture and β-decay occur simultaneously at certain stellar densities and energy is lost from stars by emissions of both ν and $\bar{\nu}$. At high densities electron chemical potential increases and e-capture on nuclei is ignited when it reaches the Q-value of the reaction. β-decay Q-values in *sd*-shell nuclei are shown in Fig. 1. In odd-mass nuclei, the Q-value becomes small for nuclear pairs with A =23, 25 and 27. Electron-capture rates increase as the density increases while β-decay rates decrease, and they become equal at a density almost independent of temperatures as shown in Fig. 2. We call such a density 'Urca density', which is determined by the Q-value of the nuclear pair (Toki et al. 2013). The Urca density is found to be $\log_{10}\rho Y_e$ = 8.92 and 8.78 for ^{23}Ne-^{23}Na and ^{25}Na-^{25}Mg pairs, respectively. There is no clear Urca density for ^{27}Mg-^{27}Al pair as the ground state (g.s.) to g.s. transition is forbidden.

Screening effects of electrons and changes of chemical potentials of ions are taken into account. These Coulomb corrections lead to reduction (enhancement) of e-capture (β-decay) rates, and result in a slight shift of the Urca density toward higher density. For example, the Urca density is modified from $\log_{10}\rho Y_e$ = 8.78 to 8.81 for the A=25 pair. Calculated e-capture and β-decay rates for ^{25}Mg-^{25}Na pair obtained with the Coulomb corrections are shown in Fig. 2 (lower panel).

The β-decay Q-values for even *sd*-shell nuclei are shown in Fig. 1. Because of the pairing effects, Q-values for decays from even-even to odd-even nuclei are smaller than those from odd-even to even-even nuclei. Therefore, once e-capture on ^{24}Mg or ^{20}Ne is ignited, successive e-capture on ^{24}Na or ^{20}F proceeds immediately and energy is produced by γ decays heating the cores (Suzuki, Toki & Nomoto 2016; Martinez-Pinedo et al. 2014).

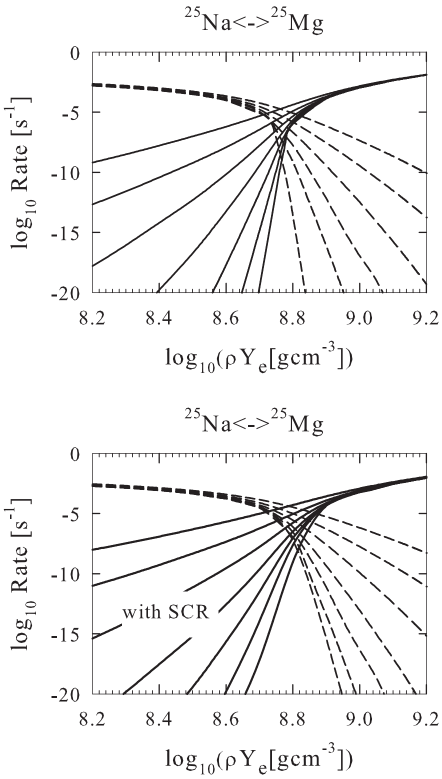

Fig. 2. Electron-capture and β-decay rates for ^{25}Mg-^{25}Na pair for temperatures $\log_{10}T(K)$ =8.3 -9.3 obtained by using GT strength from USDB Hamiltonian. Solid and dashed curves denote the e-capture and β-decay rates, respectively. The rates in the upper (lower) panel are evaluated without (with) the Coulomb corrections.

