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Global R-matrix analysis of the ^{11}B$(\alpha, n)^{14}$N reaction

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Abstract. Reactions that populate the ^{15}N system have implications for nucleosynthesis through the ^{11}B$(\alpha, n)^{14}$N and ^{14}N$(n, p)^{14}$C reactions and the ^{14}N$(n, p)^{14}$C reaction is also a key component in modeling atmospheric ^{14}C production. A convenient characteristic of this system is that the α-particle, proton, and neutron separation energies are all within ≈1 MeV of one another. Further, it has been observed that ^{11}B+α, ^{14}N+n and ^{14}C+p induced reactions all populate many of the same resonances near their reaction thresholds. This strongly facilitates the simultaneous analysis of data for all three of these entrance partitions using a global R-matrix analysis, which in turn provides a method of comparing the consistency among the different experimental measurements. In this work, a new measurement has been performed for the ^{11}B$(\alpha, n)^{14}$N reaction, which gives a more accurate description of the cross section, in particular over an important interference region. This new data is combined with results from previous measurements, which populate a similar excitation energy range in the ^{15}N system, to produce a global fit that includes ^{11}B$(\alpha, n)^{14}$N reaction data for the first time.

Keywords: R-matrix, nuclear astrophysics, neutron transport

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1. Introduction: file preparation and submission

Reactions that populate the ^{15}N system impact a variety of applications. This work presents new measurements of the ^{11}B$(\alpha,n)^{14}$N reaction at low energy. Yet the scarcity of data for this reaction and the additional possibility of decay through proton emission, naturally leads to an extension of the analysis to other reactions that populate this system. In particular, ^{14}N+n data has proved to be extremely useful in the interpretation of the data.

For nucleosynthesis of light elements, the ^{11}B$(\alpha,n)^{14}$N reaction may play a role in the synthesis of the first massive stars. In this unique stellar environment, only the light elements from the Big Bang are present, hence there is no carbon, nitrogen or oxygen to more efficiently burn hydrogen. Therefore, other reactions on light nuclei, that normally are less efficient than the CNO reactions, may rise to more dominant role in the burning cycles [1].

The ^{14}N$(n,p)^{14}$C reaction is a key nuclear physics ingredient in understanding neutron production for the main s-process (see e.g., Ref. [2]). The high cross section of the ^{14}N$(n,p)^{14}$C reaction combined with the large amount of ^{14}N present in the main s-process environment, means that it can act as an efficient neutron poison. The lowest energy resonance in the ^{14}N$(n,p)^{14}$C reaction is at $E_{c.m.}$ = 458 keV ($J^\pi = 1/2^-$, $\Gamma \approx 8$ keV). For this reason, the cross section over the low energy region is made up of contributions from the high energy tails of subthreshold states and the low energy tails of broad higher energy resonances. At low energies (61 meV $< E_n <$ 34.6 keV), the cross section has been carefully mapped by Ref. [3] who found that it was dominated by the tail contributions of subthreshold states that produce a low energy cross section that rapidly increases towards lower energy. At the higher energy end of the data of Ref. [3], several additional measurements have been made [2, 4, 5, 6] that sample only a few energies but cover an energy range from $\approx$20 $< E_n <$ $\approx$178 keV. The measurements over this range are in reasonably good agreement, except for those of Ref. [4], which are about a factor of two lower in cross section. There is then a gap in the experimental data between the measurements of Ref. [2] and Ref. [7] (178 keV $< E_n <$ 464 keV). Ref. [8] reportedly made measurements over this region, but the data are not available in tabulated form and can not be digitized from the figures reliably. As there are many broad resonances at higher energies that can contribute significantly over this region, it makes the cross section especially difficult to determine. This was recently demonstrated by Ref. [2] in their comparison between their data and the JEFF-3.2 evaluation. It should be noted that the JEFF-3.2 evaluation of ^{14}N+n [9] is the same as that of ENDF/B-VI.3 [10] and that the evaluation at low energy is based on the R-matrix analysis of Ref. [11] that has not been re-evaluated as of ENDF/B-VIII.0 [12].

