\textbf{15C-15F Charge Symmetry and the 14C(n, \gamma)15C Reaction Puzzle}

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The low-energy reaction 14C(n, \gamma)15C provides a rare opportunity to test indirect methods for the determination of neutron capture cross sections by radioactive isotopes versus direct measurements. It is also important for various astrophysical scenarios. Currently, puzzling disagreements exist between the 14C(n, \gamma)15C cross sections measured directly, determined indirectly, and calculated theoretically. To solve this puzzle, we offer a strong test based on a novel idea that the amplitudes for the virtual 15C \rightarrow 14C + n and the real 15F \rightarrow 4O + p decays are related. Our study of this relation, performed in a microscopic model, shows that existing direct and some indirect measurements strongly contradict charge symmetry in the 15C and 15F mirror pair. This brings into question the experimental determinations of the astrophysically important (n, \gamma) cross sections for short-lived radioactive targets.

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Many nuclear reactions in stellar interiors involve radioactive nuclei. Construction of radioactive beam facilities all around the world provided the opportunity to study some of these reactions directly. However, a large class of nuclear reactions, namely, neutron capture by short-lived radioactive isotopes, cannot be studied directly due to the nonexistence of neutron targets and the short neutron lifetime. Nevertheless, since the knowledge of these reactions 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.

The neutron capture on a long-lived radioactive target 14C provides one of the few possible test cases where a comparison between direct and indirect methods is possible. On the other hand, the 14C(n, \gamma)15C reaction is interesting on its own because of its important astrophysical applications. First, the knowledge of this reaction rate is necessary for making quantitative predictions for primordial abundances of heavy chemical elements in a nonstandard inhomogeneous big bang model. According to this model, neutron- and proton-rich zones may appear in the early Universe with different sequences of nuclear reactions in them. In neutron-rich zones, reaction chains composed of (n, \gamma), (t, n), and (a, n) reactions allow bypassing of the A = 8 mass gap and the production of beryllium, boron, and carbon isotopes including stable ones on the time scale of the big bang isotope 14C [1]. Further nucleosynthesis depends on reactions that destroy 14C, the most important of which is 14C(n, \gamma)15C. Second, 14C(n, \gamma)15C is a part of the 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 [2]. Such cycles may cause a depletion in the CNO abundances. The 14C(n, \gamma)15C reaction is the slowest of both of these cycles and, therefore the knowledge of its rate is important to predict the 14C abundances over the period of high neutron flux [2]. Finally, the 14C(n, \gamma)15C reaction 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 [3].

Currently, a puzzling disagreement exists between the cross sections \(\sigma_{n,\gamma}\) of 14C(n, \gamma)15C measured directly, determined indirectly, and calculated theoretically. The first direct measurements in Ref. [4] provided \(\sigma_{n,\gamma} = 1.1 \pm 0.28 \mu b\) which is about 5 times smaller than the theoretical value of 5.1 \(\mu b\) predicted earlier in Ref. [5] within a potential model. The subsequent folding model calculations [6] and microscopic cluster model calculations [7] have confirmed the large value of Ref. [5]. Recently, the 14C(n, \gamma)15C cross sections have been determined indirectly in three dissociation experiments of 15C [8–10]. In these works, \(\sigma_{n,\gamma}(23.3 \text { keV})\) has been obtained from the fit to the data at higher energies providing 2.6 \(\pm 0.9 \mu b\) [8], 4.4 \(\pm 0.6 \mu b\) [9], and 4.1 \(\pm 0.4 \mu b\) [10]. Last year, new direct measurements of \(\sigma_{n,\gamma}\) have been reported in Ref. [11]. They suggest that \(\sigma_{n,\gamma}(23.3 \text{ keV}) = 2.7 \pm 0.2 \mu b\), which is twice the value from the first direct measurements.

In this Letter, we propose to use charge symmetry between 15C(\(\frac{1}{2}^+\)) and its isobar analog 15F(\(\frac{1}{2}^-\)) as a strong and model-independent tool to discriminate between different determinations and predictions for the 14C(n, \gamma)15C cross sections.

Let us notice first that the main contribution to the 14C(n, \gamma)15C reaction rate comes from the direct E1 capture from the initial p wave to the relatively weakly bound \(\frac{1}{2}^+\) ground state of 15C. This capture occurs well outside the 14C interior, which we demonstrate in Fig. 1 by plotting the integrand of the E1 amplitude \(M_{n,\gamma}^{(E1)}\) for the (n, \gamma) reaction as a function of the distance \(r\) between \(n\) and 14C. In
This expression may not be accurate for the broad range of the strong interaction parameters from Ref. [5].

