QRPA CALCULATIONS OF STELLAR WEAK-INTERACTION RATES*

P. Sarriguren

Instituto de Estructura de la Materia, IEM-CSIC
Serrano 123, 28006 Madrid, Spain

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Weak-decay rates under various stellar density and temperature conditions are studied in several mass regions including neutron-deficient medium-mass waiting-point nuclei involved in the rp-process, neutron-rich medium-mass isotopes involved in the r-process, and pf-shell nuclei of special importance as constituents in presupernova formations. Weak rates are relevant to understand the late stages of the stellar evolution, as well as the nucleosynthesis of heavy nuclei. The nuclear structure involved in the weak-decay processes is described within a microscopic deformed quasiparticle random-phase approximation (QRPA) based on a selfconsistent mean field obtained from Skyrme Hartree–Fock + BCS calculations. This approach reproduces reasonably well both the experimental β-decay half-lives and the Gamow–Teller strength distributions measured under terrestrial conditions.

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1. Introduction

The spin–isospin response of the nucleus is an interesting issue that has received increasing attention in the last decades [1]. The interest is not only from the strict nuclear structure point of view, but also for nuclear astrophysics. Pushing further our present knowledge of this response would certainly contribute to constrain nuclear models and to approach regions with unusual isospin ratios with a better understanding of the underlying nuclear structure [2]. In astrophysics, weak interactions in nuclei are of paramount importance to understand the late stages of the stellar evolution [3, 4], where electron captures (EC) by nuclei and β decays determine to a large extent the dynamics of these phases of the star. In particular, nuclear

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physics input is a fundamental ingredient in network calculations aiming to simulate astrophysical processes related to the nucleosynthesis in explosive events [5]. Unfortunately, experimental information about the nuclear properties of the exotic nuclei involved in those processes is still very scarce and the nuclear input must be taken from predictions of theoretical models.

In this work, we study weak-decay rates in ranges of densities (ρ) and temperatures (T) of astrophysical interest in some selected examples corresponding to: *(i)* pf-shell nuclei, which are the main constituents of the stellar core in presupernova formations; *(ii)* neutron-deficient nuclei involved in the rp-process; and *(iii)* neutron-rich nuclei involved in the r-process. The theoretical approach is based on a deformed Skyrme HF+BCS+QRPA formalism, which is presented in the next section. It has been shown that this approach is able to reproduce the experimental information available on β-decay half-lives [6, 7], as well as on the more demanding Gamow–Teller (GT) strength distributions extracted from β-decay in the case of unstable nuclei [9] and from charge-exchange reactions in the case of stable ones [10].

2. Theoretical formalism

The weak-interaction rates can be expressed as follows:

$$\lambda = \frac{\ln 2}{D} \sum_{i,f} \left[P_i(T)\right] \, \left[B_{if}\right] \left[\Phi_{if}(\rho, T)\right] \, , \tag{2.1}$$

where $D = 6147$ s. The summation extends over all initial (i) and final (f) states involved in the process. The three terms within brackets contain the probability $P_i(T)$ that excited states in the parent nucleus are thermally populated; the nuclear structure information B_{if}; and the phase-space factors Φ_{if}, respectively. Assuming thermal equilibrium, the occupation probabilities of the states i are given by a Boltzmann distribution. For the range of temperatures studied in this work, $T =$ 1–10 GK, it is sufficient to consider excitation energies in the parent nucleus below 1 MeV. The nuclear structure part contains the GT strengths for allowed transitions, which are calculated within QRPA. The GT strength for a transition from i to f is given by

$$B_{if}\left(\mathrm{GT}^{\pm}\right) = \frac{1}{2J_i+1} \left(\frac{g_A}{g_V}\right)^2_{\mathrm{eff}} \langle f || \sum_j^A \sigma_j t_j^{\pm} || i \rangle^2 \, , \tag{2.2}$$

where $(g_A/g_V)_{\mathrm{eff}} = 0.7 (g_A/g_V)_{\mathrm{bare}}$, and σ and t are the spin and isospin operators, respectively. The details of the theoretical formalism have been described elsewhere [11]. In summary, the method starts with a selfconsistent deformed Hartree–Fock mean-field calculation with Skyrme interactions including pairing correlations. The force SLy4 is used as a representative of the Skyrme forces. Calculations of GT strengths are performed subsequently within QRPA for the solution of the HF+BCS problem, *i.e.*, for the deformed configuration that minimizes the energy. The calculation includes a spin–isospin separable residual interaction in particle–hole and particle–particle channels.