As indicated above by its presence in the various data evaluations, the ^{14}N+n reactions are of interest for simulating neutron transport through a variety of materials. For example, the ^{14}N$(n,p)^{14}$C reaction is the main source of ^{14}C in the earth's atmosphere. Neutrons for the reaction are either naturally produced from cosmic rays interacting with the atmosphere or were produced through above-ground nuclear weapons testing that took place between 1945 to 1963. Using the ^{14}N$(n,p)^{14}$C cross section and sampling of the increased levels of ^{14}C in the atmosphere, information about a nuclear explosion can be inferred (see, e.g., Ref. [13]).

There have been several studies of reactions that populate the ^{15}N system over the excitation energy range that corresponds to the present ^{11}B(α,n)^{14}N cross section measurements (10.7 MeV $< E_x <$ 12.9 MeV). This energy range has been of interest for study because of the similar proton (S_p = 10.207 MeV), neutron (S_n = 10.833 MeV), and α-particle (S_α = 10.991 MeV) separation energies in ^{15}N [14] (see Fig. 1). For the ^{11}B$(\alpha,n)^{14}$N reaction, there have been only a few studies [15, 16, 17], where that of Ref. [17] was the most comprehensive. Studies of the ^{11}B$(\alpha,p)^{14}$C reaction have been made by Refs. [17, 18, 19] and the ^{11}B$(\alpha,\alpha)^{11}$B reaction by Refs. [20, 21]. Studies of ^{14}C+p reactions include measurements of ^{14}C$(p,p)^{14}$C [22, 23], ^{14}C$(p,n)^{14}$N [15, 17, 24, 25, 26, 27], and ^{14}C$(p,\gamma)^{15}$N [23, 24, 28, 29]. Finally, studies of neutron induced reactions on ^{14}N include ^{14}N$(n,n)^{14}$N [30], ^{14}N$(n,p)^{14}$C [7, 8, 27, 31] (fast neutrons), ^{14}N$(n,\alpha)^{11}$B [7, 8, 31], and ^{14}N$(n,total)$ [32, 33, 34]. There have also been several studies of the thermal ^{14}N$(n,p)^{14}$C cross section [2, 3, 4, 5, 6]. In addition, a highly accurate and comprehensive measurement of the ^{14}N$(n,total)$ reaction has also been made at Oak Ridge National Laboratory, but remains unpublished. Some of the data from this measurement are considered in the analyses of Ref. [34] and Ref. [11].

We have performed new measurements of the ^{11}B$(\alpha,n)^{14}$N reaction at low energies at the Nuclear Science Laboratory (NSL) of the University of Notre Dame. In Sec. 2, the setup and measurement are described. The calculation of the cross sections from the observed yields is described in Sec. 3. A global R-matrix analysis that includes the new data combined with complementary data from other reaction partitions is discussed in Sec. 4. Closing remarks are given in Sec. 6.

2. Experimental methods

Measurements were made of the ^{11}B$(\alpha,n)^{14}$N (Q = 0.15789(1) MeV) reaction at the University of Notre Dame's Nuclear Science Laboratory using the Sta. ANA 5-MV accelerator. The reaction was studied at α-particle beam energies E_α ranging from 520 to 2000 keV with beam intensities on target between 0.03-μA and 18-μA. A ^{11}B enriched (99.9%) target with a thickness of 8.4(4) μg/cm^2 was produced by electron sputtering enriched ^{11}B powder onto a clean tantalum backing 0.5 mm in thickness. The detection system consisted of a ^{3}He proportional counter, which contained twenty ^{3}He tubes encased in a polyethylene moderator. The detector has been described previously in Refs. [35, 36].