3. Electron-capture rates in pf-shell nuclei and nucleosynthesis in Type Ia SNe

New shell-model Hamiltonians in pf-shell, GXPF1 (Honma et al. 2004) and GXPF1J (Honma et al. 2005), can describe spin properties of pf-shell nuclei quite well. The Gamow-Teller (GT) strength in ^{58}Ni (Fujita et al. 2011), for example, is nicely reproduced and M1 strengths in various pf-shell nuclei are also well described. In particular, in the case of ^{56}Ni, the GXPF1J leads to a two-peak structure in the GT strength while standard KB3G (Poves et al. 2001) or KBF (Langanke & Martinez-Pinedo 2001) gives only a single peak. The two-peak structure of the strength has been confirmed by recent (p, n) reactions (Sasano et al. 2011). Electron-capture rates are evaluated with the use of the calculated GT strength (see (Suzuki et al. 2011) for the details). The KB3G gives larger capture rates compared to GXPF1J, while KBF rates are larger (smaller) at ρY_e = 10^9 (10^8) g/cm^3 where the electron chemical potential is about 5.1 MeV (2.4 MeV).

A considerable amount of ^{56}Ni is produced in Type-Ia supernova explosions. As the e-capture process on ^{56}Ni proceeds, neutron-rich nuclei are produced and the lepton-to-baryon ratio (or proton fraction) Y_e gets smaller. If e-capture rates on ^{56}Ni are smaller, production yields of neutron-rich isotopes such as ^{58}Ni decrease and Y_e remains to be a higher value. The ratio of the production yields of ^{58}Ni over ^{56}Ni can be reduced nearly by half for GXPF1J compared to KB3G.

The problem of over-production of ^{58}Ni, ^{54}Cr and ^{54}Fe compared to the solar abundance was discussed (Iwamoto et al. 1999) with the use of the capture rates of FFN (Fuller, Fowler, & Newman 1982). A possible solution of the problem with slower e-capture rates was discussed in Brachwitz et al. (2000); Langanke & Martinez-Pinedo (2001). The problem could be solved by using the slower e-capture rates of GXPF1J. Here, we use the W7 and WDD2 model (Iwamoto et al. 1999) as explosion models of Type-Ia supernova explosions starting from C-O white dwarf with the mass of 1.38 solar mass. The W7 model proceeds by a fast deflagration while the WDD2 model proceeds by a slow deflagration with delayed detonation. Electron-capture rates of GXPF1J are used for pf-shell nuclei with $21 \leq Z \leq 32$ and those of KBF otherwise. The results of final element abundances are shown in Fig. 3 (Mori et al. 2016). It is found that over-production of neutron-rich Cr, Fe and Ni isotopes is suppressed within a factor of 2 (2-3) compared with the solar abundances in the WDD2 (W7) model. This is much smaller than the case of FFN weak rates, where the over-production factor becomes as large as up to 4-5.

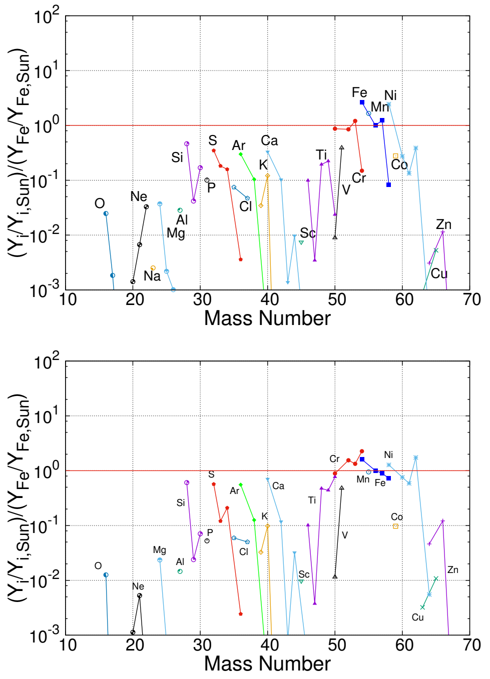

Fig. 3. Abundances of elements relative to the solar abundances obtained in Type Ia SNe with GXPF1J Hamiltonian in the explosion model with fast defragration (W7) (upper panel) and that with slow defragration with delayed detonation (WDD2) (lower panel). Figures taken from Mori et al., ApJ, 833, 179 (2016).

