Spin Responses in Nuclei and Nuclear Weak Processes in Stars

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Abstract. New shell-model Hamiltonians which can successfully describe spin-dependent transition rates in nuclei are applied to study nuclear weak processes in stars. New $\nu$-induced reaction cross sections in $^{12}$C and $^{56}$Fe evaluated by the new Hamiltonians are shown to reproduce well the experimental data. Nucleosynthesis of light elements in supernova explosions (SNe) as well as $\nu$ oscillation effects are discussed with the new cross sections. Electron capture and $\beta$-decay rates in stellar environments are re-evaluated in $fp$- and $sd$-shell nuclei. Nucleosynthesis in Type-Ia SNe, rp-process and X-ray burst are discussed with the new reaction rates in Ni isotopes. Important roles of accurate e-capture and $\beta$-decay rates in $sd$-shell nuclei on the cooling of stars with 8-10 solar masses by nuclear URCA processes and the fate of the stars are demonstrated. $\beta$-decay half-lives of waiting-point nuclei at $N=$126 are evaluated by shell-model calculations, and r-process nucleosynthesis up to Th and U region in both core-collapse SNe and binary neutron star mergers are studied.

1. Introduction

Now several new shell-model Hamiltonians, for example, SFO[1] in $p$-shell and GXPF1[2] in $fp$-shell, are available. They can reproduce Gamow-Teller (GT) strengths in C, Fe and Ni isotopes. The monopole-based universal interaction, VMU[3], is also introduced to take into account important roles of tensor forces in shell evolutions and spin responses in nuclei. Monopole terms of tensor forces obey general sign rule; they are attractive between $j_\uparrow = \ell+1/2$ and $j_\downarrow = \ell-1/2$ orbits while they are repulsive between $j_\downarrow$ ($j_\uparrow$) and $j_\uparrow$ ($j_\downarrow$) orbits[4]. This feature is embedded both in good phenomenological interactions such as GXPF1 and SFO as well as SDPF-M[5] and microscopic G-matrices derived from realistic nucleon-nucleon interactions[3]. The sign rule leads to proper shell evolutions and change of magic numbers toward drip-lines[4, 3].

We apply these new Hamiltonians to evaluate spin-dependent transition strengths and nuclear weak rates at stellar environments. In Sect. 2, $\nu$-nucleus reactions and nucleosynthesis of light elements by $\nu$-processes in SNe are studied. In Sect. 3, new GT strengths in $fp$-shell nuclei are used to obtain e-capture rates in Ni isotopes at high densities and high temperatures. Possible consequences of the new rates in nucleosynthesis in Type-Ia SNe, rp-process and X-ray burst are discussed. In Sect. 4, e-capture and $\beta$-decay rates in $sd$-shell nuclei are used study nuclear URCA processes and cooling of stars with O-Ne-Mg cores. In Sect. 5, $\beta$-decays of isotones with $N=$126 are studied and r-process nucleosynthesis in core-collapse SNe and neutron star mergers (NSM) are discussed.
2. Neutrino-nucleus reactions and light-element nucleosynthesis in SNe

2.1. \( \nu \)-induced reactions on \(^{12}\text{C} \) and \(^{56}\text{Fe} \)

The GT strength in \(^{12}\text{C} \) is well described by SFO with a small quenching for the axial-vector coupling constant: \( g_A^{eff}/g_A = 0.95 \). The exclusive reaction cross section for \(^{12}\text{C}(\nu_e, e^-)^{12}\text{N} (1^+_\text{g.s.}) \) is, therefore, well reproduced by SFO as shown in Fig. 1. SFO also reproduces neutral-current and inclusive charged-current reaction cross sections on \(^{12}\text{C} \) for DAR \( \nu \)[6]. The GT strength in \(^{56}\text{Fe} \) obtained by GXPF1J[7], together with contributions from other multipoles evaluated by RPA, can reproduce reaction cross section for \(^{56}\text{Fe}(\nu_e, e^-)^{56}\text{Co} \) induced by DAR \( \nu \)[8, 9]. Calculated value is \( 259 \times 10^{-42} \text{cm}^2 \) while the experimental one is \( (256 \pm 108 \pm 43) \times 10^{-42} \text{cm}^2 \). Thus, it becomes possible now to evaluate \( \nu \)-nucleus reaction cross sections on \(^{12}\text{C} \) and \(^{56}\text{Fe} \), the only targets with available experimental data, accurately with the use of new shell-model Hamiltonians[1, 7].

