NUCLEAR ASTROPHYSICS WITH RADIOACTIVE BEAMS AT TAMU*

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A major contribution in nuclear astrophysics is expected now and in the near future from the use of radioactive beams. This paper presents an indirect method utilizing radioactive beams to determine the astrophysical S-factor at the very low energies relevant in stellar processes (tens and hundreds of keV) from measurements at energies more common to the nuclear physics laboratories (10 MeV/nucleon). The Asymptotic Normalization Coefficient (ANC) method consists of the determination from peripheral transfer reactions of the single particle wave function of the outermost charged particle (proton or alpha particle) around a core in its asymptotic region only, as this is the part contributing to nuclear reactions at very low energies.

It can be applied to the study of radiative proton or alpha capture reactions, a very important class of stellar reactions. The method is briefly presented along with our recent results in the determination of the astrophysical factor for the proton capture reactions $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ and $^{11}\mathrm{C}(p,\gamma)^{12}\mathrm{N}$. The first reaction is crucial for the understanding of the solar neutrino production, the second is a reaction that would bypass the mass $A=8$ gap in the hot pp chains. Our study was done at the K500 superconducting cyclotron of Texas A&M University (TAMU). Proton transfer reactions with radioactive beams ^{7}Be and ^{11}C produced with MARS were measured, as well as proton transfer reactions involving stable partners. We present the experiments, then discuss the results and the uncertainties arising from the use of calculated optical potentials between loosely bound radioactive nuclei.

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1. Introduction

While we have known for some time now that nuclei are the fuel of the stars, in many cases we do not have yet enough information, or enough precise, about the nuclear reactions taking place in stars to make reliable quantitative predictions about astrophysical processes. Good and notable examples are: the production rate of ^{8}B from proton capture on ^{7}Be in the Sun, a reaction responsible for most of the solar neutrinos, and the production rate of oxygen from alpha capture on carbon in the He burning cycle. And newer results in astrophysics only increase the list of unknown but needed reaction rates. These recent major efforts and breakthroughs in astrophysical observations are matched by an increased interest in nuclear astrophysics. In short, one can say that the goal of nuclear astrophysics is to provide the knowledge and data needed to understand how nuclear processes produce or influence astrophysical phenomena, past and present. The most important challenge in the determination of the nuclear reaction rates relevant for astrophysics comes from the energies involved. We need cross sections at very low energies, in the range of tens and hundreds of keV. One approach used is to determine the cross sections from direct measurements of the same reaction in the nuclear physics laboratory or at somewhat higher energies and then extrapolate down. These cross sections, especially when charged particles are involved, are usually very low due to a very small penetration through the Coulomb barrier. They are therefore very difficult to measure directly. To overcome the limitations of the direct approach, a range of indirect methods is currently employed. What they all have in common is to measure some nuclear quantities that are then used in the calculation of the cross section at low energies. The measurements have not only to be as accurate as possible, but also the quantities measured have to be relevant and determinant for the rate at lower energies. The list of indirect methods is rather short though: the use of inverse reactions (like for example measuring the photodissociation instead of radiative capture), the determination of the resonance parameters from other reactions when resonances have a major or sizable contribution at astrophysically relevant energies [1], the Coulomb dissociation [2], the Trojan horse method [3], and more recently, the use of peripheral transfer reactions to determine the asymptotic normalization coefficients [4]. The use of radioactive beams will open enormous new possibilities for all of these indirect methods. This paper, will refer to the last of these indirect methods, developed and used by our group at the Cyclotron Institute of the Texas A&M University. The method, which we call the Asymptotic Normalization Coefficient (ANC) method, relies on the fact that at low energies a charged particle radiative capture reaction to a loosely bound state is a purely surface process, due to the Coulomb repulsion in the entrance channel. Its cross section is entirely determined by the behaviour of the wave function at very large distances from the center, and this is what we need to determine accurately in order to calculate precisely the reaction cross section. More specifically, we need to determine the tail of the radial overlap integral between the bound state wave function of the final nucleus and those of the initial colliding nuclei. At large distances, the proton (or the charged cluster) feels only the long range Coulomb interaction of the core nucleus and this overlap integral is asymptotically proportional to a well known Whittaker function. Therefore the knowledge of its asymptotic normalization alone determines the cross section. This asymptotic normalization, in turn, can be determined from the measurement of a transfer reaction involving the same vertex, provided that this transfer reaction is also peripheral. All the experiments were done at or around 10 MeV/nucleon, energies much easier to handle in the nuclear physics laboratories. In the next section we briefly describe the method used. We then present the results of some test cases using stable beams, and discuss the experiments involving radioactive beams. A discussion of the recipe we found to establish the optical model potentials needed for calculations of transfer reaction cross sections involving loosely bound stable or radioactive nuclei is included. Part of the results have been published before [5–10].

