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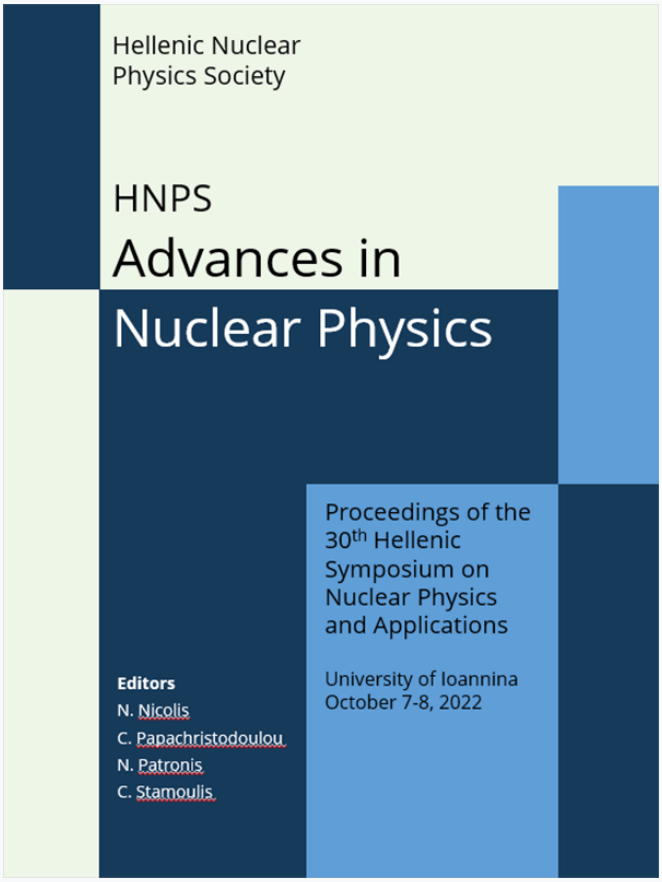

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Theoretical study of the ^{13}C + d system, in the framework of the R-Matrix model

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Abstract In the present work, a theoretical study of the ^{13}C + d system is carried out in the framework of the R-Matrix model. The experimental data used were taken from the IBANDL library. The cross-section measurements for the reactions have been carried out in the energy range of 0.49-1.65 MeV for three backscattering angles of 135°, 150° and 165°. The R-Matrix calculations were performed with the use of the AZURE2 code and involved the simultaneous analysis of the ^{13}C (d,p_0)^{14}C, ^{13}C (d,t_0)^{12}C, ^{13}C (d, a_0)^{11}B, ^{13}C(d,a_1)^{11}B reaction channels with one, coherent set of parameters.

Keywords R-Matrix Theory, NRA, Carbon

INTRODUCTION

Carbon through its various allotropic forms, its ability to form a wide variety of polymers, as well as being the main component in organic compounds, finds many uses in chemistry, metallurgy and semiconductor industries. ^{13}C being chemically the same as natural carbon, can be used as a tracer, allowing to follow carbon's path through chemical and biological reactions. Consequently, there is a great need for sensitive techniques that permit the simultaneous depth profiling of ^{12}C and ^{13}C with a single measurement. One of the most promising IBA techniques in this regard is d-NRA. More specifically, the reactions ^{13}C(d,p_0)^{14}C, ^{13}C(d,t_0)^{12}C, ^{13}C(d,a_0)^{11}B, ^{13}C(d,a_1)^{11}B and ^{12}C(d,p_0)^{13}C are well adapted to simultaneously provide accurate depth profiling data for ^{12}C and ^{13}C in a single measurement. However, while the cross section of the ^{12}C(d,p_0)^{13}C reaction is well known, there are limited experimental data on the ^{13}C(d,p_0)^{14}C ^{13}C(d,t_0)^{12}C, ^{13}C(d,a_0)^{11}B, ^{13}C(d,a_1)^{11}B reaction channels and these datasets are in certain cases discrepant. For this reason, it is important to use theoretical calculations in order to investigate the reported differential cross sections to create more reliable datasets at various angles and to take steps towards creating a first evaluation procedure.