The energy dependence of the efficiency was modeled using `MCNP` and the absolute efficiency was obtained using the activation method and the ^{51}V$(p,n)^{51}$Cr reaction at 0.7 MeV [37, 38]. The resulting efficiency was found to be consistent with that found by Ref. [35] to within 1% using a nearly identical setup. The small Q-value of the

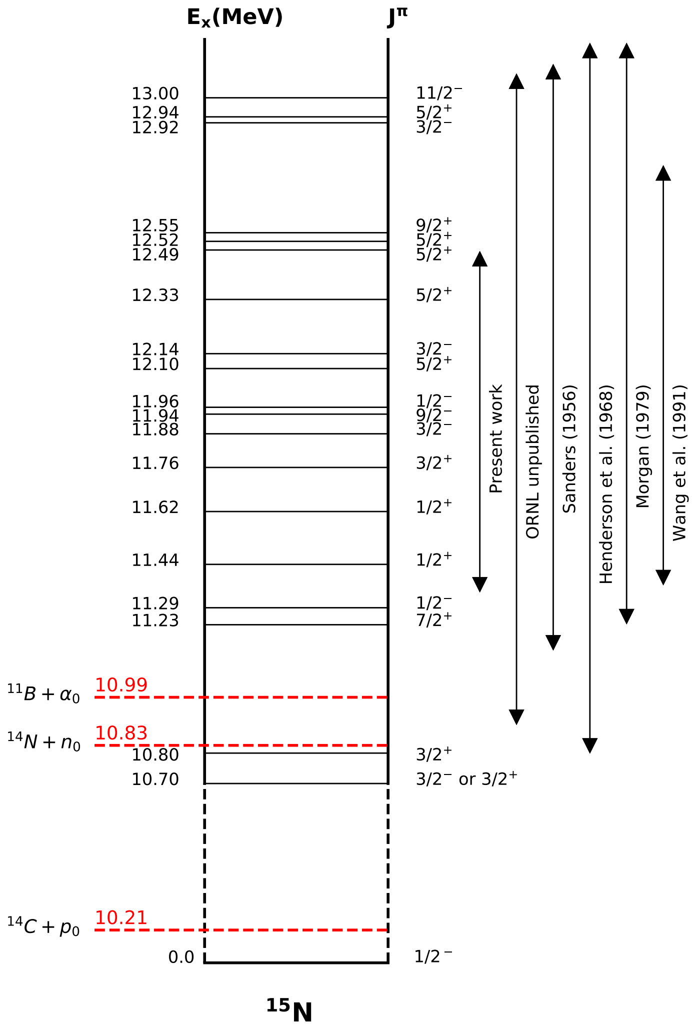

Figure 1. (Color Online) Level diagram of the ^{15}N compound system.

^{11}B$(\alpha,n)^{14}$N reaction and the range of α-beam energies that were investigated results in neutrons that cover the range from $0.36 < E_n < 2.0$ MeV, taking into account the angular kinematic spread as well. The neutron detection efficiency of the ^{3}He counter varies from about 30% to 45% over this neutron energy range. The overall uncertainty in the neutron efficiency is estimated to be ≈5%. In addition, only the ground state in the ^{14}N final nucleus is energetically accessible.

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3. Analysis

The sum of all events from the twenty ^{3}He tubes were normalized by the beam charge integration and efficiency Y assuming an infinitely thin target approximation

$$\sigma \approx \frac{Y}{N_p N_t \epsilon} \tag{1}$$

where N_p are the number of beam particles made incident on target (found to be reproducible to 2%), N_t are the number of target atoms obtained by the target thicknesses and ϵ is the ^{3}He counter efficiency. In the present experiment the range of neutron energies covered $E_n = 0.36$ MeV to 2.0 MeV. This is a function of both the incident α-particle energy as well as the kinematic spread from the nearly 4π solid angle subtended by the ^{3}He counter. In this energy region, the efficiency dependency on neutron energy for the ^{3}He counter can be considered linear. Since the detection efficiency decreases as a function of neutron energy, the neutrons emitted at 0° have a smaller efficiency than those at 180°. The central value of the cross section was calculated using the average efficiency. This inherent uncertainty in the neutron energy and thus detection efficiency is reflected in the uncertainties of the data.

The experimental data are shown in Fig. 2 compared to previous measurements by Ref. [17]. Over most of the energy range, the present measurements and those of Ref. [17] are in good agreement. However, there is an off-resonance region near $E_{c.m.} \approx 0.5$ MeV where the present data are significantly smaller than those of Ref. [17]. This region is also just below the very strong narrow $7/2^-$ state at $E_{c.m.} = 444.4(4)$ keV (not shown in the plot). This discrepancy could be the result of diffusion of some of the target material into the backing used by Ref. [17]. This type of over estimation of cross sections just above strong narrow resonances is a common issue (see, for example, Ref. [39]).