2. ANCs from peripheral proton transfer reactions

The relation of the ANCs to the direct capture rate at low energies is straightforward to obtain. The cross section for the direct capture reaction $A + p \to B + \gamma$ can be written as

$$\sigma = \lambda \left| \langle I^B_{Ap}(\boldsymbol{r}) \mid \hat{O}\,(\boldsymbol{r}) \mid \psi^{(+)}_i(\boldsymbol{r}) \rangle \right|^2 , \tag{2.1}$$

where λ contains kinematical factors, I^B_{Ap} is the overlap function for $B \to A + p$, $\hat{O}$ is the electromagnetic transition operator, and $\psi^{(+)}_i$ is the scattering wave in the incident channel. If the dominant contribution to the matrix element comes from outside the nuclear radius, the overlap function may be replaced by

$$I^B_{Ap}(r) \approx C^B_{Aplj} \frac{W_{-\eta,\, l+1/2}\,(2\kappa r)}{r} , \tag{2.2}$$

where C^B_{Aplj} is the ANC, W is the Whittaker function, η is the Coulomb parameter for the bound state $B = A + p$, and κ is the bound state wave number. Thus, the direct capture cross sections are directly proportional to the squares of these ANCs.

Traditionally, from proton transfer reactions spectroscopic factors have been obtained by comparing experimental cross sections to DWBA predictions. For peripheral transfer, we show below that the ANC is better determined and is the more natural quantity to extract. Consider the proton transfer reaction $a + A \to c + B$, where $a = c + p$, $B = A + p$. As was previously shown [4,5] we can write the transfer cross section in the form

$$\frac{d\sigma}{d\Omega} = \sum_{j_B j_a} \frac{(C^B_{Apl_Bj_B})^2}{b^2_{Apl_Bj_B}} \frac{(C^a_{cpl_aj_a})^2}{b^2_{cpl_aj_a}} \sigma^{DW}_{l_Bj_Bl_aj_a}\,, \tag{2.3}$$

where $\sigma^{DW}_{l_Bj_Bl_aj_a}$ is the calculated DWBA cross section and j_i, l_i are the total and orbital angular momenta of the transferred proton in nucleus i. The factors $b_{cpl_aj_a}$ and $b_{Apl_Bj_B}$ are the ANCs of the bound state proton wave functions in nuclei a and B which are related to the corresponding ANC of the overlap function by

$$(C^a_{cpl_aj_a})^2 = S^a_{cpl_aj_a} b^2_{cpl_aj_a}, \tag{2.4}$$

where $S^a_{cpl_aj_a}$ is the spectroscopic factor. We have used this formulation to extract ANCs from three peripheral proton transfer reactions involving stable beam and target nuclei, ^{9}Be(^{10}B,^{9}Be)^{10}B (Ref. [5]), ^{13}C(^{14}N,^{13}C)^{14}N (Ref. [6]) and ^{16}O(^{3}He, d)^{17}F (Ref. [7]). For surface reactions the cross section is best parametrized in terms of the product of the square of the ANCs

