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Deducing Stellar Reaction Rates from Mirror Nuclear Decays

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Introduction

It is impossible to predict the life cycle of stars and how the chemical composition of the Universe evolved without detailed knowledge of the rates of nuclear reactions that take place in them. To provide astrophysicists with such knowlegde is a challenge for nuclear physics.

Many nuclear reactions in stars involve two charged nuclei in the entrance channel. The most important are (p, γ), (α, γ), (p, α), (α, p) and (α, n). At low stellar energies, the Coulomb repulsion between colliding nuclei makes reaction cross sections so small that in most cases it is impossible to measure them directly in terrestrial laboratories. On the other hand, most nuclear reactions in stars involve short-lived proton-rich and neutron rich nuclei that can be studied only with radioactive beams. The (n, γ) reactions are particularly difficult to study because neither neutron nor short-lived nuclear targets exist. Although the quality of radioactive beams has improved over the last decade, not all beams necessary for astrophysics are easily available. So, in many cases, the cross-sections of interest must be studied indirectly by other methods. Presented in this article is a recent idea about how some of these cross-sections can be deduced or independently verified.

The idea is based on recent theoretical observation that the amplitudes of two nuclear decays (N, Z) $\to$ (N_1, Z_1)+(N_2, Z_2) and (Z, N) $\to$ (Z_1, N_1)+(Z_2, N_2), in which all neutrons are replaced by protons and vice versa, are related. These decays can be either real or virtual. The latter occur only in the presence of a third body to satisfy the energy conservation law.

Virtual Decays, Asymptotic Normalization Coefficients and Peripheral Reactions

The strength of a virtual decay is determined by its amplitude, called a vertex constant, which is the analog of the coupling constant in particle physics. The vertex constants are related in a simple way to the magnitudes of the tails of nuclear wave functions in their decays channels, called asymptotic normalization coefficients (ANCs) [1,2]. Both vertex constants and ANCs are important structural characteristics of nuclei. They can be calculated using an expression that contains the wave functions of nuclei (N, Z), their decay products (N_1, Z_1) and (N_2, Z_2), the sum of nucleon-nucleon (NN) interactions between (N_1, Z_1) and (N_2, Z_2), and the (N_1, Z_1)+(N_2, Z_2) virtual motion wave function. Comparison between calculated and measured ANCs is an important source of knowledge about nuclear structure and the NN interactions. The ANCs can be experimentally determined from one particular class of nuclear reactions where the contributions to the cross-sections come mainly from large distances between (N_1, Z_1) and (N_2, Z_2). Such reactions are called peripheral.

In stars, one important class of peripheral nuclear reactions is non-resonant radiative proton and α-particle capture, $B+p \to A+\gamma$ and $C+\alpha \to A+\gamma$. Perhaps the most well-known example here is the pp-chain reaction ^{7}Be(p, γ)^{8}B where the reaction amplitude includes contributions from the p–^{7}Be distances up to 200 fm. The cross-sections of peripheral (p, γ) reactions often depend on details of nuclear structure mainly through a single structure quantity, the probability amplitude for the two colliding nuclei to form the bound state A at distances outside the range of their mutual strong interaction. In other words, non-resonant peripheral stellar capture cross sections are determined by ANCs. The ANC also enters into the theory of other nuclear reactions in which a p or α is transfered to nucleus B or C to form nucleus A, or in which A breaks up into $B+p$ or $C+\alpha$ in the field of another nucleus. If the transfer or breakup reaction occurs at energies where nuclear absorption and/or Coulomb barrier effects guarantee that the reaction is predominantly peripheral, and therefore can be also expressed in terms of ANCs, then the measurements of the transfer and breakup cross-sections at available convenient terrestrial energies can be used to provide information about capture cross-sections at stellar energies [3]. This connection between low-energy radiative capture cross-sections and direct peripheral transfer and breakup reactions has led to a new and rapidly developing activity in experimental nuclear physics called the ANC method [4,5].