For odd-A nuclei, the ground state is treated as a one-quasiparticle state in which the odd nucleon occupies the single-particle state of the lowest energy. We use the equal filling approximation, treating the unpaired nucleon on an equal footing with its time-reversed state. The transitions corresponding to phonon excitations are treated similarly to the even–even case, but with the odd nucleon blocked in the calculation. The transitions involving the unpaired nucleon are treated perturbatively [12].

The phase-space factors involve EC and $\beta^{\pm}$ decays depending on the problem studied. Because in the studied astrophysical scenarios the atoms are fully ionized, ECs occur from the degenerate electron plasma. This is a difference with respect EC in the laboratory, where the electrons are captured from the atomic orbitals. The phase-space factors are given by:

$$\begin{aligned} \Phi_{if}^{\mathrm{EC}} &= \int_{\omega_\ell}^{\infty} \omega p (Q_{if}+\omega)^2 F(Z,\omega) S_{e^-}(\omega)\left[1-S_\nu(Q_{if}+\omega)\right] \mathrm{d}\omega\,, \\ \Phi_{if}^{\beta^\pm} &= \int_{1}^{Q_{if}} \omega p (Q_{if}-\omega)^2 F(\mp Z+1,\omega)\left[1-S_{e^\pm}(\omega)\right]\left[1-S_\nu(Q_{if}-\omega)\right] \mathrm{d}\omega\,, \end{aligned} \tag{2.3}$$

where $\omega(p)$ is the total energy (momentum) of the electron and Q_{if} is the total energy available in the decay, which is obtained from the experimental masses. $F(Z,\omega)$ is the Fermi function and $\omega_\ell = 1$ if $Q_{if} > -1$ or $\omega_\ell = |Q_{if}|$ otherwise. For the stellar conditions, we are interested in $S_\nu = S_{e^+} = 0$, whereas the electron distribution is given by a Fermi–Dirac distribution with temperature T and chemical potential μ_e

$$S_e = \frac{1}{\exp\left[\left(\omega-\mu_e\right)/\left(k_{\mathrm{B}}T\right)\right]+1}\,. \tag{2.4}$$

The phase-space factor, especially for EC, depends on both ρ and T through the electron distributions and, therefore, the half-lives under stellar conditions will be different from those under laboratory conditions.

3. Results

As an example of the results obtained in pf-shell nuclei, we can see in Fig. 1 the GT strength distribution corresponding to the ^{55}Mn $\rightarrow^{55}$Cr transition. We consider the transitions from the ground state [312]5/2$^-$ on the left-hand side and from the excited state [303]7/2$^-$ on the right-hand side. The data correspond to the (n,p) charge-exchange reaction [13]. In Fig. 2, the EC rates are shown as a function of T for various densities ρY_e, where Y_e is the electron-to-baryon ratio. We can see the relative contributions of the ground and excited states to the total rate. In addition, the rates from the ground state with full population are shown as 'g.s. only'. The EC rate and the relative importance of the excited states are finally determined by their thermal population at a given T, by the phase factor $\Phi^{\rm EC}(\rho,T)$, and by the structure of the GT strength distribution.