4. *R*-matrix analysis

The low energy cross section of the ^{11}B$(\alpha,n)^{14}$N reaction has been analyzed using the phenomenological R-matrix approach [40, 41] using the code `AZURE2` [42, 43]. The alternate parameterization of Ref. [44] has been used in order to work directly with physical parameters and to eliminate the need for boundary conditions.

At the energies under consideration, both reactions have other open decay modes in addition to α-particle and neutron emission. As such, to achieve a physical solution using the phenomenological model, it is advantageous (if not necessary) to include other reaction data that can constrain the decay branchings. For the ^{11}B$(\alpha,n)^{14}$N reaction, and other reactions that populate the ^{15}N system, a multi-channel fit has been achieved.

The ^{11}B(α,n)^{14}N reaction populates states in the ^{15}N system at an excitation energy range (11.2 MeV $< E_x <$ 12.6 MeV) that is also above the proton separation energy ($S_p = 10.20742(1)$ MeV). Therefore, there are three allowed particle decay modes: α-particle ($S_\alpha = 10.99118(1)$ MeV), neutron ($S_n = 10.833.30(1)$ MeV), and proton [14, 45]. At these energies, only decays to the ground states in the final nuclei are possible.

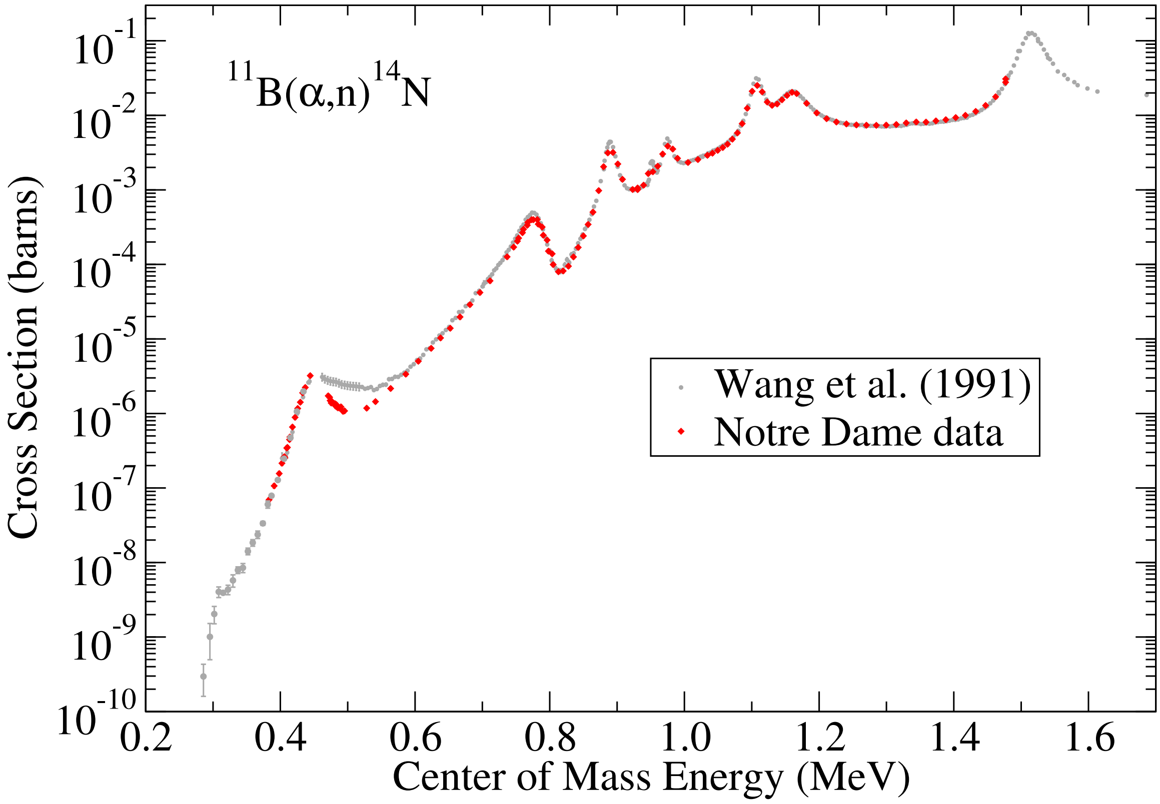

Figure 2. (Color Online) Comparison of the ^{11}B$(\alpha,n)^{14}$N data measured in the present work to that of Ref. [17]. The measurements are in good agreement with the exception of the region just above the lowest energy resonance near $E_{c.m.} = 0.5$ MeV.

The ^{15}N system has been subjected to R-matrix analyses previously [11, 15, 34, 46]. However, the present analysis is the first to include low energy ^{11}B$(\alpha,n)^{14}$N data. The present analysis is also part of an ongoing effort to re-evaluate the ^{14}N + n reactions [47]. For this analysis, data from the reactions ^{14}C$(p,p)^{14}$C [22, 23], ^{14}C$(p,n)^{14}$N [26], ^{14}C$(p,\gamma)^{15}$N [28], ^{14}N$(n,total)$ [32, 33], ^{14}N$(n,p)^{14}$C [2, 3, 4, 5, 6, 7, 8, 31], and ^{14}N$(n,\alpha)^{10}$B [7, 8, 31, 48] are included. Fig. 3 shows a sampling of the data that has been fit.

While some tension does exist between the different data sets, a fit was obtained that indicates general consistency. Most of the tension arises due to off-sets in the energy scaling of the data sets. These off-sets were generally obvious since the measurements are made with relatively good energy resolution and the energy shifts were significant compared with the widths of many of the resonances.

At low energies a good fit was obtained to data from the ^{14}N$(n,p)^{14}$C reaction. There is a fairly large gap in the data (178 keV $< E_n <$ 464 keV) as shown in Fig. 4. New measurements should be performed over this region in order to better constrain the R-matrix fit.