Mirror Nuclear Decays

Within the last decade, it has been realized that vertex constants in mirror nuclear decays $(N, Z) \to (N_1, Z_1)+(N_2, Z_2)$ and $(Z, N) \to (Z_1, N_1)+(Z_2, N_2)$ are related. Therefore, the ANCs associated with these mirror decays are related as well. This was first noticed in calculations that employ a microscopic model. Then a theoretical explanation has been given in Ref.[6]. Indeed, if the wave functions in mirror nuclei are the same then the only thing that differs in analytical expressions for mirror decay amplitudes are the relative wave functions of the $(N_1, Z_1)+(N_2, Z_2)$ and $(Z_1, N_1)+(Z_2, N_2)$ virtual motion. The difference comes from different Coulomb interactions in mirror decay channels. A very simple approximate analytical formula has been derived in Refs. [6,7] for the ratio of mirror ANCs $C_{N,Z}$ and $C_{Z,N}$,

$$\mathcal{R} = \left(\frac{C_{N,Z}}{C_{Z,N}}\right)^2 \approx \left(\frac{\kappa_{N,Z} F_l(i\kappa_{Z,N} R)}{\kappa_{Z,N} F_l(i\kappa_{N,Z} R)}\right)^2. \qquad (1)$$

Here F_l is the regular Coulomb wave function corresponding to the interaction between point charges Z_1 and Z_2 (or N_1 and N_2 in the mirror case), l is the orbital momentum in the decay channel of interest, the wave numbers $k_{N,Z}$, $k_{Z,N}$ are determined by separation energies in mirror decay channels $(N_1, Z_1)+(N_2, Z_2)$ and $(Z_1, N_1)+(Z_2, N_2)$ and R is the boundary of the nuclear interior.

The fascinating thing about formula (1) is that it tells us that the ratio of mirror ANCs should depend only on separation energies and nuclear charges of decay fragments and should be independent of either the nuclear structure or the NN potentials. The easiest way to check this is to calculate ANCs for mirror systems within a two-body model. Such a model is often used to generate single-particle wave functions in nuclei and to model overlaps between initial and final states for transfer and breakup reactions. An example of such a calculation in shown in Figure 1 for the mirror decays $(N, Z) \to (N, Z-1)+p$ and $(Z, N) \to (Z-1, N)+n$ for a range of light nuclei assuming that the nuclear $(N, Z-1)+p$ and $(Z-1, N)+n$ interactions are exactly the same. One can see that although the ratio R changes by as much as five orders of magnitude, formula (1) reproduces this general trend very well. Deviations from the formula depend on the proton separation energy and orbital momentum. For non-zero orbital momentum and large separation energies the deviations are less than 1–2%. For loosely bound s-wave protons the deviation is about 9–13%. The situation is much better for mirror α-decays $(N, Z) \to (N-2, Z-2)+\alpha$ and $(Z, N) \to (Z-2, N-2)+\alpha$ where the deviation between predictions of formula (1) and the exact ratio obtained within a two-body potential model does not exceed 2% [8].

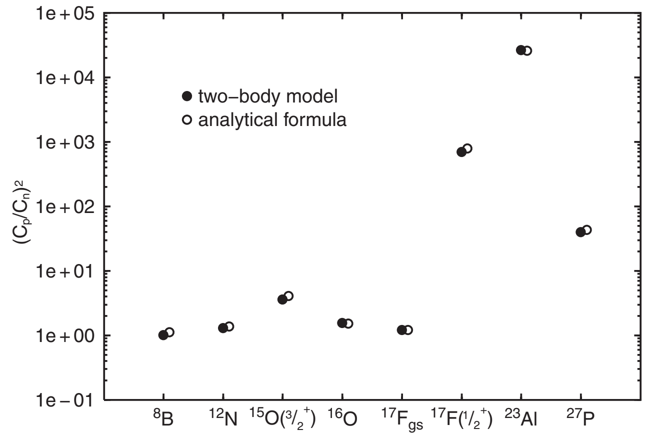

Figure 1. *Ratio of proton to neutron ANC squared* $(C_p/C_n)^2$ *calculated in the two-body potential model and using the analytical formula (1) for a range of light nuclei.*