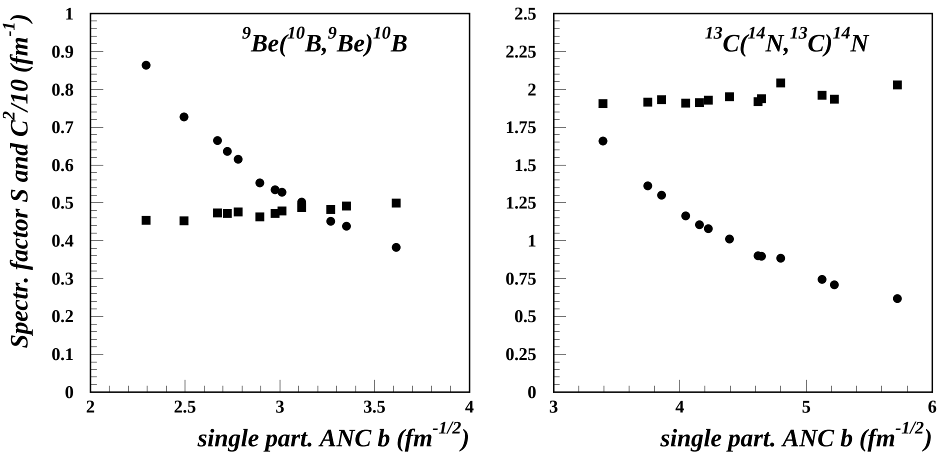

Fig. 1. Comparison between the spectroscopic factor S (dots) and the ANC C^2 (squares) extracted from the proton exchange reactions marked on each frame for ^{10}B (left) and ^{14}N (right), as a function of the single-particle ANC b calculated with the range of proton-core potentials described in the text.

of the initial and final nuclei $(C^B)^2(C^a)^2$ rather than spectroscopic factors, because of the strong dependence of the latter on the parameters of the core-proton potential used in the calculations. This is shown in Fig. 1 where the extracted spectroscopic factors vary with up to a factor two, whereas the corresponding C^2 are very stable (2%) against the reduced radius and diffuseness (r_0, a) of the potential used, when values r_0=1.0 to 1.3 fm and a=0.5 to 0.7 fm were used.

2.1. Using ANCs to predict astrophysical S-factors: test cases

The ANCs found from the proton transfer reactions can be used to determine direct capture rates at astrophysical energies using the procedure outlined above. Astrophysical S-factors have been determined for $^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}$ as a test of the technique. For $^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}$, the required C's are just the ANCs found from the transfer reaction $^{16}\mathrm{O}(^{3}\mathrm{He,d})^{17}\mathrm{F}$. Using the procedure outlined above, the S-factors describing the capture to both the ground and first excited states for $^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}$ were calculated, with no additional normalization constants, with the standard definition of the astrophysical S-factor [11]. The results obtained compare very well [7] to the two previous measurements of $^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}$. Similarly, using the ANC determined from the proton exchange reaction $^{9}\mathrm{Be}(^{10}\mathrm{B},^{9}\mathrm{Be})^{10}\mathrm{B}$ at 10 MeV/nucleon for the system $^{9}\mathrm{Be}+p \rightarrow ^{10}\mathrm{B}$ [5] we found the direct component of the astrophysical S-factor at low energies for the $^{9}\mathrm{Be}(p,\gamma)^{10}\mathrm{B}$ reaction [12] and could accurately describe the data of the direct measurement.

3. Optical model potentials for loosely bound *p*-shell nuclei

One major source of uncertainty in calculations can be the optical model potentials used in the DWBA calculations of the cross section σ^{DW} in Eq. (2.3). As we all know, we do not have at this time any reliable procedure to predict the detailed behaviour of the nucleus–nucleus potential for any mass–mass combination and for large ranges of energy. Therefore, we had to try to find a "local solution" for our problem. Parameters for Woods–Saxon type potentials were obtained from the fit of the elastic scattering angular distributions measured in 7 projectile-target combinations measured at TAMU. It did not appear that we could extract precise rules for the prediction of phenomenological potentials for other pairs of partners involved. Therefore microscopic nucleus–nucleus potentials were calculated by a double folding procedure. The nuclear densities calculated for each partner in the Hartree–Fock approximation were folded with six different nucleon–nucleon interactions. The resulting nucleus–nucleus potentials were later renormalized [13] to obtain a fit of the elastic scattering data. For each effective interaction used the normalization constants have similar values in all systems, which makes it appear likely that the procedure can be extended to the calculation of optical potentials for other similar nucleus–nucleus systems. The procedure and renormalization coefficients needed for the analysis of elastic data with these double folding potentials are extracted and discussed in [10]. We found that the factors of utmost importance in a good prediction of the potentials using a double folding procedure were:

(a) To get a good description of the mass distributions of the two partners, especially in the surface region. For this we used a Hartree–Fock procedure in which the parameters were slightly adjusted to reproduce both the experimentally determined mass or charge radii, and the binding energy. This tends to be particularly important for loosely bound nuclei.

