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ANC experiments for nuclear astrophysics: the ^{26}Si(p, γ)^{27}P case

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Abstract. The Asymptotic Normalization Coefficient (ANC) method has proven to be useful in retrieving the direct part of the radiative capture cross section for a number of reactions of astrophysical interest. In this work, the study of the ^{26}Si(p, γ)^{27}P reaction, studied via the ANC in its extension for mirror nuclei will be discussed.

1 Introduction

Among the key problems in nuclear astrophysics, one the most complicated to solve has been to experimentally measure the cross section in the range of interest: Coulomb barrier in fact heavily suppresses the probability for the various reaction to happen, with the result that the cross section at astrophysical energies (between some keV and some MeV) can be very low (even at the order of magnitude of picobarn). Furtheremore, reactions involving radioactive nuclei with a short half-life in the entrance channel are frequent, and a direct measurement sometimes is hardly feasible. For these reasons, many indirect methods have been proposed, and among these the Asymptotic Normalization Coefficient (ANC)[1, 2] one has proven to be useful to evaluate the direct part of the cross section for (p, γ) [3], (n, γ) [4] and (α, γ) [5] radiative captures of astrophysical relevance. In the case of unstable nuclei with small half-lifes, an extention to the method has been developed using the so-called "mirror reactions" [6, 7]. In this work, the ANC method will be briefly presented, and recent results regarding the study of the ^{26}Si(p, γ)^{27}P (performed using the mirror nuclei procedure)[8] will be summarized.
^{26}Si production and destruction channels are deeply involved in the problem of ^{26}Al nucleosynthesis ($T_{1/2}$ = 0.72 Myrs): the 1.809 MeV γ-ray line emitted from the first excited state of ^{26}Mg – in which ^{26}Al naturally decays – has been detected along the Galactic plane, and

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has been considered as a good tracer of the recent nucleosynthesis in our Galaxy. This isotope can supposedly be formed through nucleosynthesis in massive stars and core-collapse Supernovae [see 9, and references therein], but also Wolf-Rayet objects, AGB-stars [10] and Novae [11] have been appointed as good sites for its nucleosynthesis. All of these sites share the possibility to host proton capture, and the ^{26}Al isotope can be produced through the $^{24}\mathrm{Mg}(p,\gamma)^{25}\mathrm{Al}(\beta^{+})^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}$ reaction chain. Understanding such a process has been made difficult by the existence of an isomeric state $^{26}\mathrm{Al}^{m}(T_{1/2} = 6.34$ sec) which decays to the ground state of ^{26}Mg. Such an isomer can be produced via the $^{25}\mathrm{Al}(p,\gamma)^{26}\mathrm{Si}(\beta^{+})^{26}\mathrm{Al}^{m}$ chain, thus reducing the quantity of ^{26}Al in the interstellar medium. The unstable isotope ^{26}Si produced along the way can also be destroyed via proton capture through the $^{26}\mathrm{Si}(p,\gamma)^{27}\mathrm{P}$ reaction, interfering then with the production of $^{26}\mathrm{Al}^{m}$. The study of this reaction can therefore be useful to understand the ratio between ^{26}Al and $^{26}\mathrm{Al}^{m}$ [12, 13].

2 The ANC method

The ANC method allows to indirectly investigate direct radiative capture reactions of astrophysical interest from the one-particle (proton, neutron or alpha) transfer. In general, a direct transfer reaction can be visualized as a $X + A \rightarrow Y + B$ process, where both the X and B nuclei can be considered as $X = Y + a$ and $B = A + a$, a being the transferred particle (Fig.1).

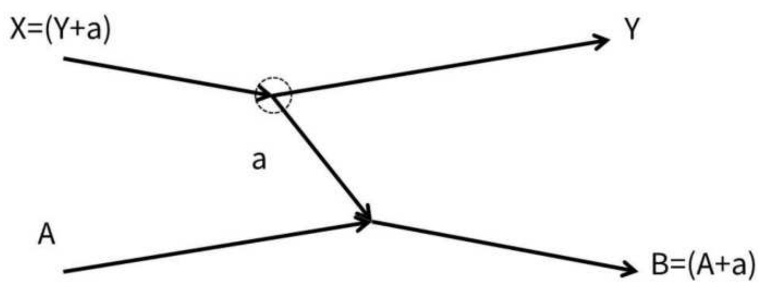

Figure 1. Sketch of a typical transfer reaction.