The ratio of mirror ANCs has been also studied in a microscopic cluster model [8]. This models assumes that clusters have internal structure described by a simple shell model, it takes antisymmetrization between the nucleons from diffrent clusters into account and applies R-matrix ideas to match the nuclear wave functions to their proper asymptotic form when clusters are far away from each other. According to this study, the interaction potential between decay products $(N, Z-1)$ and p can differ from the interaction between $(Z-1, N)$ and n in mirror analog system and this leads to smaller deviations from formula (1) than in the two-body model case. However, if clusters are strongly excited then coupling between channels with different core excitations can contribute to deviations from formula (1). The strongest deviation, obtained in the microscopic cluster model, was 12% for the case of ^{23}Ne-^{23}Al mirror pair.

Application of Formula (1) to Stellar Reactions

Formula (1) can be used to predict quickly an unknown ANC of interest (or to verify a known ANC) if its mirror ANC is known. For example, it is possible to determine the ANC for non-resonant stellar capture $(N, Z-1)+p \to (N, Z)+\gamma$ if the neutron ANC for the virtual decay $(Z, N) \to (Z-1, N)+n$ is known. It often happens that when ($N, Z-1$) and (N, Z) are radioactive, their mirror analogs are either stable or "less radioactive" (more long-lived). Experiments with them are easier to perform and the accuracy of their cross-sections is better than that obtained with "more radioactive" beams. Moreover, with intensive stable beams, energies below the Coulomb barrier can be used, which minimizes uncertainties in input parameters for transfer reaction theories used to derive ANCs. Measuring sub-Conlomb transfer reactions would be more problematic for weak radioactive beams.

The idea of relation between the amplitudes of mirror decays has been applied in Refs. [8,9] to determine the astrophysical S-factor for ^{7}Be(p,γ)^{8}B using the ^{8}Li ANC determined in the ^{13}C(^{7}Li,^{8}Li)^{12}C reaction measured using stable beam of ^{7}Li. To get a more accurate result, the ratio calculated in the microscopic ^{4}He + ^{3}He + p model has been used in Ref. [8]. The astrophysical S-factor obtained from mirror symmetry is $S_{17}(0) = 18 \pm 2$ eV.b, which agrees well with the value of 17.8 ± 2.8 eV.b determined using the ^{8}B ANC measured with ^{7}Be radioactive beam. Other applications that used formula (1) have been reported. The ^{11}C(p,γ)^{12}N reaction cross-sections have been deduced from the ^{12}B ANC measured in the ^{11}B(d,p)^{12}B reaction [10], ^{8}B(p,γ)^{9}C has been obtained from the ^{9}Li ANC measured in ^{8}Li(d,p)^{9}Li [11]. The astrophysical S-factors obtained in these works agree with those obtained with proton ANCs determined from experiments with radioactive beams. Both the ^{11}C(p,γ)^{12}N and the ^{8}B(p,γ)^{9}C reactions are the parts of the hot pp-chains that can provide alternative paths to the triple-alpha process to synthesize the CNO nuclei at some high-density and high-temperature astrophysical sites.