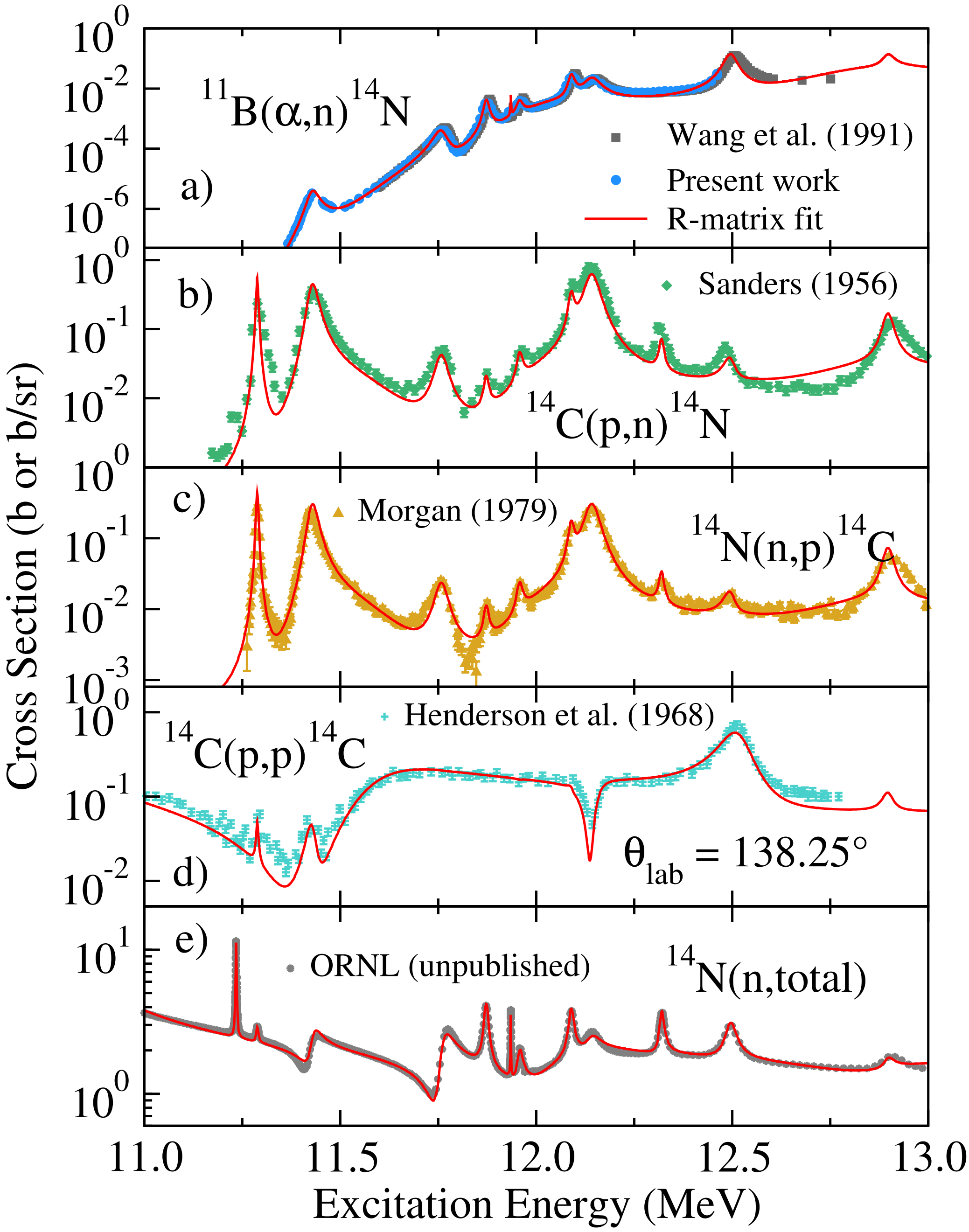

Figure 3. (Color Online) Example excitation functions from the global R-matrix fit of the ^{15}N system for the present ^{11}B$(\alpha,n)^{14}$N measurement (blue circles) and previous measurements of the ^{11}B$(\alpha,n)^{14}$N (Ref. [17], gray squares) ^{14}C$(p,n)^{14}$N (Ref. [26], green diamonds)), ^{14}N$(n,p)^{14}$C (Ref. [7], gold upward triangles), ^{14}C$(p,p)^{14}$C (Ref. [23], turquoise plus), and ^{14}N$(n,total)$ (ORNL (unpublished), gray circles) reactions.

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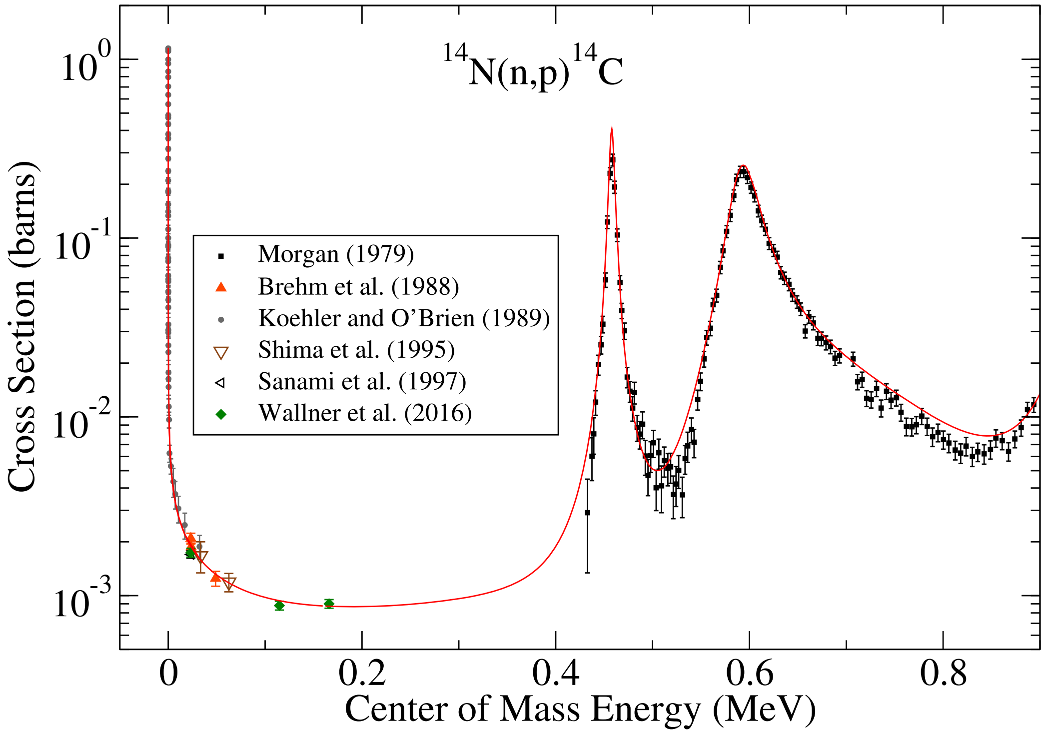