CALCULATION DETAILS

The R-Matrix calculations in this work were carried out using the AZURE2 [1] code. AZURE2 is a general-purpose R-Matrix code designed to model low energy nuclear reactions involving charged particles, γ-rays and neutrons. The aim of the calculations is to reproduce the experimental cross sections with a single set of parameters. The experimental data used in this work are from J. Colaux et al [2], taken from the IBANDL library. They include the ^{13}C(d, p_0)^{14}C, ^{13}C (d, t_0)^{12}C, ^{13}C (d, a_0)^{11}B and ^{13}C(d,a_1)^{11}B reaction channels in the energy range E_d = 490-1650 keV and scattering angles θ = 135°, 150° and 165°. The reaction channels ^{13}C (d, d_0)^{13}C and ^{13}C (d, n)^{14}N were also used in the calculations, the first as the elastic channel that is necessary for all calculations and the second as necessary for the total width. The bibliographical values for the energy levels widths and J^{π}, when available, were taken from the National Nuclear Data Center website. In total, 11 levels of the compound nucleus ^{15}N* were used in the calculations (Table 1), while only minor differences were found between the values of the energy of the levels and total width Γ used in the present work and those reported in the literature. Dependency on the channel radius α was tested and found to be negligible.

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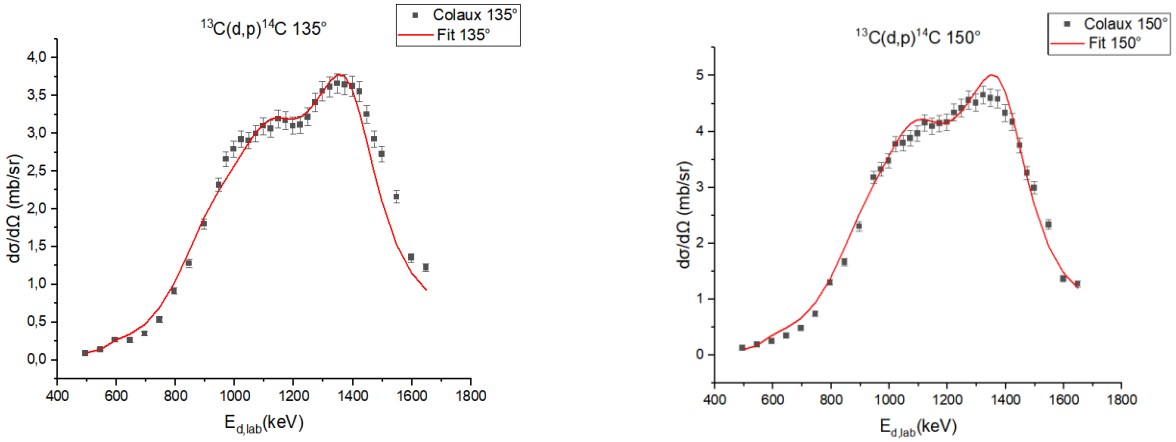
Table 1. *R-Matrix parameters used in this work compared to the available ones from literature*

Bibliography			Present Work								
E (MeV)	**J^π**	**Γ_{tot} (keV)**	**E (MeV)**	**J^π**	**Γ_{tot} (keV)**	**Γ_d (keV)**	**Γ_p (keV)**	**Γ_t (keV)**	**$\Gamma_{\alpha 0}$ (keV)**	**$\Gamma_{\alpha 1}$ (keV)**	**Γ_n (keV)**
16.59	3/2-	490	16.59	3/2-	490	7	3	7	23	6	444
16.67	1/2+	80	16.67	1/2+	134	20	1	3	20	7	83
16.85	5/2	110	16.8	5/2-	112	5	0	0	0	7	100
16.91	-	350	16.91	3/2+	310	25	38	50	50	7	140
17.05	-	-	17.07	7/2-	305	20	30	25	0	0	230
17.11	-	-	17.12	5/2+	480	100	0	15	145	10	210
17.15	1/2+ 3/2+	250	17.15	3/2+	250	50	40	0	40	10	110
17.23	-	175	17.23	5/2-	208	35	3	13	3	4	150
17.37	-	250	17.37	5/2+	245	25	45	17	60	0	98
17.58	3/2+	450	17.58	3/2+	450	50	0	40	0	0	350
17.67	3/2+	600	17.67	3/2+	600	150	0	150	220	50	30