Virtual–Real Mirror Decays

In many $N > Z$ cases when the separation energy of the virtual decay $(N,Z) \to (N_1, Z_1) + (N_2, Z_2)$ is small, the mirror decay is real and is observed as a resonance in continuum. This decay is characterized by a width, which at the same is a measure of the decay amplitude. If the resonance is narrow then the same reasoning as in the case of two mirror virtual decays suggests that the width $\Gamma_{Z,N}$ of a real decay is related to the ANC $C_{N,Z}$ of its mirror virtual decay. This relation is given by the formula [7,12],

$$\mathcal{R}_\Gamma = \left(\frac{\Gamma_{Z,N}}{C^2_{N,Z}}\right)^2 \approx \hbar \upsilon_{Z,N} \left|\frac{\kappa_{Z,N} F_l(\kappa_{N,Z} R)}{\kappa_{N,Z} F_l(i\kappa_{Z,N} R)}\right|^2, \qquad (2)$$

where $\upsilon_{Z,N}$ is the velocity in the real decay channel. As before, this aproximate relation is model independent, being governed only by energies and charges in mirror decay channels. Figure 2 shows how formula (2) works for mirror real proton and virtual neutron decays for a range of light nuclei. Its predictions are compared to predictions of both the potential two-body model and the microscopic cluster model [12].

A link between the width of a proton resonance and the neutron ANC of its miror analog can be important for predicting the rate for a particular class of resonant (p,γ) reactions at stellar energies. This class includes reactions that proceed via very narrow isolated resonance states, the proton width Γ_p of which is either comparable to or much less than its γ-decay width Γ_γ. The capture rates for these reactions, determined by $\Gamma_p\Gamma_\gamma/(\Gamma_p+\Gamma_\gamma)$, depend strongly on Γ_p. Such narrow resonances can be found in the neutron-deficient region of the *sd* and *pf* shells (for example, some levels in ^{25}Si, ^{27}P, ^{33}Ar, ^{36}K, and ^{43,46}V) and their study is important for understanding nucleosynthesis in the *rp* process. For the resonances mentioned earlier Γ_p can be much less than 1 eV. Direct measurements of such tiny widths using proton elastic scattering are impossible. Proton transfer reactions can be used instead. Their analysis (for example, within the distorted-wave formalism) provides spectroscopic factors, which are combined together with

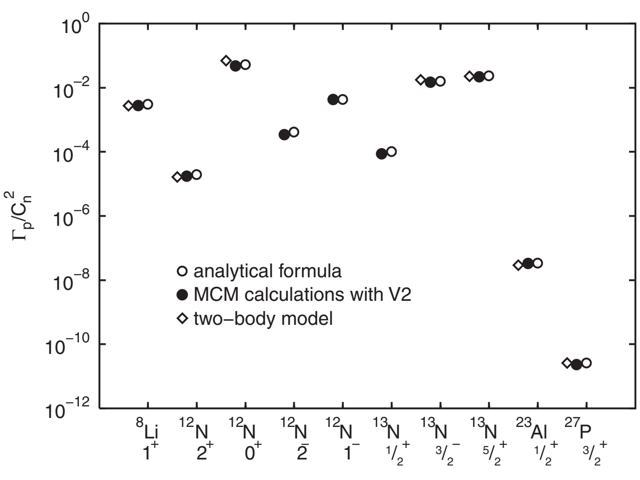

Figure 2. *Ratio of the proton width Γ_p to mirror neutron ANC squared C_n (given in units of ħc) calculated in the two-body potential model, microscopic cluster model and using the analytical formula (2) for a range of light nuclei.*

single-particle widths to get necessary partial proton widths Γ_p. However, uncertainties in Γ_p extracted using such a procedure are about 50%. These uncertainties arise because of problems in the theoretical treatment of stripping reactions to the continuum and due to uncertainties in prediction of single-particle proton widths.

An alternative way to determine very small proton widths is to use formula (2). The neutron ANCs C_n of mirror analogs can be determined from experiments with transfer reactions to bound states, the theoretical analysis of which encounters less problems than that of stripping to continuum. The neutron ANCs can be determined with typical accuracy of 10 to 20%. If the uncertainties in $\mathcal{R}_\Gamma$ are less than 10%, then the accuracy of determination of $\Gamma_p = \mathcal{R}_\Gamma C_n^2$ can be between 10 to 30%. This is more accurate than the distorted wave analysis of stripping to the continuum can provide. If the determination of C_n requires experiments with stable beams rather than with radioactive beams, then even better accuracy may be achieved. This idea has been used in Ref. [10] to determine the unknown width of narrow 2^+ state in ^{12}N from the ^{12}B ANC measured by the ^{11}B(d,p)^{12}B reaction.