(b) The real and imaginary parts of the potentials have different geometries. Therefore the usual procedure in which a real folded potential is normalized with a real and an imaginary renormalization coefficient is not appropriate. From all effective interactions used, we conclude that the interaction of Jeukenne *et al.* [14] gives the best results. It provides us with an imaginary part that has a geometry which is independent from that of the real part of the potential. In addition, this interaction was smeared with two gaussians of different ranges for the real and imaginary part.

(c) Use, check and extract an appropriate density dependence of the effective interaction.

We found that while the depth of the real potential needs a substantial renormalization ($\langle N_V \rangle = 0.366 \pm 0.014$), the imaginary part does not ($\langle N_W \rangle = 1.000 \pm 0.087$). This suggests that the imaginary part of the effective interaction is well accounted for. The renormalized double folded potentials obtained were also used in the DWBA analysis of the proton transfer reactions with stable nuclei, and the results were found to be in excellent agreement with those given by the phenomenological Woods–Saxon potentials.

The procedure found was successfully applied to extract the optical model potentials for the ^{7}Be, ^{8}B, ^{11}C and ^{12}N radioactive projectiles needed in the description of the ^{7}Be+^{10}B, ^{7}Be+^{14}N and ^{11}C+^{14}N experiments, described below.

4. Transfer reactions with radioactive beams

We have measured the (^{7}Be,^{8}B) reaction on a 1.7 mg/cm^2 ^{10}B target [8] and a 1.5 mg/cm^2 Melamine target [9] in order to extract the ANC for $^8\text{B} \to {}^7\text{Be} + p$. The radioactive ^{7}Be beam was produced at 12 MeV/nucleon by filtering reaction products from the ^{1}H(^{7}Li,^{7}Be)n reaction in the recoil spectrometer MARS, starting with a primary ^{7}Li beam at 18.6 MeV/nucleon from the TAMU K500 cyclotron. The beam was incident on an H_2 cryogenic gas target, cooled by LN_2, which was kept at 1 atmosphere (absolute) pressure. Reaction products were measured by 5 cm×5 cm Si detector telescopes consisting of a 100 μm ΔE strip detector, with 16 position sensitive strips, followed by a 1000 μm E counter.

A single 1000 μm Si strip detector was used for initial beam tuning. This detector, which was inserted at the target location, allowed us to optimize the beam shape and to normalize the ^{7}Be flux relative to a Faraday cup that measured the intensity of the primary ^{7}Li beam. Following optimization, the approximate ^{7}Be beam size was 6 mm×3 mm (FWHM), the energy spread was ≈ 1.5 MeV, the full angular spread was $\Delta\theta \approx 28$ mrad and $\Delta\phi \approx 62$ mrad, and the purity was $\geq 99.5\%$ ^{7}Be for the experiment with the ^{10}B target. The beam size and angular spread were improved for the experiment with the ^{14}N target to 4 mm×3 mm (FWHM), $\Delta\theta \approx 28$ mrad and $\Delta\phi \approx 49$ mrad. The typical rate for ^{7}Be was ≈ 1.5 kHz/pnA of primary beam on the production target. Primary beam intensities of up to 80 pnA were obtained on the gas cell target during the experiments.

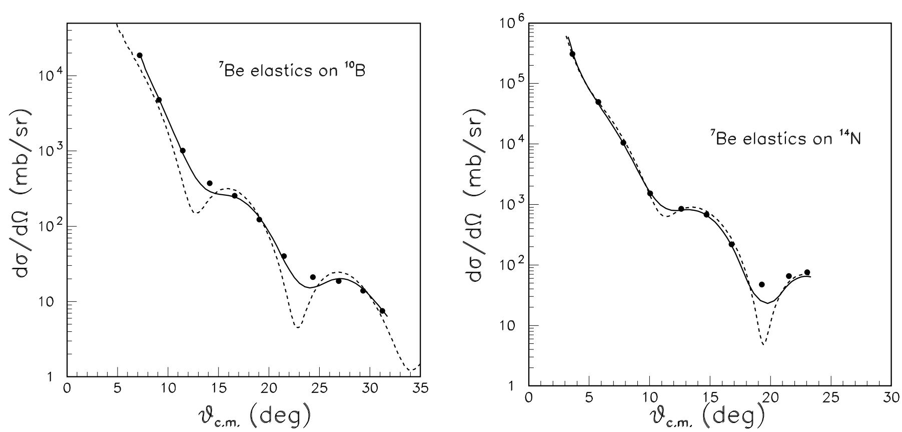

Fig. 2. Angular distributions for elastic scattering from the ^{10}B and ^{14}N targets. The dashed curves are coherent sums of optical model calculations for the target's components and the solid curves are smoothed with the experimental resolution.