RESULTS AND DISCUSSION

As can be seen in the Figures 1-4, the present R-Matrix calculations were able to reproduce the experimental cross section for the case of the $^{13}C(d,p_0)^{14}C$, $^{13}C(d,t_0)^{12}C$ and $^{13}C(d,a_0)^{11}B$ reaction channels with good accuracy, while larger discrepancies were observed in the case of the $^{13}C(d,a_1)^{11}B$ reaction channel. More specifically, for the case of $^{13}C(d,p_0)^{14}C$, there is a generally good agreement between the experimental data and the R-Matrix reproduction over the whole energy range. Similar are the results for the $^{13}C(d,t_0)^{12}C$ reaction channel, with some small discrepancies at energies around 1200keV and 1300keV. In Figure 3, we can see that for the $^{13}C(d,a_0)^{11}B$ reaction channel more discrepancies are observed in the behaviour of the cross sections at higher energies. This difference could be explained by the existence of several broad overlapping states with J^π uncertainties. Finally, for the $^{13}C(d,a_1)^{11}B$ reaction channel, in Figure 4 we can see large discrepancies over the whole energy range. These discrepancies could be attributed to the experimental difficulty in extracting the (d,a_1) cross section.



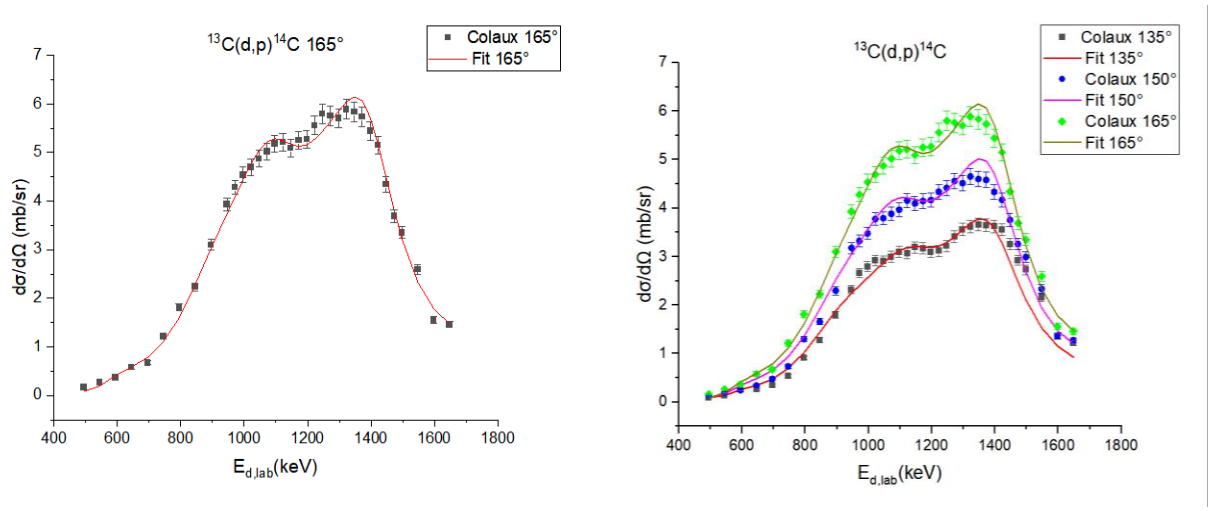


Figure 1 a – d: *Comparison between the cross sections from the R-Matrix calculations and experimental data for the ^{13}C (d, p$_0$)^{14}C reaction at a) 135° b) 150° c) 165° and d) all three angles*