Mirror Symmetry in ^{15}C – ^{15}F and the Stellar Reaction ^{14}C(n,γ)^{15}C

This reaction appears in three astrophysical scenarios: (i) primordial nucleosynthesis of heavy chemical elements in a nonstandard inhomogeneous big bang model; (ii) it is a part of neutron induced CNO cycles in the helium burning layer of asymptotic giant branch stars, in the core helium burning of massive stars, and in subsequent carbon burning; (iii) it triggers synthesis of heavy carbon and oxygen isotopes in the hot-bubble scenario of gravitational core-collapse Type II supernovae explosions with neutrino driven winds.

Until recently, a puzzling disagreement existed between the cross-sections of ^{14}C(n,γ)^{15}C measured directly, determined indirectly via Coulomb dissociation of ^{15}C and calculated theoretically (see Figure 3). To resolve this disagreement, the idea of symmetry between mirror decays has been used in Ref. [13]. However, the implementation of this idea has been modified for the following reason.

The ^{15}C nucleus is bound by 1.2 MeV. Its mirror analog ^{15}F is unbound and is seen as a broad s-wave resonance in the ^{14}O + p continuum. Formula (2) should not be valid for broad resonances. However, the calculations performed in various versions of a microscopic cluster model suggest that there still should be a link between the ANC of the neutron virtual decay ^{15}C $\rightarrow$ ^{14}C + n and the width of the proton real decay ^{15}F $\rightarrow$ ^{14}O + p. Using this link, the ^{15}C ANC has been determined from the ^{15}F width and then used in Ref. [13] to deduce the low-energy capture cross-sections of ^{14}C(n,γ)^{15}C. It has been shown that earlier direct measurements and Coulomb dissociation experiments are not consistent with requirement of mirror symmetry. New direct measurements published this year in Ref. [17] have confirmed the conclusions made on the base of mirror symmetry.

An independent way to discriminate between different measurements and predictions for ^{14}C(n,γ)^{15}C using mirror symmetry is very valuable because the neutron capture on a long-lived radioactive target ^{14}C is a rare example of a large class of nuclear reactions, namely, neutron capture by radioactive isotopes, where a comparison between direct and indirect methods is possible. In most cases, such reactions cannot be studied directly due to the non-existence of neutron targets and the short-lived nuclear targets. Nevertheless, because the knowledge of neutron capture reactions on short-lived neutron-rich isotopes is important for predictions of chemical evolution of the universe, they are studied indirectly, for example, using inverse dissociation reactions and will be done so for a long time in the future. Therefore, the consistency between direct and indirect methods must be achieved.

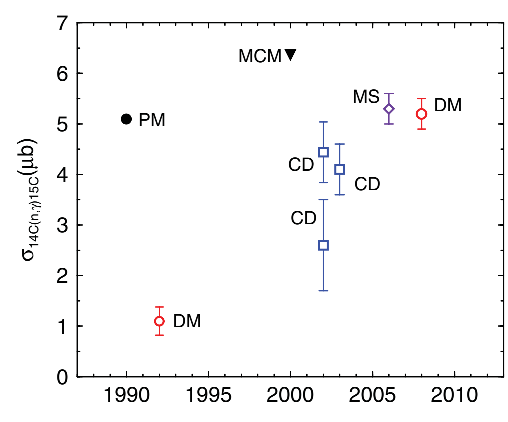

Figure 3. *The ^{14}C(n,γ)^{15}C reaction cross-sections calculated in potential model (PM) [14], microscopic cluster model (MCM) [15], measured directly (DM) in 1990 [16] and 2008 [17], indirectly through the Coulomb dissociation (CD) [18–20] and obtained in [13] using mirror symmetry (MS) between the ^{15}C ANC and the ^{15}F proton width.*

