# Experimental Cross Section Data Selection by a SAMMY Parameterization: $^{9}$Be($\alpha$, n) Cross Section Evaluation up to 4 MeV

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**Abstract.** This paper reports an evaluation work on the resolved resonance parameters of the $\alpha$ + $^{9}$Be reaction from 0 to 4 MeV performed with the SAMMY code. The use of the Reich-Moore approximation of the R matrix theory allows a definitive assessment of the magnitude of the ($\alpha$,n) excitation function at zero degree by selecting the best data sets among the experiments available for the $^{13}$C compound nucleus. The by-product of this work is the generation of a full set of point wise integrated and differential $^{9}$Be($\alpha$,n)$^{12}$C cross section data up to 4 MeV.

## INTRODUCTION

The $^{9}$Be($\alpha$,n) reaction has been of importance as a source of neutrons since two or three well separated, mono-energetic neutron groups can be obtained from incident $\alpha$ particles coming either from an accelerator or from radioactivity. Furthermore this reaction is still of importance for other applications like astrophysics (during a supernova explosion, the reaction chain $^{4}$He($\alpha$n,$\gamma$)$^{9}$Be($\alpha$,n)$^{12}$C dominates the creation of C, which leads to the creation of heavier elements produced by neutron capture in the succeeding *s*- and *r*- processes), reactor start-up (e.g.: Am-Be, Cm-Be radioactive sources), detector calibration purposes or even diagnostics.

Experimental campaigns have been performed periodically to measure cross sections for this reaction, essentially in the sixties, the seventies and more recently in the nineties. The corresponding database is one of the most exhaustive among the $(\alpha,n)$ reactions on light nuclei but contains conflicting data sets, sometimes by more than a factor of two.

In such a situation, a confident test to assess the magnitude of the absolute cross sections is to search for a fully consistent resonance parameter **(RP)** set which can be used to reproduce all types of measured cross sections. This objective was achieved by using the latest version[1] (M6) of the SAMMY code which now handles input-output charged-particles experimental data. SAMMY[2] adjusts prior RP in order to get a Bayes agreement between experimental and theoretical data within the experimental and prior parameters uncertainties. The cross sections are reconstructed using the Reich-Moore simplified form of the R-matrix theory[3]. The validity of the Reich-Moore approximation in light nuclei analyses has been already debated in a previous study[4] which served as a warm up for this task. The parameterization of light nuclei resonances remains scarse; the tabulation of pointwise cross sections being usually preferred because of the small resonances number and of the usual negligible Doppler and experimental energy resolution broadening width contributions.

In addition to newly fitted RP, this work leads to a re-evaluation of the integrated and angular $^{9}$Be($\alpha$,n$_0$)$^{12}$C and $^{9}$Be($\alpha$,n$_1$)$^{12}$C cross sections between 0 and 4 MeV (current upper limit).

## OPEN R-MATRIX REACTION CHANNELS AND MULTIPLICITIES

The $^{9}$Be($\alpha$,n)$^{12}$C differential data analysis, with an incident alpha energy range 0 to 4 MeV, involves three excited states of the target nuclide $^{9}$Be and also two of the residual nucleus $^{12}$C. The review of the number and the characteristics of all the open reaction channels was easily dealt with the improved version of the SAMQUA module[5, 6] of SAMMY. This module greatly simplifies the determination of the quantum numbers for the definition of the reaction channels. In addition to the $^{9}$Be($\alpha$,n$_0$)$^{12}$C and $^{9}$Be($\alpha$,n$_1$)$^{12}$C reactions which are always open, the $^{9}$Be($\alpha$,n$_2$)$^{12}$C channel opens at $E_\alpha =$ 1.965 MeV in the laboratory system. As incident energy increases, $(\alpha,\alpha_1)$, $(\alpha,\alpha_2)$ and $(\alpha,\alpha_3)$ inelastic scatter-

