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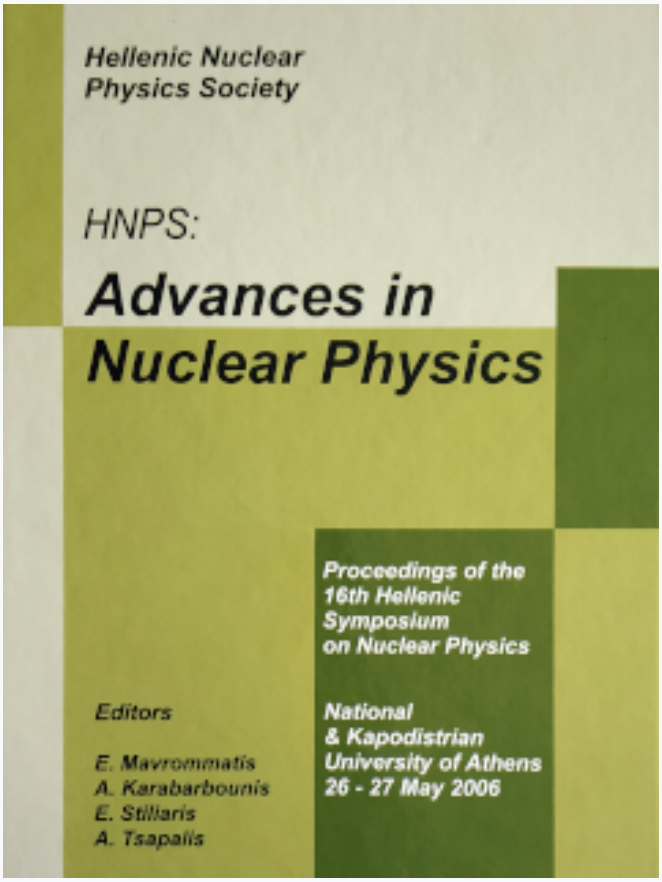

Differential Cross Section Measurements of the $^{12}C(d,p_{1,2,3})^{13}C$ Reaction, in the Energy Range E$_{d,lab}$= 900-2000 keV, Suitable for NRA

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Differential Cross Section Measurements of the C(d,p , ,) C Reaction, in the Energy Range E = 900-2000 keV, Suitable for NRA

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Absolute differential cross section measurements of the $^{12}C(d,p_{1,2,3})^{13}C$ reaction were performed in the projectile energy region $E_{d,lab}$ = 900-2000 keV (in steps of 25 keV) and for detector angles between 145 ° and 170 ° (in steps of 5 °) using as targets 99.9% purity self-supported natural carbon (98.9% ^{12}C – 1.1% ^{13}C) foils of nominal thickness ca. 1×10^{18} at/cm^2. The overall error in the absolute differential cross section measurements varied between ∼8-30%. The results, presented in both graphical and tabular form, are compared with already published data and an attempt is made to explain the occurring differences. The strong influence of the resonance mechanism is presented and discussed.

1. Introduction

In the framework of NRA, the most important reaction for the determination of low concentration and depth profiling of carbon in heavy matrices in the presence or absence of other low-Z elements is the$^{12}C(d,p_0)^{13}C$ reaction [1]. The relatively low deuteron energies required, render this reaction especially useful for small accelerators. This reaction has been thoroughly studied in literature [2-9]. Unfortunately this is not the case for the (d,p_1), (d,p_2) and (d,p_3) reaction channels [10,11]. Especially the former, due to its high cross section could be proven extremely useful for NRA purposes, providing an additional fingerprint for carbon depth profiling in certain cases. Such a case could occur in the analysis of thin films comprised of several light elements, where the $^{12}C(d,p_0)$ peak could be contaminated due to overlaps.

Moreover, following the pioneer works of A. F. Gurbich [12-15], it is evident that the problem of theoretical evaluation of differential cross section data is extremely complicated in the case of deuteron induced reactions, due to the three mechanisms contributing to the cross section, namely direct stripping, resonant mechanism and formation of a

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compound nucleus, as well as due to the multiplicity of open channels at usual NRA energies, namely (d,d), (d,p), (d,n) and (d,α). It is the aim of the present work to facilitate such an evaluation in the case of carbon by supplying additional experimental data at steep backscattering angles, not studied in the past, for the competing channels ^{12}C(d,p$_{1,2,3}$).

Thus, the present study could be considered as a continuation of recent works presented by the authors for the ^{12}C+d system [9,16], in the energy range E$_{d,lab}$=900-2000 keV (in steps of 25 keV) and for detector angles between 145° and 170° (in steps of 5°). The results are compared to relevant data already existing in literature [10-11,17]and an attempt is made to explain the occurring similarities and discrepancies.