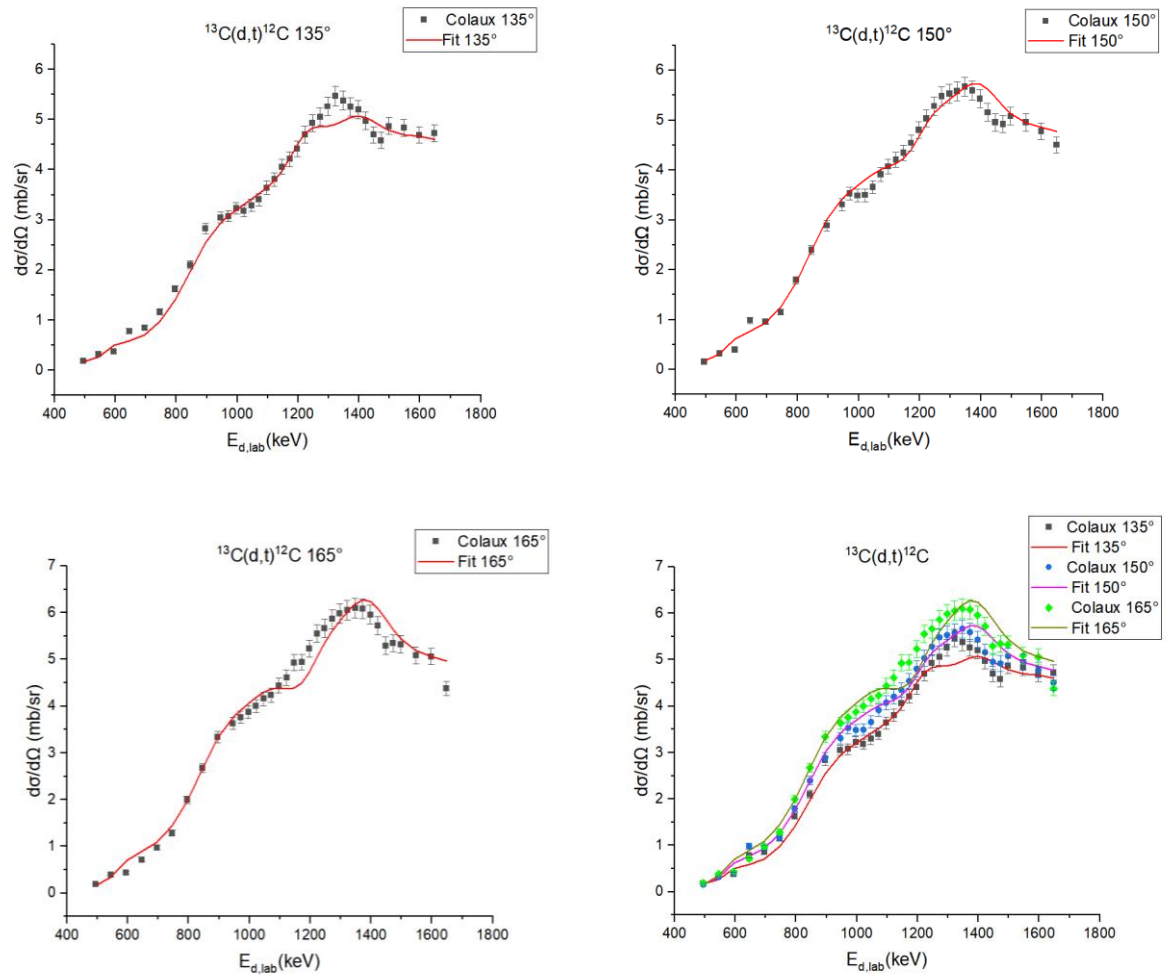


Figure 2 a – d: *Comparison between the cross sections from the R-Matrix calculations and experimental data for the ^{13}C (d, t$_0$)^{12}C reaction at a) 135° b) 150° c) 165° and d) all three angles*