2.2. Synthesis of \(^{11}\text{B} \) and \(^{7}\text{Li} \) and effects of \( \nu \) oscillations

New \( \nu \)-induced cross sections for \(^{12}\text{C} \), enhanced compared with those by conventional Hamiltonians, are used to study light element synthesis in core-collapse SNe[6, 10]. \(^{11}\text{B} \) is produced mainly by \(^{12}\text{C}(\nu, \nu'p)^{11}\text{B} \) reaction as well as \( \alpha \) capture on \(^{7}\text{Li} \), while \(^{7}\text{Li} \) is produced mostly by \(^{4}\text{He}(\nu, \nu'p)^{3}\text{H} \). The enhancement of \(^{11}\text{B} \) and \(^{7}\text{Li} \) abundances compared with previous calculations[11] are found.

![Figure 1](image-url)

**Figure 1.** (Left figure) Exclusive charge-exchange reaction cross sections for \(^{12}\text{C} \) induced by DAR neutrinos. The calculated values obtained by shell model Hamiltonians, SFO[1] and PSDMK2[12, 13], as well as the experimental values, LSND[14], are shown. (Right figure) Dependence of the abundance ratio \(^{7}\text{Li}/^{11}\text{B} \) on the mixing angle \( \theta_{13} \) and the \( \nu \) mass hierarchies. Figures taken from Ref. [10].

Effects of \( \nu \) matter oscillations (MSW effects) on the abundances of \(^{11}\text{B} \) and \(^{7}\text{Li} \) are also examined. Increase in the rates of charged-current reactions induced by \( \nu_e \) converted from \( \nu_\mu \) and \( \nu_\tau \) with higher energies occur in the He layer. The abundance ratio for \(^{7}\text{Li}/^{11}\text{B} \) is found to be sensitive to the \( \nu \) mass hierarchy[10]. In case of normal hierarchy, because of MSW
effect at high-density resonance, charged-current reactions induced by $\nu_e$ become more effective to enhance the abundance ratio, while in case of inverted hierarchy there is no high-density resonance and no enhancement of the ratio. The dependence of the ratio on the mixing angle $\theta_{13}$ and the mass hierarchy is shown in Fig. 1 for the new Hamiltonians (SFO-WBP[15], where WBP is used to evaluate $\nu$-$^4$He cross sections) and previous one (HW92[11]). As the value of $\sin^22\theta_{13}$ is now known to be about 0.1[16], it is in principle possible to determine the $\nu$ mass hierarchy from the abundance ratio. Recent analysis of supernova X-grains[17] lead to a result that inverted mass hierarchy is statistically more favored[18].

2.3. $\nu$-$^{13}$C and $\nu$-$^{16}$O reactions

The SFO is applied to evaluate new cross sections for $\nu$-$^{13}$C reactions leading to low-lying states in $^{13}$C and $^{13}$N[19]. Since the threshold energy for $\nu$-$^{12}$C reactions is about 13 MeV, $^{13}$C is a good candidate for detection of low energy $\nu$ with $E_\nu < 10$ MeV such as reactor neutrinos. Detailed discussion is given in Ref. [19].

New reaction cross sections for $\nu$-$^{16}$O are obtained with the use of SFO-tls Hamiltonian[20], which has been modified from SFO by inclusion of tensor components of $\pi+\rho$-meson exchanges in the p-sd cross-shell matrix elements. Energies of spin-dipole states in $^{16}$O are found to be well described by SFO-tls. The cross section for $\alpha$ emission channel, which produces $^{11}$B, is found to be as large as about 20% of $^{13}$C($\nu$, $\nu'$ p)$^{11}$B reaction cross section. A certain amount of $^{11}$B is also produced from $\nu$-$^{16}$O reactions in the O layer[21].