Eq. (1), \( \varphi_\omega(r) \) is the neutron scattering wave function in the entrance channel and \( I(r) \) is the radial part of the overlap integral \( \langle 14C|15C \rangle \). In this case, \( M_{E1}^{15C} \) is mostly determined by the \( I(r) \) tail that behaves as

\[
\sqrt{15I(r)} = C_n e^{-\kappa_n r} / r, \quad r \to \infty
\]

Here \( C_n \) is the neutron asymptotic normalization coefficient (ANC), \( \kappa_n = \sqrt{2\mu \varepsilon_n / \hbar} \), \( \varepsilon_n \) is the neutron separation energy in \( 15C \) and \( \mu \) is the n + 14C reduced mass. The factor \( \sqrt{15} \) accounts for antisymmetrization. The \((n, \gamma)\) cross sections are therefore determined by the ANC squared \( C_n^2 \) and all theoretical models using the same \( C_n^2 \) should provide approximately the same \( \sigma_{n,\gamma} \).

In this Letter, we determine \( C_n^2 \) using a recently established relation between the neutron ANC of a bound state and the proton width \( \Gamma_p \) of its mirror analog resonance [12], which follows from the charge symmetry of one-nucleon decay amplitudes. As shown in Ref. [12], the ratio

\[
R_\Gamma = \Gamma_p / C_n^2
\]

for narrow resonances can be approximated by a model-independent analytical expression that contains the neutron separation energy, the energy \( E_R \) of the proton resonance, charge of the core, and the range of the strong interaction between the last neutron (or proton) and the core. However, this expression may not be accurate for the broad s-wave resonance \( 15F(1+^1) \). To predict \( R_\Gamma \) more reliably in this case, more accurate model calculations should be performed. The only requirement for a model should be its ability to reproduce exactly the asymptotic behavior of the valence neutron in \( 15C \) given by Eq. (2) and its applicability to the elastic scattering calculations. The microscopic cluster model (MCM) of the type we used in [13] is well suited for such calculations. Previous study of some broad s-wave resonances within this model has shown that \( R_\Gamma \) is not very sensitive to model assumptions even if \( C_n^2 \) and \( \Gamma_p \) strongly depend on them [13]. The theoretical uncertainty of \( R_\Gamma \) is less than 10% [13]. A similar uncertainty in \( R_\Gamma \) for the \( 15C-15F \) mirror pair would be sufficient to determine \( C_n^2 \) and, therefore, to predict \( \sigma_{n,\gamma} \) accurately enough to reduce its uncertainty from the current factor of 5.

To calculate \( R_\Gamma \), we use the MCM from Ref. [14] where \( 15C(1^F) \) is represented by the \( 14C + n(14O + p) \) configuration. The internal structure of \( 14C(1^F) \) is described by the 0p translation-invariant oscillator shell model. We performed both single-channel and multichannel calculations. In the latter case, we have taken into account the \( 0^+, 1^+, \) and \( 2_{1/2}^+ \) core excitations. Each calculation has been performed with two values of the oscillator radius, 1.5 fm and 1.75 fm. We use effective nucleon-nucleon (NN) interactions well adapted for such calculations, the Volkov potential V2 [15] and the Minnesota (MN) potential [16]. The two-body spin-orbit force [17] with \( S_0 = 30 \text{ MeV fm}^3 \) and the Coulomb interaction are also included. Both V2 and MN have one adjustable parameter that gives the strength of the odd NN potentials \( V_{11} \) and \( V_{33} \). We fit this parameter in each case to reproduce the experimental values for \( e_n \) or \( E_R \). Slightly different adjustable parameters in \( 15C \) and \( 15F \) needed to reproduce \( e_n \) and \( E_R \), simulate charge symmetry breaking of the effective NN interactions.

First, we calculate \( R_\Gamma \) assuming for \( E_R \) the value of 1.47 MeV obtained in Ref. [14] using an R-matrix analysis of the \( 14O + p \) scattering measured in Ref. [18]. The resulting value of \( R_\Gamma \) changes from 0.280 to 0.313 MeV \cdot fm with different model assumptions and NN potentials (see Table I). We adopt its average value \( R_\Gamma = 0.297 \pm 0.017 \text{ MeV} \cdot \text{fm} \). Using the experimental value \( \Gamma_p = 0.56 \text{ MeV} \) from Ref. [14], we obtain from Eq. (3) for \( 15C \) the \( C_n^2 \) value equal to 1.89 ± 0.11 fm\(^{-1}\). Below, we refer to \( C_n^2 \) obtained using \( R_\Gamma \) from the MCM calculations as \( C_{n15}^2 \).