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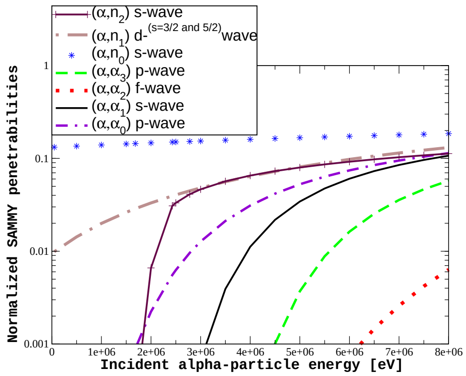


**FIGURE 1.** Normalized exit channels SAMMY penetrabilities vs. energy of an $\alpha$-particle interaction with a $^{9}Be$ target nucleus for the $J^{\pi} = 0.5^{+}$ compound nucleus resonance. Penetrabilities have been normalized by dividing them by the sum of all penetrabilities at the maximum energy of 8 MeV.

ing reactions also become possible. Hopefully on the basis of effective (due to the Coulomb barrier) rather than actual alpha thresholds, one can make the reasonable assumption that the contribution of the alpha inelastic scattering remains negligible for an incident alpha energy less than 4 MeV. This is well demonstrated on Figure 1 which gives an overview of the available channels for the $J^{\pi} = 0.5^{+}$ compound nucleus resonance. At first glance, seven reactions are possible $(\alpha,\mathrm{n}_{0,1,2})$ and $(\alpha,\alpha_{0,1,2,3})$; the $(\alpha,\mathrm{n}_1)$ can be reached with two different channel spin values ($\frac{3}{2}^{+}$ and $\frac{5}{2}^{+}$). Nevertheless the charged-particle penetrability becomes appreciable only when the incident alpha energy approaches the Coulomb barrier $B = Z_{\alpha} Z_{^9Be} e^2/a_{\alpha} \approx 2.8$ MeV with $a_{\alpha}$, the effective alpha channel radius, empirically calculated as $a_{\alpha}[fm] = (1.4 M_{^9Be}^{1/3} + 1.2) \approx 4.1$ fm. In this simple $J^{\pi} = \frac{1}{2}^{+}$ case, $(\alpha,\alpha_0)$ and $(\alpha,\alpha_1)$ penetrabilities remain smaller than 0.01 for energies lower 2.8 and 4 MeV, respectively. On Figure 1, the $(\alpha,\alpha_3)$ reaction appear to be more likely than the $(\alpha,\alpha_2)$ reaction (associated to p- and f- waves, respectively) because of the smaller centrifugal potential barrier value which is added to the Coulomb potential barrier term.

## PRIOR SET OF RESONANCE PARAMETERS

Having defined the quantum-number information for all channels for each compound nucleus state, the second step of the input data preparation for the SAMMY calculation is the collection of all the experimental information available on the $^{13}$C compound nucleus.

**TABLE 1.** List of the experimental data available within the [0.4-0.7] MeV range.

| Measurement type | Author | Year | Energies [keV] |
|---|---|---|---|
| $\sigma_{(\alpha,\mathrm{n_{tot}})}(E)$ | Ramström[8] | 1979 | 0-800 |
| | Wrean *et al*.[8] | 1993 | 0-2670 |
| $\sigma_{(\alpha,\mathrm{n}_0)}(E)$, $\sigma_{(\alpha,\mathrm{n}_1)}(E)$ | Kunz *et al*.[9] | 1996 | 0-3500 |
| $\sigma_{(\alpha,\mathrm{n}_0)}(E,0^{\circ})$, $\sigma_{(\alpha,\mathrm{n}_1)}(E,0^{\circ})$ | Davids[8] | 1968 | 0-700 |
| $\sigma_{(\alpha,\mathrm{n}_0)}(E,\theta)$, $\sigma_{(\alpha,\mathrm{n}_1)}(E,\theta)$ | Davids[8] | 1968 | 480, 520, 592, 608 |