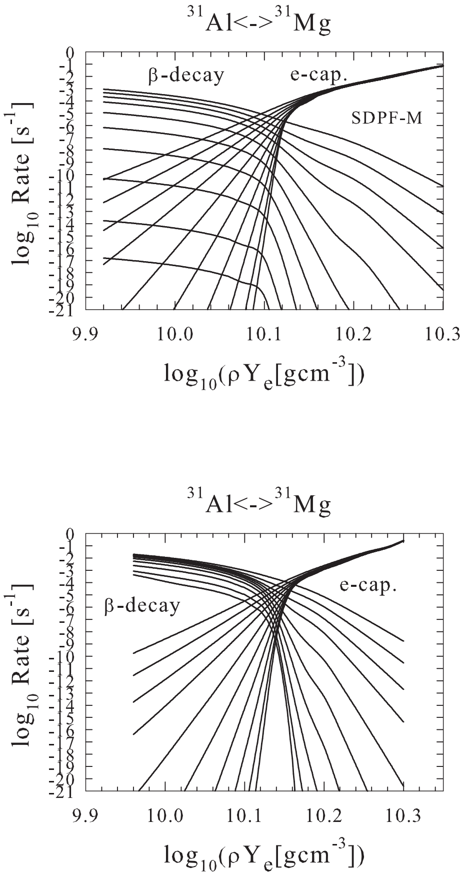

Fig. 4. Electron-capture and β-decay rates for ^{31}Mg-^{31}Al pair obtained for SDPF-M (upper panel) and those evaluated with experimental energy and GT data (lower panel).

4. Weak rates for nuclei in the island of inversion

Urca processes for nuclear pairs in the island of inversion (Warburton, Becker & Brown 1990) such as ^{31}Mg-^{31}Al and ^{33}Mg-^{33}Al pairs have been pointed out to be important for the cooling of neutron star crusts (Schaz et al. 2014). Large $sd-pf$ shell admixtures are found in neutron-rich Ne, Na and Mg isotopes near N =20. Lowering of 2_1^+ states and enhancement of $E2$ transition strengths show evidence for the breaking of the magicity at N =20 (Warburton, Becker & Brown 1990). Energy levels of 2_1^+ states and $B(E2: 2_1^+ \rightarrow 0_{g.s.}^+)$ are sucessfully reproduced by SDPF-M Hamiltonian (Utsuno et al. 1999) with $sd-pf$-shell configurations. The important contributions from 2p-2h components are found in ^{30}Ne and ^{32}Mg.

We discuss the weak rates for ^{31}Mg-^{31}Al pair. The SDPF-M fails to reproduce the energy levels of ^{31}Mg, that is, $7/2^-$ state becomes the ground state while the experimental g.s. is $1/2^+$. The weak rates obtained for SDPF-M are compared with those obtained by using experimental energies and GT strengths in Fig. 4. The Urca density can be assigned for the case for the rates with the experimental data, while it is not clearly assigned for the pure SDPF-M case. This short-coming can be improved f(the effective interaction obtained by EKK (e: tended Kuo-Krenciglowa) method (Tsunoda (al. 2017). Energy levels in ^{31}Mg are well repr(duced, and the more important roles of p-h e: citations are noticed compared with the SDPl M case. The 4p-4h components are found to t as much as the 2p-2h components in ^{32}Mg. Tl weak rates are evaluated with the EKK methc and they prove to be close to those obtained t taking into account the available experiment data (Suzuki et al. 2017).

5. Weak rates in *p*-shell nuclei

Electron-capture reactions on light nuclei a1 important for the study of convective carbc burning prior to the onset of explosive burnir and neutralization during carbon simmering i Type Ia SN progenitors (Martinez-Rodrigu(et al. 2016). The ^{13}N (e^-, ν) ^{13}C reaction aft((p, γ) reaction on ^{12}C is especially important 1 determine the neutron excess in the progenit(and subsequent synthesis of neutron-rich is(topes.