2. Experimental Procedure

The experiments were performed using the deuteron beam of the 5.5 MV TN11 Tandem Accelerator of N.C.S.R. "Demokritos", Athens, Greece. The experimental setup and followed procedure have been presented in detail elsewhere [9]. A typical experimental spectrum taken at 160° and E$_{d,lab}$=2000 keV is presented in fig. 1, along with the corresponding peak identification.

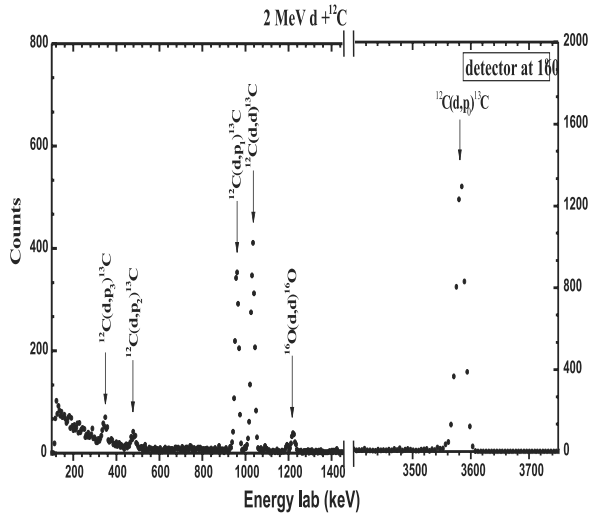

Figure 1. Experimental spectrum taken at 160° and E$_{d,lab}$=2000 keV, along with the corresponding peak identification.

3. Results and Discussion

The main source of error in the absolute differential cross section measurements was the variation in the target thickness due to – primarily – carbon buildup. This error is critical in the study of the ^{12}C(d,p$_{1,2,3}$) reaction because it does not only contribute to the uncertainty in the energy of the incoming beam, but directly affects the obtained experimental yield. The effect of sputtering, although it cannot in principle be excluded, was of minor importance.

One has also to take into account that *ab initio* lateral variations of the order of 10% in the foil thickness due to the manufacturing process [18], as well as micro-perforations, in the case of thin carbon foils are not surprising. Moreover, the observed formation of wrinkles before and/or during data acquisition in the foil, as well as the angular divergence of the beam, despite the long collimation system, enhanced the uncertainty in the correct assessment of the target thickness.

Thus, despite the implementation of liquid nitrogen traps and the use of multiple targets in the measuring process, in the case of carbon foils, a constant monitoring of the sample's thickness was considered to be mandatory, much more preferable than the traditional measurement of the target thickness, implementing low energy α-particles before and/or after the experiment. For this purpose, elastic scattering spectra from the monitor detector at 160° were analyzed, using a 2-parameter χ^2 fit, with namely α, the ratio $d\sigma_{Elastic}/d\sigma_{Rutherford}$, and d, the target thickness in at/cm^2 as free fitting parameters. Since the critical parameter α is considered as non-varying over the whole target thickness, the validity and accuracy of this method critically depends on the absence of thin, narrow spaced, sharp resonances, over the whole energy range studied, since the beam energy loss inside the targets varied only between 2 to 6 keV. This is indeed the case in the 12C+d system [17] where broad overlapping resonances dominate, with the only exception being the sharp resonance ($\Gamma \cong 7$ keV) around $E_{d,lab} \cong 1449$ keV [10-11,17] which was not thoroughly scanned due to the large adopted energy step (25 keV); in any case, the expected error was significantly higher around that value.

The average thickness of the irradiated samples for all the experimental points was found to be $(988\pm108)*10^{15}$ at/cm^2 using this approach. Thus, the overall error in the absolute differential cross section measurements varied between ∼8-30% depending mainly on the target. The reported cross section values correspond to the half of the target's thickness according to the usual convention, following SRIM 2003 calculations [19].