Concerning $\alpha$-particles impinging on light target nuclei, the main source of information is the huge work of F. Ajzenberg-Selove which collects all measured, evaluated or calculated data leading to the same compound nucleus. In particular for the $^{13}$C compound nucleus[7], 15 energy levels are listed between 0 and 4 MeV of incident $\alpha$-particle energy. This collection contains mainly resonance energies and spins, total resonance widths (in center of mass), de-excitation modes and sometimes total partial neutron widths. No resonances belonging to a $J^{\pi}$ state larger than $\frac{9}{2}^{-}$ are listed in this energy range but we had to include 2 more resonance spin value descriptions ($\frac{9}{2}^{+}$, $\frac{11}{2}^{-}$) on the basis of the corresponding non-negligible hard-sphere potential elastic scattering terms (larger than $10^{-5}$ at 4 MeV) calculated by SAMQUA. Where information is missing on neutron partial width values, a prior estimation can be made (see ref.[4]) from two well-known average parameters which are usually tabulated in data compilations: the neutron strength function and the mean resonance spacing . The major difficulty of the adjustment on light nuclei RP is the numerous partial widths opened for each reaction for a compound nucleus state given. For instance the width of a $J^{\pi} = \frac{9}{2}^{-}$ resonance can result of the combination of two $\alpha$ elastic scattering channel widths (with $l$ equal to 4 and 6, respectively), one $(\alpha,\mathrm{n}_0)$ channel width (with $l$ equal to 5), five $(\alpha,\mathrm{n}_1)$ channel widths (with $l$ equal to 3 (from two different channel spin values), 5 (2 times as well) and 7, respectively) and, finally one $(\alpha,\mathrm{n}_2)$ channel width with $l$ equal to 5.

## EXPERIMENTAL DATA BASE

The experimental data selected for this work include essentially integrated and angular, total and partial $(\alpha,\mathrm{n})$ data. Angular integrated experimental data are much easier to reproduce than angular distributions because they

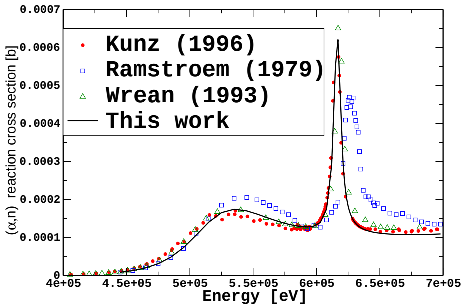


**FIGURE 2.** Angle integrated $^9$Be$(\alpha,\mathrm{n_{tot}})$ reaction cross section fitted by SAMMY (solid curve) compared to the experimental data of Kunz *et al*. (diamonds), Wrean *et al*. (triangles) and Ramström (squares) between 400 and 700 keV.

do not involve interferences between different relative orbital angular momentum values and, so, only the total partial neutron width values are important (i.e.; $\Gamma_{\mathrm{n}_0}$, $\Gamma_{\mathrm{n}_1}$, $\Gamma_{\mathrm{n}_2}$, etc.).

## Low Energy Range: 0.4$< E <$0.7 MeV

This energy range exhibits only two resonances of spins $\frac{1}{2}^+$ and $\frac{1}{2}^-$ at 520.3 keV and 616.5 keV, respectively. The experimental data collected in this energy range are listed in Table 1.

$(\alpha,\mathrm{n_{tot}})(E)$ cross section measurements of Kunz *et al*. and Wrean *et al*. are consistent whereas the Ramström data show a disagreement (see Figure 2) likely due to some experimental effects (energy calibration and resolution, background). Neutron widths values (reported on Table 2) have been obtained from a SAMMY sequential fit on the $\sigma_{(\alpha,\mathrm{n}_0)}(E)$ and $\sigma_{(\alpha,\mathrm{n}_1)}(E)$ measurements from Kunz *et al*.