Mirror Decays in a Multichannel Problem

Many nuclear states lying between closed shells can be considered as a mixture of various core-plus-valence-nucleon configurations. If such states are loosely bound then the coupling between these configurations can depend on whether the Coulomb nucleon–core interaction is present or not. This can create additional uncertainties in applying formulae (1) and (2) to mirror nuclear decays. The most intriguing here is the case of the $^{27}P(3/2^+) \to {}^{26}Si + p$ and $^{27}Mg(3/2^+) \to {}^{26}Mg + n$ mirror decays. The narrow resonance $^{27}P(3/2^+)$ at 340 keV is of astrophysical interest as it is produced in novae by the proton capture reaction $^{26}Si(p,\gamma)^{27}P$. This reaction destroys ^{26}Si that β-decays to ^{26}Al and thus can influence the observed intense distribution of ^{26}Al throughout the galactic plane. The shell model predicts that the proton decay width of $^{27}P(3/2^+)$ is comparable to the width of γ-emission. Therefore, the $^{26}Si(p,\gamma)^{27}P$ reaction rate explicitly depends on Γ_p.

A recent theoretical study of these mirror decays in a multichannel microscopic cluster model has revealed an unexpected and curious result [21]. The probability for the valence proton in $^{27}P(3/2^+)$ to occupy the unbound $d_{3/2}$ orbit around the non-excited core ^{26}Si strongly decreases with the number of core-excited channels added to the coupling scheme. This proton prefers to occupy the bound s-wave orbit around the excited core $^{26}Si(2^+)$ instead. A similar effect occurs in the mirror analog $^{27}Mg(3/2^+)$. However, due to the Coulomb proton–core interaction this effect is stronger in ^{27}P. As a result, the mirror channel wave functions differ, leading to noticeable deviations between ratio $\mathcal{R}_\Gamma$ calculated in the microscopic cluster model and the prediction of formula (2). This deviation disappears when the $^{27}P(3/2^+)$ is artificially made bound with a large binding energy. Interestingly, no strong deviation from formula (1) occurs in the ground states of mirror pair $^{27}Mg(1/2^+) - {}^{27}P(1/2^+)$, which are based on the ground core state 0^+ and the s-wave valence nucleon state, irrespectively of how many channels are added into the coupling scheme.

It has been estimated in Ref. [21] that the deviation from formula (2) for the mirror pair $^{27}Mg(3/2^+) - {}^{27}P(3/2^+)$ could be about 18%. This deviation correlates with symmetry breaking in the weights of the $^{26}Mg(0^+) + n$ and $^{26}Si(0^+) + p$ configurations, which suggests a general recipe for correcting formula (1) for multichannel cases. The estimate of 18% has been used in Ref. [21] to deduce the unknown $^{27}P(3/2^+)$ width from the $^{27}Mg(3/2^+)$ ANC measured in the peripheral reaction $^{26}Mg(t,d)^{27}Mg$.