The data for e.g. 150^o, obtained during the present study are presented in fig. 2 along with the combined experimental errors. Despite the large adopted energy step, the resonances reported in the past [17] for the ^{12}C(d,p$_1$) reaction at $E_{d,lab}$= 920 keV (Γ=95 keV), 1190 keV (Γ=190 keV), 1300 keV (Γ=30 keV), 1449±1.5 keV (Γ=7.0±0.5 keV), 1640±20 keV (Γ=150±20 keV), 1738±6 keV (Γ=78±6 keV), 1792±7 keV (Γ=119±9 keV) and 1870±6 keV (Γ=101±9 keV), corresponding to excited states of ^{14}N, were also identified in the present work. At the steep backscattering angles studied in the present work (small angular range) the resonant structure remains coherent and most of the resonances (broad and/or overlapping) are evident through constructive interference patterns, with the exception of the resonances at $E_{d,lab}$= 920 keV (Γ=95 keV) and 1870±6 keV (Γ=101±9 keV) which present destructive interference patterns. On the other hand,

the consistent increase observed around $E_{d,lab}$=1950-2000 keV could be related to the combined influence of the broad, overlapping resonances at $E_{d,lab}$=1870±6 keV (Γ=101±9 keV) and at $E_{d,lab}$=2250±19 keV (Γ=300±30 keV). The whole constructive/destructive interference pattern, caused by the predominance of the resonant mechanism, as shown in figure 2, is in general more complicated at higher $E_{d,lab}$ energies, namely in the energy region between 1600 and 2000 keV. The differential cross section values reported in the present work are in general in good agreement with values reported in the past over a much broader angular and energy range [10-11]. The existing discrepancies can safely be attributed to differences in the determination of the target thickness and/or the absolute energy calibration.

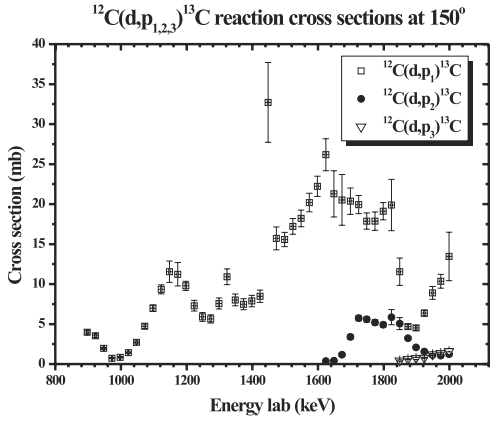

Figure 2. Differential cross section spectra (mb/sr) of the $^{12}C(d,p_{1,2,3})^{13}C$ reactions at 150 ° for $E_{d,lab}$=900-2000 keV.

In the case of the $^{12}C(d,p_2)$ reaction, the reported resonances at $E_{d,lab}$= 1715±6 keV (Γ=40±9 keV) (constructive interference pattern) and 1870±6 keV (Γ=101±9 keV) (destructive interference pattern) were identified. The slow decline of the differential cross section values observed around $E_{d,lab}$=1900-2000 keV could be attributed mainly to the competition by the $^{12}C(d,p_3)$ reaction channel whose differential cross section values are slowly rising from threshold, up to $E_{d,lab,max}$=2000 keV.

The differential cross section values of the $^{12}C(d,p_{1,2,3})$ reactions present a rather slow angular variation over the whole energy range studied. This behavior is consistent with the corresponding angular variation of the $^{12}C(d,p_0)$ and$^{12}C(d,d_0)$ reactions [9,16], and greatly facilitates NRA measurements, allowing – to a good approximation – a linear interpolation of the cross section values for intermediate detector angles.

4. Conclusions

In the present work, a study of the differential cross section of the $^{12}C(d,p_{1,2,3})^{13}C$ reactions is presented for $E_{d,lab}$=900-2000 keV (in steps of 25 keV) and for detector angles between 145 $^\circ$ and 170 $^\circ$ (in steps of 5 $^\circ$), in the framework of NRA. In the case of the $^{12}C(d,p_1)$ reaction, for all the detector angles under study, there seems to be a good agreement with data already existing in literature [10,11]. Angular distributions of the differential cross section values at steep backscattering angles are presented and analyzed. The results of the present work are available in both tabulated and graphical forms at IBANDL for the IBA community.

The experimental data could be considered as complementary to the ones presented by the authors for the $^{12}C(d,p_0)$ and $^{12}C(d,d_0)$ reactions recently [9,16] in the same angular and energy range. Thus, the present work aims at enhancing the analyzing power of the $^{12}C(d,p)$ reaction for NRA purposes. It is evident that deuteron induced reactions at low energies present interesting theoretical, as well as, experimental challenges. The predominance of the resonant mechanism renders the possible future evaluation of the differential cross section data at steep backscattering angles completely indispensable. Moreover, the study of deuteron induced reactions in other elements (e.g. $^{10,11}B$, ^{14}N, ^{19}F, etc.) would further enhance IBA capabilities when complex matrices are involved, since the deuteron beam can simultaneously excite multiple co-existing light elements.

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