3. The electron capture rates in fp-shell nuclei at stellar environments

3.1. GT strength in Ni isotopes and e-capture rates

GT strength in fp-shell nuclei are studied with GXPF1J[7] and applied to e-capture reactions at stellar environments[25]. Calculated GT strengths in $^{56}$Ni and $^{55}$Co obtained with GXPF1J with the quenching factor of $f_q = g_A^{eff}/g_A =0.74$ are shown in Fig. 2, and compared with those obtained by KB3G[22]. The distribution of the GT strengths by GXPF1J are found to be generally more spread compared to those by KB3G in Fe and Ni isotopes. In particular, the characteristic two-peak structure is found in the GT strength in $^{56}$Ni for GXPF1J as shown in Fig. 2(a). This two-peak structure has been recently confirmed by ($p$, n) reaction experiment [24]. The experimental GT strength in $^{55}$Co[24] is also well reproduced by GXPF1J.

The evaluation of the electron capture reaction rates in type-Ia SNe is important for the synthesis of nuclei around Ni and Fe region. As more strength is found at higher energy region for GXPF1J than for KB3G, the capture rates for GXPF1J become smaller compared to KB3G at high temperatures and densities (see Ref. [25] for $^{56}$Ni for the details). A systematic difference is found for the calculated capture rates between GXPF1J and KB3G.

3.2. Applications to astrophysical processes

Accretion of matter to white-dwarfs from their binary stars ignites type-Ia supernova explosions when the white-dwarf mass exceeds the Chandrasekhar limit. A large amount of $^{56}$Ni is produced in type-Ia SNe. As 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. The smaller the e-capture rates on $^{56}$Ni, the less production yields of neutron-rich isotopes such as $^{58}$Ni and the higher value for $Y_e$ in statistical equilibrium calculations. The production yield ratio, $^{58}$Ni/$^{56}$Ni, can be reduced nearly by half for GXPF1J compared to KB3G[26]. The problem of over-production of $^{58}$Ni, $^{54}$Cr and $^{54}$Fe compared to the solar abundance[27] could be solved by using smaller e-capture rates of GXPF1J.

Though main processes of rp-process in stars are ($p$, $\gamma$), ($\alpha$, $\gamma$) and ($\alpha$, p) reactions, nuclear weak processes such as $\beta^+$-decay and e-capture reactions on $^{56}$Fe and e-capture reactions on
Figure 2. GT strengths in (a) $^{56}$Ni and (b) $^{55}$Co obtained by shell-model calculations with GXPF1J and KB3G (and KBF for $^{56}$Ni).

$^{55}$Ni, which is a mirror nucleus of $^{55}$Co, are important and give sizable contributions to the rp-process nucleosynthesis. In particular, e-capture reaction on $^{55}$Ni succeeded by ($p$, $\gamma$) reaction produces $^{56}$Ni.

At the envelopes of accreting neutron stars, X-ray bursts can occur through nucleosynthesis by rp-process. The temperature at the surface of the star rises up with the synthesis of proton-rich nuclei, and comes to the peak value when $^{56}$Ni is produced. Then, the temperature decreases rapidly, and there appears a bump in the temperature curve when waiting point nuclei such as $^{60}$Zn, $^{64}$Ge and $^{68}$Se are formed. It continues to decrease gradually till the Sn-Sb-Te cycle, where the temperature rises up a little. Then, the temperature decreases rapidly. The peak value of the temperature depends on the e-capture rates on $^{55}$Ni. As the rates are smaller for GXPF1J compared to KB3G and KBF\cite{22}, the maximum temperature for GXPF1J becomes a bit smaller. Thus the e-capture rates in Ni and Fe region at densities around $\rho Y_e = 10^6$ g/cm$^3$ and at temperatures $T_9 = 1-10$ ($T = T_9 \times 10^9$ K) play important roles in the rp-process and X-ray bursts.

4. Electron capture and $\beta$-decay rates in sd-shell and nuclear URCA processes

Evolutions of stars with 8-10 solar masses and nuclear URCA processes are discussed. The fate of the stars is sensitive to its mass and nuclear e-capture and $\beta$-decay rates. The stars with 8-10 $M_\odot$ can end with O-Ne-Mg white dwarfs, or e-capture SNe with neutron star (NS) remnant, or core-collapse SNe with NS. Cooling of the O-Ne-Mg core by nuclear URCA processes determines whether the star ends with e-capture SNe or core-collapse SNe. Important URCA processes in sd-shell occur at $A=23$, 25 and 27, where Q-values for the capture reactions become quite small.