The experimental cross section is related to the theoretical one, using the DWBA formalism, through the spectroscopic factors (SF):

$$\frac{d\sigma^{exp}}{d\Omega} = \sum_{j_B, j_X} S_{Aa,l_B,j_B} S_{Ya,l_X j_X} \sigma^{DW}_{l_B,j_b,l_X,j_X} \tag{1}$$

Here the experimental and theoretical differential cross sections – $\frac{d\sigma^{exp}}{d\Omega}$ and $\sigma^{DW}_{l_B j_b l_X j_X}$, respectively – are related via the two SF for $A + a$ and $Y + a$ systems: while one of those is usually known, the other is left to be determined. The SF in general depends on the binding potential and on the optical model parameters (OMP)[14]: the depth of the former is in fact adjusted considering the binding energy to reproduce the bound state, while the latters are normally extracted from the elastic scattering. In general the SF is therefore very sensitive to the selection of the optical model adopted, and the experimental angular distributions can be reproduced by different families of potentials [15].
In 1990, Mukhamedzhanov and Timofeyuk [1] pointed out that suitable direct transfer reactions share the same radial overlap integral (I^{c}_{ab,l_c,l_j}) with the direct part of a radiative cross

section at low energies, due to the fact that such capture occurs at large distances from the nucleus, where the behaviour of the wave function can be considered asymptotic. This property can be used to get the cross section of many reactions of astrophysical interest. In fact, the radial overlap functions and bound-state wave functions can be written as:

$$I^{B}_{Aa,l_c,j_c}(r_{ab}) \xrightarrow{r_{ab}>R_n} C^{c}_{ab,l_b,j_b} \frac{W_{-\eta,l_c+\frac{1}{2}}(2k_{ab}r_{ab})}{r_{ab}} \tag{2}$$

and

$$\phi_{ab,l_c,j_c}(r_{ab}) \xrightarrow{r_{ab}>R_n} b^{c}_{ab,l_c,j_c} \frac{W_{-\eta,l_c+\frac{1}{2}}(2k_{ab}r_{ab})}{r_{ab}} \tag{3}$$

$W_{-\eta,l_c+\frac{1}{2}}$ being the Whittaker function, which asymptotic behaviour is equal to $W_{-\eta,l_c+\frac{1}{2}}(-2k_I r) \rightarrow e^{-k_I r+\eta_I ln(2k_I)}$. The coefficients b and C are the so-called single-particle ANC (SPANC) and ANC, respectively. Using equations 2 and 3 in equation 1, we can finally obtain:

$$\frac{d\sigma}{d\Omega} = \sum_{j_B,j_X} \left(C^{B}_{Aa,l_B,j_B}\right)^2 \left(C^{X}_{Ya,l_X,j_X}\right)^2 \frac{\sigma^{DWBA}_{l_B,j_B,l_X,j_X}}{b^2_{Aa,l_B,j_B} b^2_{Ya,l_X,j_X}} \tag{4}$$

where one of the two C^2 constants is the ANC for the direct part of the radiative cross section of interest. This approach is useful because the ANC's have a small dependence on the chosen nucleon binding potential [14], making the cross section nearly independent from b^2. This is true once the OMP are set: the ANC's are, in fact, dependent on the chosen OMP. Also, the relation between the ANC and the S factor sometimes is not unique: for example, in the case of strongly bound systems the final-state interaction can lead to sizable changes in the zero-energy SF [16].

In order to apply the ANC method, just one condition has to be met: the one-particle transfer from which the ANC's are deduced must be peripheral. Such a condition (called peripherality) is really important and must be ascertained.