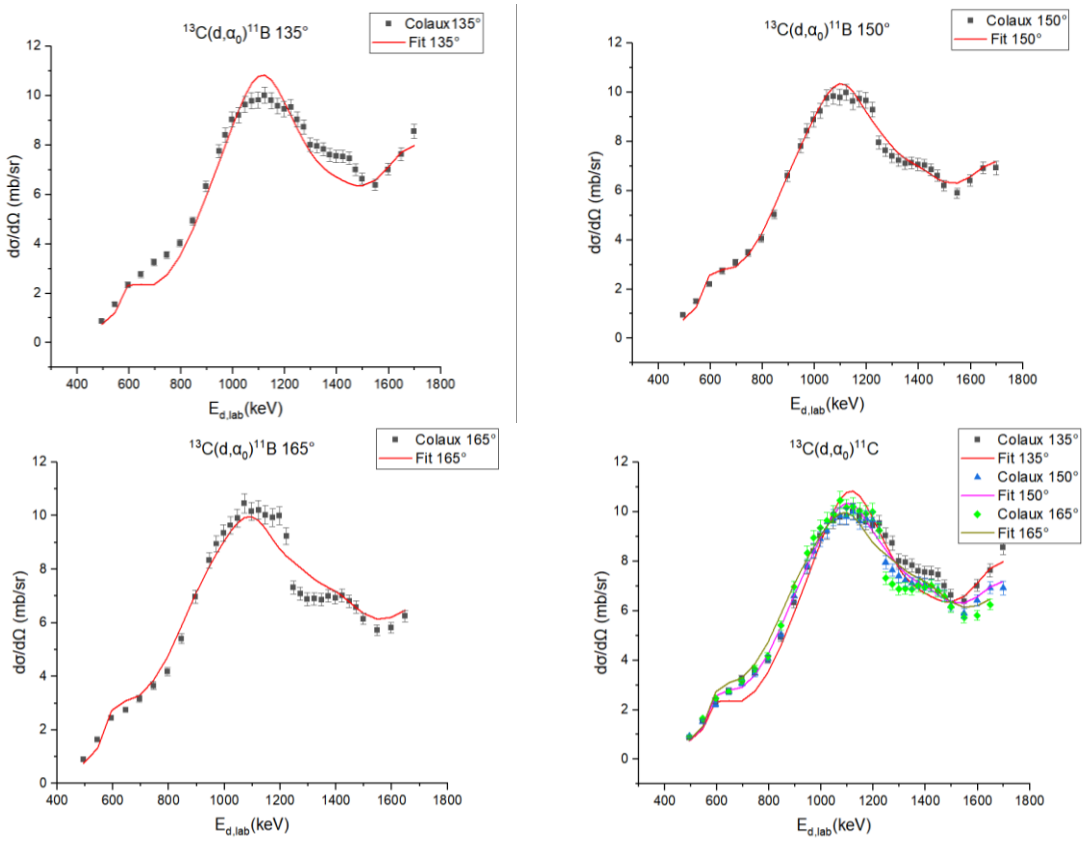


Figure 3 a – d: *Comparison between the cross sections from the R-Matrix calculations and experimental data for the ^{13}C (d, α$_0$)^{11}B reaction at a) 135° b) 150° c) 165° and d) all three angles*