Often, a two-body potential model is used to predict the \( \langle 14C|15C \rangle \) overlap. For the magnitude of its tail to be determined by \( C_{n15} \), the single-particle wave function should be multiplied by a spectroscopic amplitude \( S_{15}^{1/2} = C_{n15}^2 / b_{sp} \), where \( b_{sp} \) is the single-particle ANC obtained in such a model. Table II shows \( S_{15} \) for a range of the Woods-Saxon potentials used in earlier work. \( S_{15} \) from the first four lines agrees with the spectroscopic factors either determined or used in these works, \( S_{exp} \) within the error bars. The corresponding ANCs squared \( C_{exp}^2 = S_{exp}^2 b_{sp}^2 \) also agree with \( C_{n15}^2 \) within the error bars. These \( C_{exp}^2 \) were used in the analysis of the \( 14C(d, p)15C \) reaction within the distorted wave Born approximation [19], direct \((n, \gamma)\) calculations [5], time-dependent [20], and distorted

<table>
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<th>Potential</th>
<th>single-channel MCM</th>
<th>multichannel MCM</th>
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<tbody>
<tr>
<td>V2</td>
<td>0.297</td>
<td>0.301</td>
</tr>
<tr>
<td>MN</td>
<td>0.309</td>
<td>0.313</td>
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</table>

![Figure 1](image-url)
TABLE II. The depth $V_0$ (in MeV), radius $r_0$ and diffuseness $a$ (in fm) of the Woods-Saxon potentials, the single-particle ANC $b_s$ (in fm$^{-1/2}$), the spectroscopic factor $S_{\text{sp}}$ for the works listed in the first column and the corresponding ANC squared $C_{\text{sp}}^2 = S_{\text{sp}} b_s^2$ (in fm$^{-1/2}$). Also shown are the spectroscopic factor $S_{\text{mir}} = (C_{\text{mir}}/b_s)^2$, corresponding to $C_{\text{mir}} = 1.89 \pm 0.11$ fm$^{-1}$, the coefficients $S(0)$ (in 10$^{20}$ fm$^3$ s$^{-1}$), $s_1$ (in MeV$^{-1}$) and $s_2$ (in MeV$^{-2}$) in the Taylor expansion of $\sigma_{n,\gamma}$ [Eq. (4)] and the $\sigma_{n,\gamma}$ value at 23.3 keV (in $\mu$b), calculated with the corresponding values of $V_0$, $r_0$, $a$, and $S_{\text{mir}}$.

<table>
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<tr>
<th>Ref.</th>
<th>$V_0$</th>
<th>$r_0$</th>
<th>$a$</th>
<th>$b_s$</th>
<th>$S_{\text{sp}}$</th>
<th>$C_{\text{sp}}^2$</th>
<th>$S_{\text{mir}}$</th>
<th>$S(0)$</th>
<th>$s_1$</th>
<th>$s_2$</th>
<th>$\sigma_{n,\gamma}(23.3\text{ keV})$</th>
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<tr>
<td>[18]</td>
<td>54.15</td>
<td>0.71</td>
<td>1.45</td>
<td></td>
<td>0.90 ± 0.05</td>
<td>11.4 ± 0.65</td>
<td>-0.843</td>
<td>0.540</td>
<td>3.53 ± 0.30</td>
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<td>[20]</td>
<td>52.79</td>
<td>1.228</td>
<td>0.6</td>
<td>1.38</td>
<td>1.0</td>
<td>1.91</td>
<td>0.99 ± 0.06</td>
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<td>-0.872</td>
<td>0.607</td>
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<td>[22]</td>
<td>55.36</td>
<td>1.225</td>
<td>0.5</td>
<td>1.30</td>
<td>0.90</td>
<td>1.53</td>
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<td>-0.894</td>
<td>0.652</td>
<td>2.58 ± 0.30</td>
</tr>
<tr>
<td>[19]</td>
<td>46.46</td>
<td>1.3</td>
<td>0.7</td>
<td>1.49</td>
<td>0.88</td>
<td>1.96</td>
<td>0.85 ± 0.05</td>
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In summary, the charge symmetry of the $^{15}\text{C} \rightarrow ^{14}\text{C} + n$ and $^{15}\text{F} \rightarrow ^{14}\text{O} + p$ decays offers a strong test for the direct $E1$ $^{14}\text{C}(n, \gamma)^{15}\text{C}$ cross sections. It significantly reduces the uncertainty in the current knowledge of the $^{14}\text{C}(n, \gamma)^{15}\text{C}$ cross sections and favors the earlier theoretical predictions for this reaction from Ref. [5]. It also shows that directly and some indirectly measured cross sections in [4,8,11] strongly contradict charge symmetry in the $^{15}\text{C}-^{15}\text{F}$ mirror pair. This contradiction deserves thorough attention because it brings into question the determination of the astrophysically important $(n, \gamma)$ cross sections for short-lived radioactive targets.

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