Results for the elastic scattering angular distributions from the two targets are shown in Fig. 2. A Monte Carlo simulation was used to generate the solid angle factor for each angular bin and the smoothing needed for the calculation to account for the finite angular resolution of the beam. The absolute cross section is then fixed by the target thickness, number of incident ^{7}Be, the yield in each bin, and the solid angle. In both cases, the optical model calculations are compared to the data without additional normalization coefficients. Overall, the agreement between the measured absolute cross sections and the optical model predictions is excellent thus providing confidence that our normalization procedure is correct.

The ANC for $^8\mathrm{B} \to {}^7\mathrm{Be} + p$ was extracted based on the fit to the present data and the known ANCs [5,6] for the other vertices $^{10}\mathrm{B} \to {}^9\mathrm{Be} + p$ and $^{14}\mathrm{N} \to {}^{13}\mathrm{C} + p$, following the procedure outlined above in our test case. Two ^{8}B orbitals, $1p_{1/2}$ and $1p_{3/2}$, contribute to the transfer reaction but the $1p_{3/2}$ dominates in both cases. Angular distributions for the (^{7}Be,^{8}B) reactions populating the ground states of ^{9}Be and ^{13}C are compared to DWBA calculations in Fig. 3.

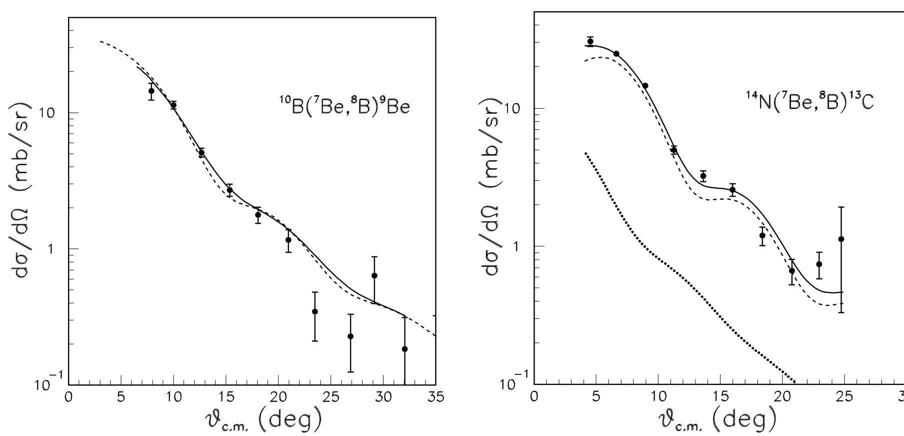

Fig. 3. Angular distributions for ^{8}B populating the ground state of ^{9}Be from the ^{10}B target (left) and ^{13}C from the Melamine target (right). In both cases, the solid curve is smoothed over the angular acceptance of each bin.

The astrophysical S-factor for $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ has been determined from the ANC which includes a 8% uncertainty for optical model parameters, a 11% uncertainty for experimental fits and normalization of the absolute cross section and the uncertainty in the ANC's for $^{10}\mathrm{B} \to {}^9\mathrm{Be} + p$ and $^{14}\mathrm{N} \to {}^{13}\mathrm{C} + p$. The relative contribution of the two angular momentum couplings to the S-factor is straightforward to calculate and introduces a negligible additional uncertainty in our result [4]. The values that we find are $S_{17}(0) = 18.4 \pm 2.5$ eV b for the ^{10}B target, and 16.6 ± 1.9 eV b for the ^{14}N target. Both are consistent with each other and in good agreement with the recommended value [15] of 19^{+4}_{-2} eV b.

