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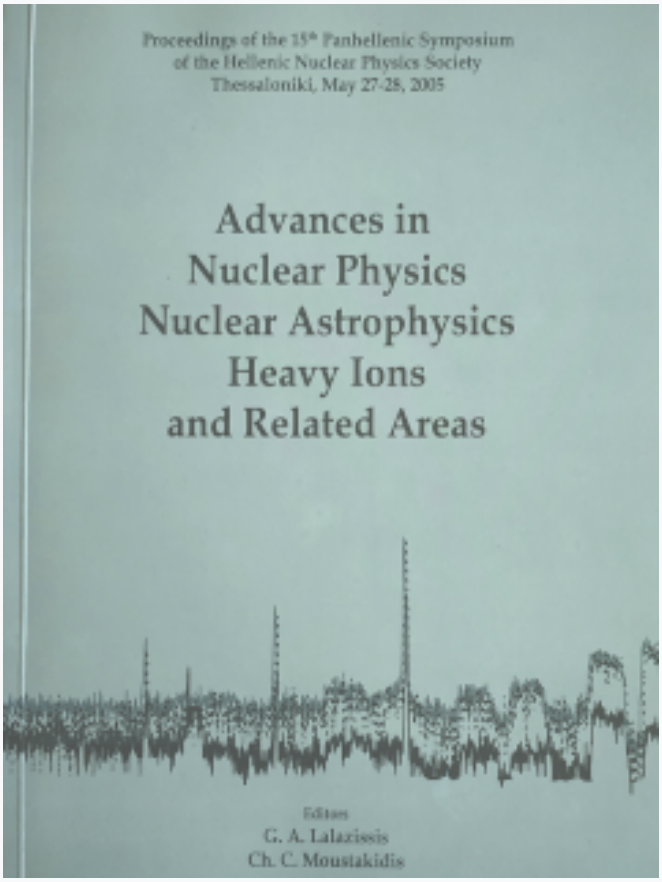

A Detailed Study of the 12C(d,p0)13C Reaction at Detector Angles between 135 ° and 170 °, for the Energy Range Ed,lab = 900-2000 keV

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A Detailed Study of the $^{12}C(d,p_0)^{13}C$ Reaction at Detector Angles between 135 ° and 170 °, for the Energy Range $E_{d,lab}$ = 900-2000 keV

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Abstract

The differential cross sections of the $^{12}C(d,p_0)^{13}C$ reaction applied to the determination of the depth distribution of carbon in near-surface layers of materials were determined in the projectile energy region $E_{d,lab}$ = 900-2000 keV (in steps of 25 keV) and for detector angles between 135 ° 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 ~6-22%. The results were compared with already published data and the explanation of the occurring differences was attempted.

1 Introduction

Nuclear reaction analysis (NRA) is nowadays well established as one of the principal ion beam analysis (IBA) methods, due to its high isotopic selectivity, enhanced sensitivity for many nuclides, capability of least destructive depth profiling, and the possibility of simultaneous analysis of more than one light element in near-surface layers of materials [e.g. 1]. As NRA quantifies individual light isotopes absolutely, and can depth profile with nanometer resolution, it is the most suitable ion beam technique for the determination of the concentration and depth profiling of light elements in complex matrices. Moreover,

for many elements (e.g. O, N, C, F, Al, Mg and S) the use of a deuterium probing beam (rather than protons or helium) can give enhanced sensitivity and accuracy, owing mainly to larger nuclear reaction cross sections, at the expense sometimes of background interference (as in the case of peak overlaps, or 3-body reaction kinematics). However, in certain cases, the implementation of NRA in light element depth profiling is impeded by the lack of reliable cross section data in literature over a wide range of energies and scattering detector angles.

One of the most important reactions for the determination of low concentrations 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. In the present work, a detailed study of the $^{12}C(d,p_0)^{13}C$ reaction is presented for $E_{d,lab}$=900-2000 keV (in steps of 25 keV) and for detector angles between 135 ° and 170 ° (in steps of 5 °). The results are compared to relevant data already existing in literature [2-8] and an attempt is made to explain the occurring 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 deuterons, accelerated to $E_{d,lab}$=900-2000 keV in steps of 25 keV, were introduced to a scattering chamber equipped with a precision 4-motor goniometer capable of determining the target orientation with an accuracy of 0.01 ° . The final ion energy of the deuteron beams was determined via NMR with an estimated ripple of 1.6 keV, and a maximum offset of less than 0.5 keV, as verified using the 872.11 keV resonanceof the $^{19}F(p,\alpha\gamma)$ reaction at the beginning and at the end of the experiment. The maximum error in the determination of $E_{d,lab}$ was thus estimated to be ca. 2 keV. The detection system consisted of five (300-2000 μm thickness) Si surface barrier detectors (4 rotating, set at 10 ° intervals, and 1 fixed at 160 ° as monitor) along with the corresponding electronics. For every $E_{d,lab}$, five (4+1) detector spectra were simultaneously recorded and the procedure was repeated by turning the four Si detectors by 5 ° . The beam spot size was approximately 3×3 mm^2, while the current on target did not exceed 100 nA. The high-purity (99.9%) self-supported natural carbon foils (98.9% ^{12}C – 1.1% ^{13}C) used as targets had a nominal thickness of $\sim 1\times10^{18}$ at/cm^2 and were placed at a distance of ~27 cm from the detectors. No absorber foils or slits were placed in front of the detectors. The solid angle subtended by the detectors as well as their energy resolution were determined via a triple 81.1 nCi, $^{241}Am/^{239}Pu/^{244}Cm$ α-source, along with RBS data from high purity thick gold and aluminum foils. The subtended solid angle ranged