The comparison of the differential cross sections reconstructed from these new RP with the zero degree measurements performed by Davids reveals a strong disagreement on $\sigma_{(\alpha,\mathrm{n}_0)}(E)$ in shape and normalization (factor 4) whereas his $\sigma_{(\alpha,\mathrm{n}_1)}(E)$ measurement seems to be more trustable. A further comparison with the $\sigma_{(\alpha,\mathrm{n}_0)}(E,\theta)$ angular data of Davids (tabulated in arbitrary units which imply no information on the normalization factor value) is satisfactory and then do not reveal any wrong spin assignment of these two resonances.

Finally, we can consider the new parameters of these two resonances as trustable because:

- these two resonances involve quite a few number of RP (one $\alpha$, one $\mathrm{n}_0$ and only two $\mathrm{n}_1$ channels widths; the capture width remains negligible (equal to 3 eV on average)),

**TABLE 2.** Posterior resonance energy, partial and total width values obtained from a SAMMY fit. The apparent negative sign of a partial width correspond to a negative value of the associated decay amplitude.

| Resonance Energy | | 520.3 keV | 616.5 keV |
|---|---|---|---|
| $\Gamma_{\alpha_0}^{l_1}$ $[keV]$ | | -0.0097 | -0.0031 |
| $\Gamma_{n_0}^{l'_1}$ $[keV]$ | | -59 | -5.1 |
| $\Gamma_{n_1}^{l''_1,s_1}$ $[keV]$ | | 10.3 | 1.1 |
| $\Gamma_{n_1}^{l''_2,s_2}$ $[keV]$ | | 13.1 | -0.4 |
| $\Gamma_{tot}[keV]$ | this work | 82. | 6.5 |
| | ref.[7] | 53.4 or 79.4 | <5.8 |

- Our sequential SAMMY fit of the most recent measurements (Kunz *et al*. and Wrean *et al*.) is consistent.

## Medium Energy Range: 700$< E <$4000 keV

The main experimental data sets available in this energy range are listed in Table 3.

In the beginning of the seventies, Obst *et al*. performed a set of measurements to find out the recurrent disagreement observed on the $(\alpha,\mathrm{n}_0)$ and $(\alpha,\mathrm{n}_1)$ excitation function values at zero degree (factor 2 in magnitude) between Van der Zwan and Geiger from one side and Risser *et al*. from the other side. This new set of measurements was definitively in favor of Van der Zwan and Geiger. The release of a new set of integrated measurements by Kunz in 1996, of especially good energy resolution, gives the opportunity, from a theoretical point of view, to invalid definitively the absolute magnitude of the cross sections given by Risser *et al*. Since the Reich-Moore approximation must reproduce quasi-exactly with the same set of RP all type of cross sections leading to a same compound nucleus, a first attempt of fine-tuning has been made during this work. The major difficulty of this SAMMY fit is the numerous RP belonging to each resonance of large, not definitively assigned, spin values (up to $\frac{9}{2}^-$).

A sequential SAMMY fit was performed on both the $(\alpha,\mathrm{n}_0)$ *and* $(\alpha,\mathrm{n}_1)$ cross section data of Kunz *et al*. and the $(\alpha,\mathrm{n_{tot}})$ cross section data of Gibbons and Macklin in the energy range (0-4)MeV. Since the recent $(\alpha,\mathrm{n_{tot}})$ cross section data of Kunz *et al*. (1996) are in agreement with the Wrean data (1993), it was decided to re-normalize the data of Gibbons and Macklin (1965) of a 0.85 factor. Although Gibbons and Macklin did not discriminate between compound nucleus reactions and break-up reactions during their measurement, this correction can be made directly since no significant