We also concluded a successful run for a similar measurement with radioactive ^{11}C on a melamine target. Radioactive ^{11}C was obtained with a primary ^{11}B beam on the same hydrogen cryotarget and was separated with MARS as above. Elastic scattering of ^{11}C on the melamine target and the proton transfer reaction ^{14}N(^{11}C,^{12}N)^{13}C were measured with good resolution and statistics using a beam of about 0.4×10^6 particle/sec ^{11}C at 110 MeV. We obtained data for the evaluation of the contribution of the direct capture in the reaction ^{11}C$(p,\gamma)^{12}$N of importance in the hot *pp* cycles. The optical model potential predicted according to the recipe outlined above gave a very good description of our elastic scattering data of ^{11}C on the melamine target (that is on a mixture of ^{12}C and ^{14}N nuclei) without need for any major change in our parameters. This is another confirmation of its correctness, as it was the good prediction of the elastic scattering of ^{7}Be on the two targets above. DWBA calculations for the transfer reaction cross section predict very well the shape of the observed angular distribution and are stable to within 5% when the optical potentials used are varied within their uncertainties. Preliminary results are shown in Fig. 4, where

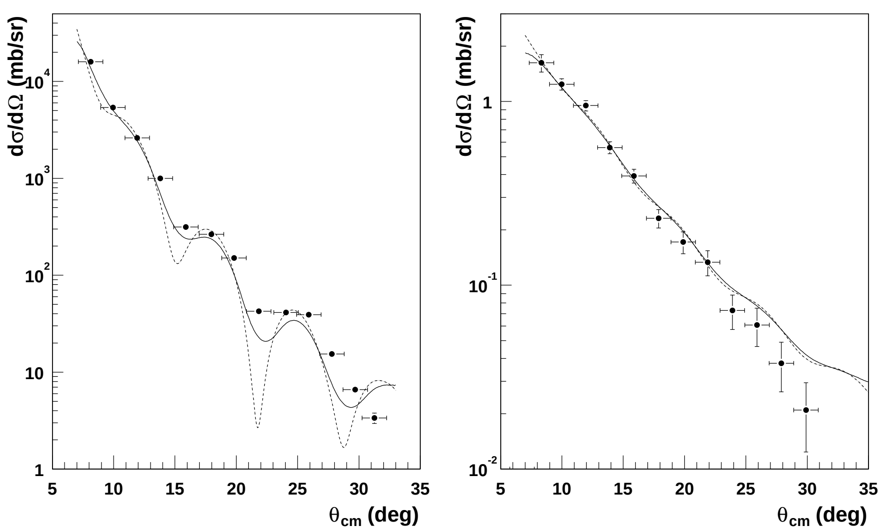

Fig. 4. Preliminary angular distributions for elastic scattering (left) of ^{11}C on the melamine target and for the proton transfer reaction ^{14}N(^{11}C,^{12}N)^{13}C. The dashed curves are initial optical model calculations of the target components (left) or DWBA calculations (right) which are then smeared with the experimental resolution using a Monte Carlo simulation (solid curves).

elastic (left) and proton transfer (right) angular distributions are presented. The ANC measured allows us to determine the direct (non-resonant) component of the astrophysical S-factor for $^{12}\mathrm{N}\to^{11}\mathrm{C}+p$ with improved accuracy. A full account of this experiment will be published [16].

5. Summary

In conclusion, in a series of experiments we show that transfer reactions induced by radioactive beams can be successfully used to obtain accurate data for nuclear astrophysics. We start with proving that peripheral proton transfer reactions can be used to extract asymptotic normalization coefficients and show them to be a more precise and relevant quantity than the usual spectroscopic factors extracted in such cases. We describe a test case where, based on an ANC extracted from the transfer reaction $^{16}\mathrm{O}(^{3}\mathrm{He}, d)^{17}\mathrm{F}$, we calculate S-factors for the radiative capture $^{16}\mathrm{O}(p, \gamma)^{17}\mathrm{F}$ that compare very well with those measured directly. Finally we discuss the radioactive beam transfer reactions $^{10}\mathrm{B}(^{7}\mathrm{Be},^{8}\mathrm{B})^{9}\mathrm{Be}$ and $^{14}\mathrm{N}(^{7}\mathrm{Be},^{8}\mathrm{B})^{13}\mathrm{C}$ and the astrophysical factor S_{17} extracted with the method above, including sources for uncertainties. The data analysis of a similar experiment with $^{11}\mathrm{C}$ is in the concluding phase. From it the direct (non-resonant) part of the astrophysical S-factor for $^{11}\mathrm{C}(p, \gamma)^{12}\mathrm{N}$ is determined.

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