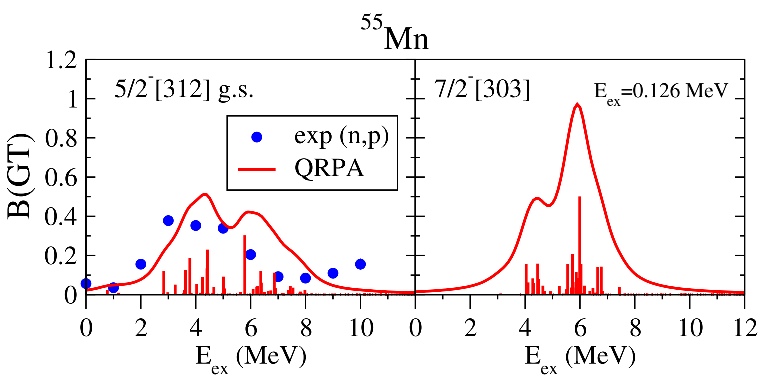

Fig. 1. The Gamow–Teller strength distribution $B(\mathrm{GT}^+)$ for the transition ^{55}Mn to ^{55}Cr plotted *versus* the excitation energy of the daughter nucleus. Experimental data extracted from (n,p) reactions [13] are compared with SLy4–QRPA results for the decay of the ground state in ^{55}Mn. The GT strength distribution of the excited state at $E = 0.126$ MeV is also shown.

Figure 3 contains the temperature dependence of the weak-decay rates in ^{76}Sr, which is a waiting point in the rp-process. The left panel shows the contributions to the total rate from the 0^+ ground state and from the excited 2^+ state. This nucleus is well-deformed, having a 2^+ rotational state at very low energy (0.62 MeV), which is thermally populated at relatively low T. As a result, non-negligible contributions are found already at $T = 2$ GK within the range of temperatures typical for the rp-process. The three lines labeled 2^+ in the figure correspond to the allowed decays of the 2^+ state into 1^+, 2^+, and 3^+ states in the daughter nucleus. The population of the excited state at high T naturally implies a corresponding depopulation of the ground state, decreasing its contribution to the total rate.

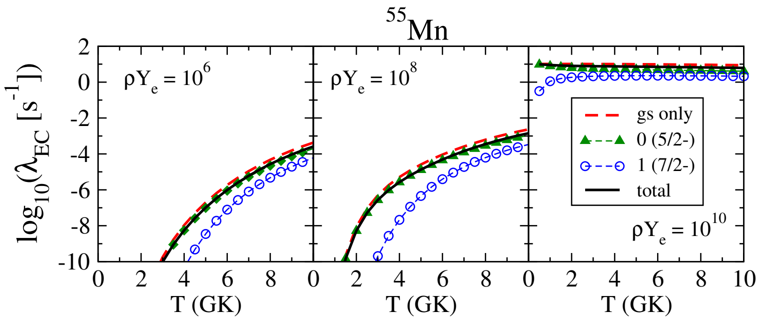

Fig. 2. Weak-decay rates for ^{55}Mn from SLy4–QRPA calculations as a function of T (GK) for densities $\rho Y_e = 10^{10}, 10^8, 10^6$ mol/cm^3. The separate contributions from the ground and excited states are shown.

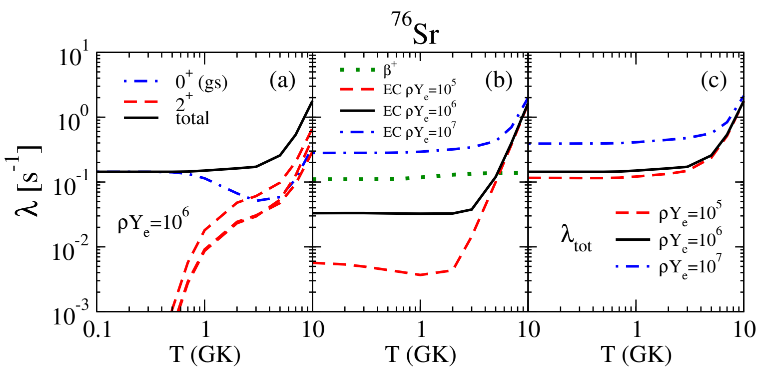

Fig. 3. Weak-decay rates of ^{76}Sr as a function of the temperature T (GK). (a) Contributions from the ground and excited 2^+ states to the total rates. (b) Decomposition of the rates into their β^+ and EC components, evaluated at various densities ρY_e (mol/cm^3). (c) Total rates for various densities.