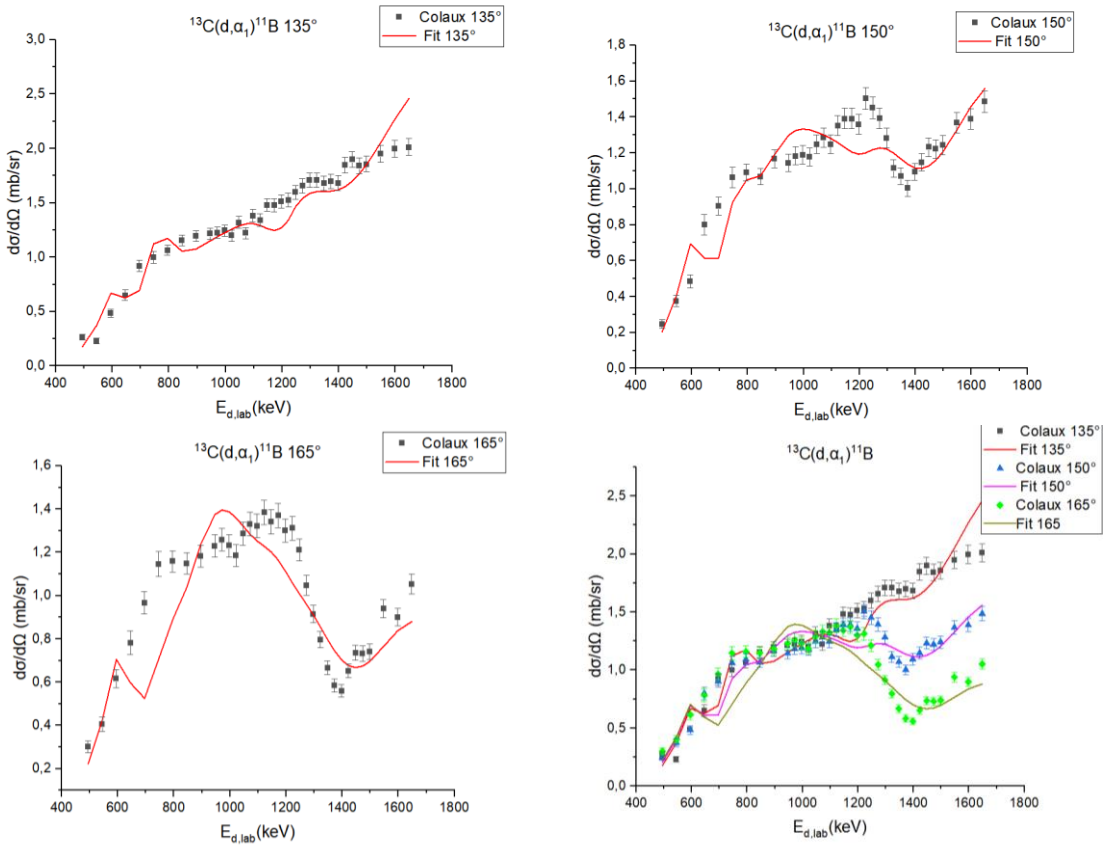


Figure 4 a – d: *Comparison between the cross sections from the R-Matrix calculations and experimental data for the ^{13}C (d, α$_1$)^{11}B reaction at a) 135° b) 150° c) 165° and d) all three angles*

CONCLUSIONS

In the present work, a theoretical study of the ^{13}C + d system is carried out in the framework of the R-Matrix model using the AZURE2 code for the $^{13}C(d,p_0)^{14}C$ $^{13}C(d,t_0)^{12}C$, $^{13}C(d,a_0)^{11}B$, $^{13}C(d,a_1)^{11}B$ reaction channels in the energy range E_d = 0.49 - 1.65 MeV for the backscattering angles of 135°, 150° and 165°. The calculations were able to reproduce the experimental datasets with one set of coherent parameters, yielding a quite satisfactory agreement, and can be used for determination of the cross section in energies between 0.49-1.65 MeV and angles between 135° and 165°. For more accurate R-Matrix results, more experimental results at more detection angles, including the elastic channel are deemed necessary. These experimental datasets could then be used for an update of the results obtained in the present work, in order to finalize the evaluation process on the ^{13}C + d reaction channels.

References

[1] R. E. Azuma et al., Phys. Rev. C 81, 045805 (2010)
[2] J. L. Colaux, Nucl. Instrum. Methods Phys. Res. B 254, 25 (2007)