Detailed e-capture rates on $^{24}$Na, $^{25}$Mg and $^{27}$Al and $\beta$-decay rates on $^{24}$Ne, $^{25}$Na and $^{27}$Mg are obtained at high densities and temperatures. At URCA densities, where e-capture and $\beta$-decay rates coincide each other and both the processes occur simultaneously emitting $\nu_e$ and $\bar{\nu}_e$, thus resulting in remarkable cooling of the O-Ne-Mg core of the star.

The GT strengths for sd-shell nuclei are evaluated by USDB interaction with a quenching factor of $q=0.764\cite{28}$. The URCA densities for $A=23$ and $A=25$ are obtained at $\log_{10}(\rho Y_e) =$
8.92 and 8.78, respectively, while no clear URCA density is found for \( A=27 \)\(^{29} \). The cooling of O-Ne-Mg core is found to occur at URCA densities for \( A=23 \) and 25 in \( 8.8M_\odot \) star\(^{30} \). The \( 8.8M_\odot \) star collapses triggered by subsequent e-captures on \( ^{24}\text{Mg} \) and \( ^{20}\text{Ne} \), thus leading to the e-capture SNe. For \( 9.5M_\odot \) star, neon-burning shell propagates to the center of the core before the core density reaches the URCA densities and end with a core-collapse SNe\(^{30} \). Screening effects on the capture rates shift the URCA densities toward a higher density region; the URCA density is increased to \( \log_{10}(\rho Y_e) = 8.81 \) for \( A=25 \).

5. \( \beta \) half-lives of waiting-point nuclei at \( N=126 \) and \( r \)-process nucleosynthesis

\( \beta \)-decay rates for exotic nuclei at \( N=126 \) relevant to \( r \)-process nucleosynthesis are studied by shell-model calculations. The half-lives for \( N=126 \) isotones are evaluated in a range of \( Z=64-78 \), which is an extension of our previous work for the isotones with \( Z=64-73 \)\(^{31} \). Half-lives obtained by including both the Gamow-Teller (GT) and first-forbidden (FF) transitions are found to be short compared with standard values by FRDM\(^{32} \), while they are close to another shell-model evaluation\(^{33} \) as shown in Fig. 3. Here, a quenching factor of \( g_{A}^{\text{FF}}/g_{A} =0.70 \) is adopted for the GT transitions, while quenching factors for \( g_{A} \) and \( g_{V} \) for FF transitions are taken to be 0.34 and 0.67, respectively, which are determined to explain FF beta-decay rates in nuclei near \( ^{208}\text{Pb} \)\(^{34, 35} \). The FF contributions are important for larger \( Z \) and dominant at \( Z>72 \). Calculated half-life for \( Z=78 \) is found to be consistent with the experimental data\(^{36} \).

![Figure 3](image.png)

**Figure 3.** Half-lives of \( N=126 \) isotones obtained by shell-model calculations and FRDM\(^{32} \). The present shell-model results with GT only and GT+FF are shown by dashed and solid curves, respectively. Results from Refs. \(^{32} \) (FRDM) and \(^{33} \) are denoted by dash-dotted and short-dashed curves, respectively.

The short half-lives obtained here are used to study \( r \)-process nucleosynthesis in core-collapse SNe and binary neutron star mergers (NSM). The element abundances are obtained up to Th
and U region in both SNe and NSM. The abundances of Th and U are found to be enhanced about by three times for the present half-lives at \( N = 126 \) in the SNe model[37]. In case of binary NS-NS mergers, based on fully general relativistic simulation of a NS-NS merger that allows mixing of various values of \( Y_e = 0.09 - 0.45 \)[38], calculated abundances are found to be in reasonable agreement with the solar r-process abundance in full-mass range, \( A = 90 - 240 \)[37]. It is expected that the r-process site can be determined by extending our study on nucleosynthesis in both the astrophysical sites.

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