In the middle panel of Fig. 3, we can see the competition between the β^+ and EC rates. Whereas the former is almost independent of ρ and T, the latter exhibits a strong dependence that makes EC contributions dominant at high densities and high temperatures. The right panel shows the total rates.

4. Conclusions

Weak-decay rates as a function of the density and temperature have been calculated within a model that includes thermal population of the initial states and phase-space factors from EC and β decay. The Gamow–Teller strength distributions are obtained within a QRPA formalism based on deformed Skyrme HF+BCS calculations. We have shown that the present model describes fairly well the half-lives and GT strength distributions measured from β decay and charge-exchange reactions. Contributions of the excited states to the total rates have been calculated, showing that their relative importance increases with T. Competition between EC and β-decay has been shown to be important in neutron-deficient nuclei. The particular conditions of ρ and T finally determine which process is the dominant one.

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REFERENCES

[1] Y. Fujita, B. Rubio, W. Gelletly, *Prog. Part. Nucl. Phys.* **66**, 549 (2011).

[2] F. Osterfeld, *Rev. Mod. Phys.* **64**, 491 (1992).

[3] E.M. Burbidge, G.R. Burbidge, W.A. Fowler, F. Hoyle, *Rev. Mod. Phys.* **29**, 547 (1957); G. Wallerstein *et al.*, *Rev. Mod. Phys.* **69**, 995 (1997).

[4] G.M. Fuller, W.A. Fowler, M.J. Newman, *Astrophys. J. Suppl.* **42**, 447 (1980); *Astrophys. J.* **252**, 715 (1982); *Astrophys. J. Suppl.* **48**, 279 (1982); *Astrophys. J.* **293**, 1 (1985).

[5] K. Langanke, G. Martínez-Pinedo, *Rev. Mod. Phys.* **75**, 819 (2003).

[6] P. Sarriguren, J. Pereira, *Phys. Rev. C* **81**, 064314 (2010); P. Sarriguren, A. Algora, J. Pereira, *Phys. Rev. C* **89**, 034311 (2014); P. Sarriguren, *Phys. Rev. C* **91**, 044304 (2015).

[7] P. Sarriguren, R. Álvarez-Rodríguez, E. Moya de Guerra, *Eur. Phys. J. A* **24**, 193 (2005); P. Sarriguren, *Phys. Rev. C* **79**, 044315 (2009).

[8] P. Sarriguren, *Phys. Lett. B* **680**, 438 (2009); *Phys. Rev. C* **83**, 025801 (2011).

[9] E. Nácher *et al.*, *Phys. Rev. Lett.* **92**, 232501 (2004); E. Poirier *et al.*, *Phys. Rev. C* **69**, 034307 (2004); A. Pérez-Cerdán *et al.*, *Phys. Rev. C* **88**, 014324 (2013); M.E. Estévez Aguado *et al.*, *Phys. Rev. C* **92**, 044321 (2015); J.A. Briz *et al.*, *Phys. Rev. C* **92**, 054326 (2015).

[10] P. Sarriguren, E. Moya de Guerra, R. Álvarez-Rodríguez, *Nucl. Phys. A* **716**, 230 (2003); P. Sarriguren, *Phys. Rev. C* **87**, 045801 (2013); **93**, 054309 (2016).

[11] P. Sarriguren *et al.*, *Nucl. Phys. A* **635**, 55 (1998); **691**, 631 (2001); **658**, 13 (1999).

[12] K. Muto *et al.*, *Z. Phys. A* **341**, 407 (1992); P. Sarriguren *et al.*, *Phys. Rev. C* **64**, 064306 (2001).

[13] S. El-Kateb *et al.*, *Phys. Rev. C* **49**, 3128 (1994).