More recently an extension of the use of mirror nuclei in transfer reactions to the ANC method has been proposed [6]: this has been useful in case of (p) or neutron (n) transfers that involve strongly unstable nuclei (such as ^{26}Si) [6–8]: if $A + p \rightarrow B$ is a certain proton capture, the proton ANC (C_p^{A+p}) can be extracted from the neutron ANC (C_n^{D+n}) of a suitable mirror partner $D + n \rightarrow E$, D and E having inverted number of protons and neutrons with respect to A and B, respectively. The two ANC are tied by the relation

$$\left(C_p^{A+p}\right)^2 = R_{mirr}\left(C^{C+n}\right)^2 \tag{5}$$

with R_{mirr} that can be written as

$$R_{mirr} = \left|\frac{F_l\left(ik_pR_N\right)}{k_pR_n j_l\left(ik_nR_N\right)}\right|^2 \tag{6}$$

In Eq.6, F_l is the regular Coulomb wave function, j_l the Bessel function of $l-$th order, and R_N the radius of the nuclear interior. The quantities k_p and k_n are instead related to the neutron and proton separation energy, via the relation $k = \sqrt{\frac{2\mu\epsilon}{\hbar^2}}$ [6, 7].

If in the proton channel an excited state near the threshold is present, the corresponding mirror state will exist as a resonance, and a relation exists that ties the C^2 of the direct radiative capture in the excited state and the Γ of the unbound state in the mirror counterpart exists[6]:

$$\frac{\Gamma_{p(n)}}{\left|C_{n(p)}\right|^2} = R_\Gamma \approx R_0^{res} = \frac{\hbar^2 k_{p(n)}}{\mu}\left|\frac{F_l\left(ik_{p(n)}R_N\right)}{k_{p(n)}R_N j_l\left(ik_{n(p)}R_N\right)}\right|^2 \tag{7}$$

3 The ^{26}Si(p, γ)^{27}P reaction reaction

Experiments involving ^{26}Si are difficult, given that the half-life of such an isotope of Silicon is quite short($T_{1/2}$ = 2.24 sec). For this reason, an indirect measurement of the ^{26}Si$(p,\gamma)^{27}$P has been performed using the ^{26}Mg$(d,p)^{27}$Mg transfer reaction, applying the method described in Section 2 that involves mirror nuclei [8]. The experiment has been carried out at the Nuclear Physics Institute of the Czech Academy of Sciences, using the deuteron beam (E_{beam} = 19.2 MeV, I≈ 14 enA) available at the U-120M isochronus cyclotron operated by the CANAM infrastructure (Řež, Czech Republic). Such a beam has been sent on a ^{26}MgO (with ^{12}C as backing) target, produced by the target laboratory of the Laboratori Nazionali del Sud - Istituto Nazionale di Fisica Nucleare (LNS–INFN). The experimental apparatus was composed by five ΔE–E telescopes composed of a thin (250 μm) and thick (5000 μm) anular silicon detectors, covering the 7° – 60° range thanks to a rotating plate.
In order to extract the ANC related to the ^{26}Mg + n $\rightarrow$ ^{27}Mg capture, we need to retrieve the OMP's for the ^{26}Mg$(d,p)^{27}$Mg reaction. Therefore, we need to extract the OMP's of both the entrance(^{26}Mg + d) and the exit (^{27}Mg + p) channels. To do so, the ΔE–E telescopes have been used to select the deuteron and proton loci. Those two have been studied separately: using the FRESCO code [17], the angular distribution for the scattered deuterons has been fitted to extract the OMP's for the entrance channel. Those have been used – again by fitting procedures using the OMP's from [20] as seed values, using FRESCO – to finally retrieve the OMP's from the proton angular distribution of the exit channel, in this case ^{27}Mg + p.
The selected optical model is

$$U = V_c\,(r_c) - V_0 f\,(x_0) - \left[W f\,(x_w) - 4 W_D \frac{d}{dr} f\,(x_D) \right] + \\ + \frac{\hbar^2}{m_\pi c} V_{LS}\,(L\sigma)\,\frac{1}{r}\frac{d}{dr} f\,(x_{LS})\,. \tag{8}$$

$V_c\,(r_c)$ being the Coulomb potential, V_0 and W the depth of the real and imaginary parts of the volume potential, V_{LS} the depth of the real spin-orbit one, and W_D the depth of the surface term for the imaginary part of the potential, respectively. The term $f\,(x_i)$ represents the radial form of the Woods-Saxon potential, and can be written as