Proton Capture on Loosely Bound Nuclei

Various scenarios of stellar hydrogen burning involve synthesis of proton-rich nuclei by the (p,γ) reaction. Some of these nuclei have relatively large proton separation energies but others, close to the proton drip line, are loosely bound. For example, ^{9}C, ^{13}O, and ^{18}Ne are produced by proton capture from ^{8}B, ^{12}N, and ^{17}F, the proton separation energies of which are only 133 keV, 600 keV, and 605 keV, respectively. The cross-sections of these reactions are determined by ANCs, which can be determined experimentally from peripheral transfer, breakup, or Coulomb dissociation reactions. However, the problem is that the latter reactions, studied in laboratories at much higher energies, are sensitive to a different part of the valence proton wave function than the stellar proton capture is. More precisely, these proton removal reactions are sensitive to the near-surface part of the proton wave function that does not influence the proton capture cross-sections at all. It has been recently realized that in nuclei, where the two-proton decay threshold lies just above the one proton decay threshold, the near-surface part of the valence proton wave function can be influenced by the proton–proton correlations and, therefore, it can expose pre-asymptotic abnomalities in its behavior [22,23]. If the latter are significant, then what is extracted from such reactions may not correspond to the true ANCs. In these cases, determining C_p from a mirror neutron ANC can be very helpful because the mirror neutron-rich system is always more bound and possible threshold abnormalities in the mirror strongly bound neutron wave functions should be absent. The accuracy of the determined C_p depends then on the the validity of formula (1) for such nuclei.

The ratio of mirror ANCs for $^{9}C \to {}^{8}B + p$ and $^{18}Ne \to {}^{17}F + p$ has been studied in Ref. [24] using a three-body model ($^{7}Be + p + p$ for ^{9}C and $^{16}O + p + p$ for ^{18}Ne), for which the Schrödinger equation can be solved exactly. It has been found that, because the ^{8}B binding energy is small, the geometrical mismatch between the ^{8}B two-body wave function, stretched toward the classically forbidden region, and the spatially confined three-body functions of ^{9}C reduces the norm of the $\langle {}^{9}C | {}^{8}B \rangle$ overlap. For mirror overlap $\langle {}^{9}Li | {}^{8}Li \rangle$, this mismatch is much weaker. As a result, the deviation between the exact ratio of mirror ^{9}C and ^{9}Li ANCs and the predictions of formula (1) occurs. This deviation is about 7%. Therefore, the astrophysical S-factor determined earlier in Ref. [11] from ^{9}Li ANCs should be reduced by about 7% as well. However, for ^{18}Ne, apart from this mismatch, the situation is complicated by the mixing between the ^{17}F + p configurations with different proton orbital momentum, $l = 0$ and $l = 2$. In mirror system ^{17}O + n, the mixing between these orbital momenta can be different, leading to deviation between exact ratio of mirror ANCs and formula (1). The extent of these deviations is different for different states in ^{18}Ne. For example, these deviations are negligible for ^{18}Ne(4$^+$) but can reach 45% for the [^{17}F($5/2$) $\otimes$ $d_{5/2}$] configuration in ^{18}Ne(0^+_2). Thus, special care should be shown if the ^{18}Ne ANC is to be determined from the ^{18}O ANC. In general, the ideas of how to modify formula (1) for proton capture on loosely bound nuclei are considered in Ref. [24].

Concluding Remarks

Studying mirror nuclear decays is a new and interesting direction in modern nuclear physics. It reveals new aspects of nuclear structure and is very helpful for deducing cross-sections of stellar reactions. At the same time, it poses new questions about the old problem of how different the nuclear wave functions in mirror systems are. The answers to these questions will help to understand how the difference in mirror nuclear wave functions can be taken into account when used to predict stellar reaction rates from mirror decays.

Until now, the relation between mirror decays has been studied only theoretically. To study them experimentally is a real challenge. The problem is that to see any deviations from formulae (1) and (2), the ANCs and the widths of resonances should be measured to a high precision. The best precision for ANCs, obtained up to now, is about 10%. Therefore, the uncertainty of the experimentally determined ratio of mirror ANCs can reach 20%. Thus, only those deviations that are larger than 20% can currently be unambigously observed. The candidate mirror pairs where this can happen are ^{18}Ne(0^+_2) – ^{18}O(0^+_2) and ^{27}Mg($3/2^+$) – ^{27}P($3/2^+$). Experimental study of these mirror pairs will test validity of the theoretical structure models used to predict large mirror symmetry breaking in mirror ANCs and, therefore, is a timely and extremely important task.

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