Figure 4. (Color Online) View of the low energy region of the ^{14}N$(n,p)^{14}$C cross section. The red solid line represents the R-matrix fit. The data of Ref. [2, 3, 4, 5, 6, 7] are shown for comparison.

5. Discussion

There have been at least three previous comprehensive R-matrix analyses [11, 15, 34] of the ^{15}N system over the same energy range as the present data. The earliest analysis by Ref. [15] focuses on polarization measurements of the ^{14}C$(p,n)^{14}$N and ^{11}B$(\alpha,n)^{14}$N reactions. Unfortunately the R-matrix code used in the present work is not capable of calculating polarization observables so this data could not be utilized. The works of Ref. [11] and Ref. [34] focus on the ^{14}N+n reaction. All of these analyses were made before the publication of Ref. [17] and so only include a limited amount of ^{11}B+α data.

As a general remark, it was found that it was possible to reproduce the cross section data for the ^{14}N$(n,p)^{14}$C and its inverse reaction with previously reported levels in ^{15}N with in the energy range of the data. A good fit to the low energy data was also achieved as shown in Fig. 4. On the other hand, it was impossible to reproduce the observed cross sections for the ^{11}B$(\alpha,n)^{14}$N and ^{14}N$(n,total)$ reactions without the presence of background states with large partial widths. For the ^{11}B$(\alpha,n)^{14}$N reaction, this seems physically reasonable since higher energy data, see for example Refs. [7, 16, 31], observe very strong broad resonances at energies just above the region of the present measurements. For the ^{14}N$(n,total)$ cross section, the saturation is less clear.

The ^{14}N$(n,total)$ cross section was found to be particularly difficult to reproduce with only the resonances observed in the data region. In particular, the low energy region where the cross section is dominated by neutron scattering. The difficulty seems to stem from the contribution of a strong subthreshold state(s) as discussed by Ref. [11]. As in that work, we do not obtain an "entirely satisfactory" reproduction of the low energy cross section. In addition, the fit to the ^{14}N$(n, total)$ data is extremely sensitive to the neutron channel radius and requires a value that is smaller than usual. Here a radius of 4 fm was used, the same as that used by Ref. [34], but larger than the value of 2.6 fm used by Ref. [11]. In principle, any value for the channel radius can be used with appropriately compensating background levels. Usually a value close to $a_{ch} \approx a_0(A_1^{1/3} + A_2^{1/3})$ works well (where a_{ch} is the channel radius, $a_0 \approx 1.4$ fm, and A_1 and A_2 are the unit masses of the particle partition), but in this case a smaller value is highly favored.

6. Summary

New measurements have been presented for low energy cross sections of the ^{11}B$(\alpha,n)^{14}$N reaction. The present measurements largely confirm the previous data of Ref. [17] but improve on measurements over a low cross section region. A comprehensive R-matrix analysis of the reaction data that populate the ^{15}N system over a similar excitation energy range as the present data has been performed. Work is in progress to expand the present analysis to include additional data sets, especially angular distribution and capture data. A study of the low energy cross section will continue at the new CASPAR underground facility [49].

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