$$f\,(x_i) = (1 - e^{x_i})^{-1} \tag{9}$$

where $x_i = \left(r - r_i A^{1/3}\right)/a_i$, r_i being the radius parameter and a_i the diffuseness one, while A the atomic mass number. Once the OMP's are set, the ANC values for the ^{26}Mg + n $\rightarrow$ ^{27}Mg capture in the ground and first excited states have been found using Eq.4, in which the value of C^2_{pn} = 0.77 fm^{-1} [18] has been used (he results of the calculation are reported in [8]).
In order to apply the ANC method, the peripherality for the process – in this case the (d,p) reaction – in exam must be ascertained. The main way to do so is to check the dependence of the C^2 to the geometry – r_0 and a parameters – of the Wood-Saxon potential: if its values variate weakly in a wide range of b^2, then the reaction can be considered peripheral. In the same range of b^2 the SF must show a bigger variation.
In this case (Figure 2), the C^2 for the ^{27}Mg→ ^{26}Mg+n shows a variation of ≈ 13%, while the SF varies by ≈ 55%, and the process can be therefore considered predominantly peripheral.
Once the neutron ANC's are extracted, the procedure for mirror nuclei has been used with

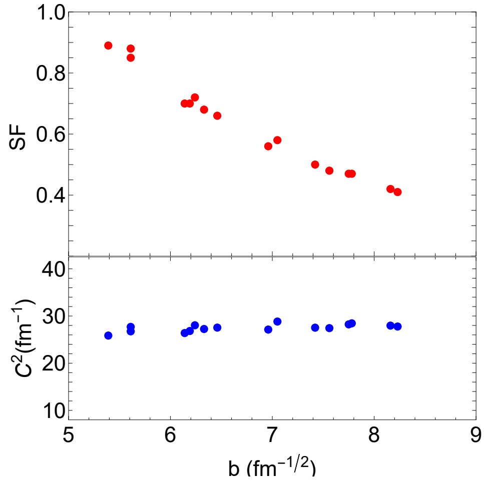

Figure 2. Spectroscopic factors (upper panel, red circles) and ANC values (lower panel, blue circles)extracted for the ground state of ^{27}Mg versus the value of the SPANC b. The calculations have been done using the optical potential P1 of [8]. In this calculations the r_0 parameter has been varied between 1.1 and 1.4 fm and a_0 between 0.5 and 0.7 fm.

Table 1. Values found in [8] and compared with [19] and [20]. The ANC values for the capture in the ground (first column) and the 1^{st} excited state (second column) for the neutron capture ^{26}Mg$(n,\gamma)^{27}$Mg from the three publications are reported, along with the proton ANC (third column) for the capture in the ground state and the proton width Γ_p for the ^{26}Si$(p,\gamma)^{27}$P (fourth column).

ref.	$(C^{Mg}_{g.s.})^2$ [fm^{-1}]	$(C^{Mg}_{1^{st}})^2$ [fm^{-1}]	$(C^{p}_{g.s.})^2$ [fm^{-1}]	$\Gamma^p_{1^{st}}$ [MeV]
[8]	28.26 ± 5.30	3.40 ± 0.32	1420 ± 255	$(5.23 \pm 1.05) \times 10^{-9}$
[19]	24.50 ± 4.90	1.1 ± 0.15	1058 ± 273	$(4.04 \pm 0.77) \times 10^{-9}$
[20]	44.00 ± 5.30	3.40 ± 0.32	1840 ± 240	$(5.4 \pm 0.1) \times 10^{-9}$

the aim to determine the proton ANC and the proton width Γ_p for the ^{26}Si$(p,\gamma)^{27}$P.
The results (Table 1) show a substantial agreement between [8] and [19] , if the different binding energies are properly taken into account: in this calculation, the value of 0.807 MeV for the proton separation energy of ^{27}P experimentally extracted by [21] has been used (instead of the 0.859 MeV used in [19]). This updated value of the separation energy comes from the first experimental evidence for the observation of a 1.125 MeV β-delayed γ-ray from the decay of ^{27}S: the excitation energy for the first excited state of ^{27}P and the proton decay energy from the first excited state of ^{27}P to the ground state of ^{26}Si retrived in [21] brought to a more precise evaluation of the proton-separation energy and the mass excess. Now that the C^2 and Γ_p have been correcly extracted, the reaction rate for the direct capture in the ground state and the resonant one in the first excited state have been calculated using the formulas from [22], finding an enhancement by a factor 1.4 for the ground state and 2.2 for the first excited state contribution with respect to [21]. To calculate the latter, the value of Γ_γ has been calculated using the ratio I_γ/I_p taken from [21, 23]

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