The e-capture rates on ^{13}N are evaluated t shell-model calculations with the use of YSO Hamiltonian (Yuan et al. 2012), which can sy tematically well reproduce the GT strengths i *p*-shell nuclei. Calcuated GT strengths and (capture rates obtained with YSOX and SF (Suzuki et al. 2003) as well as the experiment ones (Zegers et al. 2008) are shown in Fig. : The experimental GT strengths are well reproduced by YSOX. Electron-capture rates with YSOX also reproduce well the rates evaluated with the experimental GT strength. We thus have a good shell-model Hamiltonian for *p*-shell and are able to evaluate transition rates relevant for astrophysical processes.

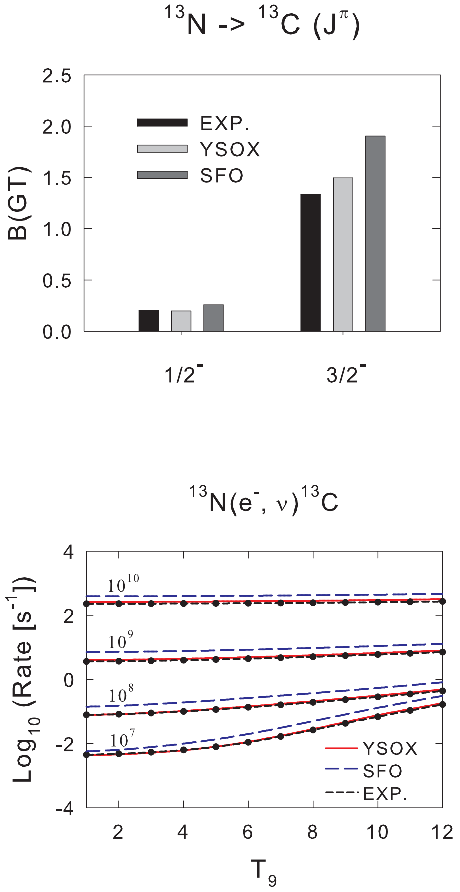

Fig. 5. GT strengths and e-capture rates on ^{13}N obtained with YSOX and SFO as well as the experimental data.

6. Conclusions

New weak rates for *sd*-shell and *pf*-shell nuclei are obtained with USDB and GXPF1J Hamiltonians, respectively. The rates for *sd*-shell are used to study the evolution of the O-Ne-Mg cores of stars with 8-10 solar masses. Nuclear Urca processes for A = 23 and 25 nuclear pairs are found to be important for the cooling of the cores and determination of the fate of the stars whether they end up with ECSNe or CCSNe.

The rates for *pf*-shell are used to study nucleosynthesis of iron-group elements in Type Ia SNe. Relatively smaller e-capture rates for GXPF1J compared with KB3G, KBF and FFN are found to considerably suppress the over-production of neutron-rich iron-group isotopes, especially in the WDD2 explosion model with detonation.

Evaluation of new weak rates is extended to nuclei in the island of inversion, where substantial admixtures of both *sd*-shell and *pf*-

shell components are noticed. Nuclear weak rates for ^{31}Mg-^{31}Al pair, important for Urca processes in neutron star crusts, are evaluated with a new interaction obtained by the EKK method. Study of nuclear structure and weak rates for $pf-g$-shell nuclei near ^{78}Ni, which play important roles in nucleosynthesis in CCSNe, is also under way (Tsunoda et al. 2014; Suzuki et al. 2017). Shell-model calculations within $pf-g_{9/2}d_{5/2}$-shell configurations can explain the excitation energy of the first 2^+ state in ^{78}Ni (Tsunoda et al. 2014), but the configuration space needs to be extended to include the full gds-shells to obtain reliable weak rates as dominant contributions come from spin-dipole forbidden transitions.

The weak rates for p-shell nuclei, in particular for ^{13}N (e^-, ν) ^{13}C, are evaluated with a new Hamiltonian YSOX. Experimental GT strengths to the g.s. and first $1/2^-$ states of ^{13}C are reproduced well by YSOX. Systematic evaluations of the weak rates with YSOX will be promising for the study of properties of the progenitors of SNe.

Nuclear weak rates, thus, play important roles in the final evolution of degenerate cores in stars. Accurate evaluation of the weak rates is essential for the studies of various astrophysical processes sensitive to the rates.

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