between 3.6×10^{-4}-1.5×10^{-3} sr. The total estimated error in the product $Q^*\Omega$ did not exceed 4.3% in the least favorable case. The statistical error was kept as low as <1% in all cases. Two different algorithms were implemented for peak fitting and integration, yielding results within 1%. The oxygen contamination of the samples due to their manufacturing process was practically negligible (1-3 at %). A long Faraday cup was implemented for the charge collection, while voltage suppression (300 V) was employed in front of the collimator set and on target. Two liquid nitrogen traps were set on both ends of the goniometer in order to reduce the carbon build-up on the targets, while the vacuum was kept constant $\sim5\times10^{-7}$ Torr.

3 Results and Discussion

The data obtained during the present study are presented in figs. 1a-h along with existing data from literature at certain backscattering angles. No significant deviations (exceeding 15%) – taking into account the experimental errors – were observed at 135°, 150° and 165°, with the exception of a single dataset [8] taken from IBANDL, which is presented in the corresponding figure, scaled down by a factor of 2. The reason behind this single large, systematic discrepancy is not clear. The other smaller discrepancies can safely be attributed to differences in the determination of the target thickness and/or the absolute energy calibration.

The main source of error in the absolute cross section measurements was the variation in the target thickness due to carbon buildup and/or sputtering. 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 mandatory. One has also to take into account that *ab initio* variations of the order of 10% in the foil thickness due to the manufacturing process [9] are not surprising. 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. The validity of this method implies the absence of thin, narrow spaced, sharp resonances, as is indeed the case in the $^{12}C(d,p_0)^{13}C$ reaction, taking also into account the fact that the beam energy loss inside the targets varied only between 2 to 6 keV, over the whole energy range. The only exception was the sharp resonance ($\Gamma \cong 7$ keV) around $E_{d,lab} \cong 1449$ keV [3, 10] 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 ~6-22%. The reported cross

section values correspond to the half of the target's thickness according to the usual convention, following SRIM 2003 calculations [11].

The cross section maxima reported in the past [3, 10] at $E_{d,lab}$= 920, 1190, 1310, 1449 and 1792 keV, corresponding to excited states of ^{14}N, were also identified in the present work. The consistent increase observed around $E_{d,lab}$ = 1900-2000 keV could be related to the influence of the broad, overlapping resonances at $E_{d,lab}$=1870 keV (Γ=101±9 keV) and $E_{d,lab}$=2250 keV (Γ=300±30 keV).

Following the pioneer works of E. Kashy [3] and A. F. Gurbich [12-15], it is evident that in the case of deuteron induced reactions, the three mechanisms contributing to the cross section, namely direct stripping, resonant mechanism and formation of a compound nucleus, as well as the multiplicity of open channels at usual NRA energies, namely (d,d), (d,p), (d,n) and (d,α), render the problem of theoretical evaluation of differential cross section data extremely complicated. It is the aim of the present work to facilitate such an evaluation by supplying experimental data at steep backscattering angles, not studied in the past.

4 Conclusions

In the present work, a detailed study of the ^{12}C(d,p$_0$)^{13}C reaction is presented for $E_{d,lab}$=900-2000 keV (in steps of 25 keV) and for detector angles between 135 $^\circ$ and 170 $^\circ$ (in steps of 5 $^\circ$). For all the detector angles under study, there seems to be a good agreement with data already existing in literature. The results of the present work are available at IBANDL for the IBA community.

However, further work is required before a complete understanding of the effect of the reaction mechanisms involved in the ^{12}C(d,p$_0$)^{13}C reaction at low deuteron energies is accomplished. Such an understanding, along with the proper theoretical treatment, would lead to the valuable evaluation of the differential cross section data at steep backscattering angles. Furthermore, the study of deuteron induced reactions in other light contaminants (e.g. ^{19}F, ^{10,11}B etc.) would further enhance the analyzing power of the ^{12}C(d,p$_0$)^{13}C reaction in complex matrices.