**TABLE 3.** List of the experimental data available within the [0.7-4] MeV range.

| Measurement type | Author | Year | Energies [keV] |
|---|---|---|---|
| $\sigma_{(\alpha,n_{tot})}(E)$ | Gibbons & Macklin[8] | 1965 | 1700-10300 |
| | Wrean *et al*.[8] | 1993 | 0-2670 |
| $\sigma_{(\alpha,n_0)}(E)$, $\sigma_{(\alpha,n_1)}(E)$ | Kunz *et al*.[9] | 1996 | 0-3500 |
| $\sigma_{(\alpha,n_1)}(E,0°)$ | Risser *et al*.[8] | 1957 | 1600-4830, 3100-4777 |
| | Obst *et al*.[10] | 1972 | 1600-6500 |
| | Van der Zwan & Geiger[8] | 1970 | 1470-7480 |
| $\sigma_{(\alpha,n_0)}(E,\theta)$ | Klages & Schölermann[8] | 1969 | 1750, 1960 |
| | Risser *et al*.[8] | 1957 | 2020, 2290, 2500, 2690 |

break-up reactions are expected below 4.5 MeV.

A satisfactory RP fit was simultaneously obtained on these three integrated cross sections data. Several attempts were made to get also an agreement with Risser data at zero degree but they remained unsuccessful. On the contrary the new RP set reproduces well the magnitude of the Obst excitation functions at zero degree. The final curves fitted on the $(\alpha,n_0)$, $(\alpha,n_1)$ angle integrated cross sections measured by Kunz are shown on Figure 3. The $\frac{5}{2}^+$ spin value of the 1886 keV resonance gives a better fit than other possible spin values ($\frac{7}{2}^-$ or resonance doublet ($\frac{5}{2}^+$ with $\frac{7}{2}^-$)). Around 2600 keV, two more resonances must be added to the resonance of $\frac{7}{2}^-$ spin value given by the literature to reproduce the various bumps. The 2800 keV $(\alpha,n_0)$ bump requires an additional resonance ($\frac{9}{2}^+$). The steep slope above 3 MeV observed on the $(\alpha,n_1)$ curve justifies one more res onance (currently assigned ($\frac{1}{2}^+$)) at 3400 keV since the broad pygmy resonance of width equal to ($(5\pm1)$ MeV) seen in ($\gamma$,n) reactions has no effect on ($\alpha$,n) reactions. But this steep slope will also be dependent of the final adjustment above 4 MeV.

## CONCLUSION

The various cross section components of the $^9$Be$(\alpha,n)^{12}$C reaction were obtained by using the Reich-Moore approximation of the R-matrix formalism together with a selection among the experimental results.

In particular the zero degree excitation function

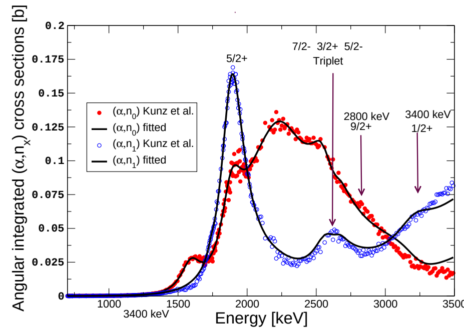


**FIGURE 3.** SAMMY $(\alpha,n_0)$ and $(\alpha,n_1)$ cross section calculations (dotted-dashed and solid curves respectively) compared to the experimental data of Kunz (triangles and circles respectively) in the energy range [700-3500]keV.

value proposed by Risser *et al.* must be definitively re-normalized by a factor of 2. In this context, the recent high resolution $(\alpha,n_0)$ and $(\alpha,n_1)$ cross section measurements by Kunz *et al.* were very helpful to elaborate a new resolved resonance parameterization up to 4 MeV. In general, the calculated angular differential cross sections are in satisfactory agreement with the experimental values.

From this new set of resolved RP, the generation of a complete set of point wise integrated and differential cross section data up to 4 MeV is straight forward.

The extension of the parameterization above 4 MeV clearly needs new high resolution measurements in order to be able to isolate the various high energy resonances.

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