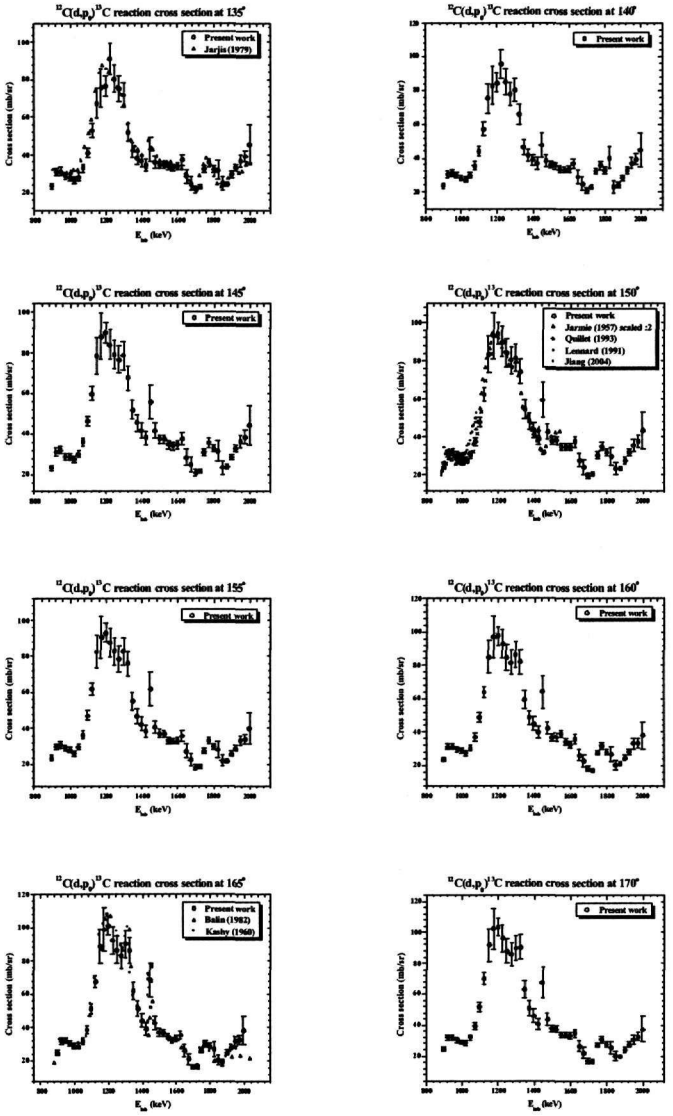

Fig. 1. a-h: Differential cross section spectra (mb/sr) of the ^{12}C(d,p$_0$)^{13}C reaction between 135 ° and 170 °, for $E_{d,lab}$=900-2000 keV, along with existing data from literature.

References

[1] J. R. Tesmer and M. Nastasi (eds), *"Handbook of modern ion beam materials analysis"*, Materials Research Society, Pittsburgh, PA, (1995).

[2] V.G.Balin, A.F.Gurbich and V.S.Shorin, *Preprint FEI-1341, Obninsk* (1982).

[3] E.Kashy, R.R. Perry and J.R. Risser, *Phys.Rev.*, **117** (1960), 1289.

[4] V. Quillet, F. Abel and M. Schott, *Nucl. Instr. and Meth.*, **B 83** (1993) 47.

[5] R.A.Jarjis, Int..Rep., Univ. of Manchester (1979).

[6] W.N. Lennard, G.R. Massoumi, P.F.A. Alkemade, I.V. Mitchell and S.Y. Tong, *Nucl. Instr. and Meth.*, **B 61** (1991) 1.

[7] W. Jiang, V. Shutthanandan, S. Thevuthasan, D. E. McCready and W. J. Weber, *Nucl. Instr. and Meth.*, **B 222** (2004) 538, W. Jiang, V. Shutthanandan, S. Thevuthasan, D. E. McCready and W. J. Weber, *Nucl. Instr. and Meth.*, **B 227** (2005) 450.

[8] N.Jarmie and J.D.Seagrove, *Los Alamos Report LA-2014* (1957).

[9] W. Thalheimer, W. Hartmann, J. Klemm, B. Lommel, *Cryst. Res. Tech.* **34** (1999) 175.

[10] F. Ajzenberg-Selove, *Nucl. Phys.* **A** 268 (1976) 1.

[11] J.F. Ziegler, J.P. Biersack and U. Littmark, *"The Stopping and Range of Ions in Solids"*, Pergamon Press, New York (1985).

[12] A.F. Gurbich, IAEA Report of the Advisory Group Meeting on Long Term Needs for Nuclear Data Development (Vienna, 28/11-1/12, 2000).

[13] A.F. Gurbich, *Nucl. Instr. and Meth.*, **B 129** (1997) 311.

[14] A.F. Gurbich, *Nucl. Instr. and Meth.*, **B 136-138** (1998) 60.

[15] A.F. Gurbich, *Nucl. Instr. and Meth.*, **B 161-163** (2000) 125.