Simultaneous measurement of the (d,d) and (d,p) resonant reactions using thick deuterated polyethylene targets

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Recibido el 14 de mayo de 2004; aceptado el 11 de agosto de 2004

The thick target technique is extended here to study reactions induced by deuterons. Deuterated target production and characterization is reviewed in detail. The experimental setup used in a previous work, to study proton induced resonances, is complemented here with an additional thin transmission detector for standard particle identification with the E-ΔE technique. Through the measurement of the excitation functions of the ^{2}H(^{12}C,d) and ^{2}H(^{12}C,p) reactions, resonant states in ^{14}N are studied. Using known energies and widths for resonances in the relevant energy range, good fits were obtained with R-matrix calculations.

Keywords: (deuterated) target preparation; elastic recoil analysis; resonant reactions

El uso de la técnica del blanco grueso en cinemática inversa desarrollado por nuestro grupo es extendido en este trabajo para estudiar reacciones resonantes inducidas por deuterones. Se detalla la preparación de los blancos deuterados. El arreglo experimental ha sido también mejorado sustituyendo el detector de partículas cargadas por un telescopio E-ΔE que permite identificación de partículas. Un conjunto de estados resonantes en ^{14}N son resueltos e identificados mediante las reacciones elástica, ^{2}H(^{12}C,d) y de transferencia de un neutrón,^{2}H(^{12}C,p). La comparación de nuestros datos con cálculos de matriz R usando valores conocidos de las energías y anchuras de las resonancias es excelente.

Descriptores: Preparación de blancos (deuterados); análisis de retroceso elástico; reacciones resonantes.

PACS: 24.30 Gd, 25.45.De, 25.45.Hi

1. Introduction

The thick target technique [1,2], originally developed to study proton induced resonant reactions, is extended in this work to deuteron induced reactions. With the irruption of radioactive beams, especially neutron rich, the interest on deuterium targets has been renewed [3]. The procedure is tested by studying resonant states in ^{14}N through the (d,d) and (d,p) reactions on ^{12}C. Thick (1400 μg/cm^2) polyethylene (C_2D_4) targets were used with an experimental setup similar to the one in [2], but with an additional large area transmission (ΔE) silicon detector in front of the DSSD for particle identification. The resonant behavior of the resulting deuteron and proton spectra (excitation functions) are well reproduced using the R-matrix code "MULTI" [4], with the parameters of known states [5]. In Sec. 2, the experimental details are given. Because of its relevance, a detailed account of the manufacture and characterization of the deuterated targets is included. In Sec. 3 the measured (d,d) and (d,p) excitation functions are discussed, together with the fits from theoretical calculations. Finally in Sec. 4, conclusions and an outlook for future work were presented.

2. Experimental procedure

The fact that neutrons are unstable, with a half-life of 10.5 minutes, chemically inert, and with no electric charge, turns the task of preparing pure neutron targets a hard one. Deuterons and tritons have been traditionally used as neutron targets as well as a mean to produce neutron beams through (d,p), (t,p), and (t,d) reactions.

2.1. Target preparation and characterization

Target preparation:

Neutron beams of known flux and energy, can be produced using the associated particle technique (APT) through the ^{2,3}H(d,n)^{3,4}He reaction. This requires an unambiguous detection of ^{3,4}He, and a fast coincidence arrangement permits the tagging of the outgoing neutron, fixing its energy and direction according to the reaction's kinematics. The targets need to be thick enough to produce a significant neutron flux, usually a few hundreds of micrograms per square centimeter, and thin enough in order to avoid considerable ^{3}He energy losses, and thus, assure a good energy resolution. These are the same characteristics of the targets we need for (d,p) studies, namely: thick enough to stop the heavy beam's particles, and thin enough to allow the protons to exit the target with small energy loss.

Self-supported deuterated polyethylene targets are made, basically following the technique described by Trippard *et al.* [6]. Polyethylene powder is dissolved into (near) boiling xylene and promptly poured onto glass slides, which have been previously prepared with thin layers of detergent (*e.g.*, Extran II). The polyethylene films are left to dry over

the glass slides for 24 hours, and then cut to a convenient size with a cutter blade. Fasten by one extreme, the slides are dipped in a recipient containing pure water at room temperature, in order to free the films from the glass. The floating foils are picked off and simultaneously mounted on appropriate (holed) target frames, taking care that the frames, starting from a horizontal position, end up vertically when they leave the water surface.

Target thickness is dependent on the ratio of deuterated polyethylene to xylene, and is also dependent on the pouring process. A 5° to 10°inclination and previous warm-up of the slides (40° C) produce better uniformity in the films, at expenses of the thickness. Several authors [7,8], reported the use of thin coatings of aluminum and carbon, including thin layers evaporated on both sides of deuterated targets. We commonly use 70 mg of polyethylene powder from Merck (C_2D_4) dissolved in 8.5 ml of xylene. The pouring can also be made over glass slides with 10 to 20 μg/cm^2 carbon foils on their surface. The target's thickness obtained with this mixture lies in the range from 100 to 300 μg/cm^2. The concentration of this solution can be increased up to three times without saturation, to reach a target thickness near 900 μg/cm^2, and very thin targets can also be obtained by reducing that concentration (we have prepared self-supported 30 μg/cm^2 targets).

Thin carbon backings on polyethylene targets [9] have proven to be adequate to avoid surface deformations of the films during irradiation; having the advantage of not adding a substantial quantity of carbon, which besides helps to enhance electrical and thermal conductivity.

Target characterization:

The uniformity of the targets can be reliably tested through conventional alpha energy loss. We used a collimated triple-alpha source (^{244}Cm- ^{241}Am- ^{239}Pu) to measure energy losses in different points of each target. Depending on the application, a criterion should be established to determine the acceptable level of uniformity. In the case of targets for the measurements of reaction cross sections, we selected targets that have less than five per cent of variation in thickness. As an example, we obtained 508 μg/cm$^2\pm$ 4 % through the 9 points thickness test of a representative (2 cm^2) sample of the useful area of one on the targets used in the experiment.

In order to determine the composition of the deuterated polyethylene targets we employed standard elastic recoil detection analysis (ERDA), using ^{7}Li^{++} ions (4.5 - 5 MeV), and ^{12}C^{+++} ions (10.0 MeV), as projectiles provided by the EN tandem facility at ININ, and the pelletron accelerator at IFUNAM, respectively.

A commercial (3.5 μm) Mylar film can be used as a reference material. Figure 1 shows an energy spectrum of recoiled particles by 5 MeV lithium projectiles from this target, together with a simulated computer-program spectrum (filled line). The detection angle employed was 45°, and the Mylar target was set at 60 degrees with respect to the ^{7}Li-beam direction. Using the same experimental conditions, the C_2D_4 polyethylene film (with a 10 μg/cm2 carbon backing) was analyzed with a 4.5 MeV ^{7}Li beam. As expected, this energy change was adequate to raise the sensitivity for hydrogen determination (due to the enhancement of the elastic cross sections involved). Figure 2 shows the energy spectrum of recoiled particles from this target, accompanied by a (computer) simulated spectrum, illustrated by a continuous line. The first fact that can be extracted from the spectrum in Fig. 2, is that the isotope concentration is essentially constant throughout the depth of the target.

A similar procedure was followed at IFUNAM's Pelletron laboratory using the carbon beam. The concentration profile of deuterium and hydrogen obtained in both experiments was the same.

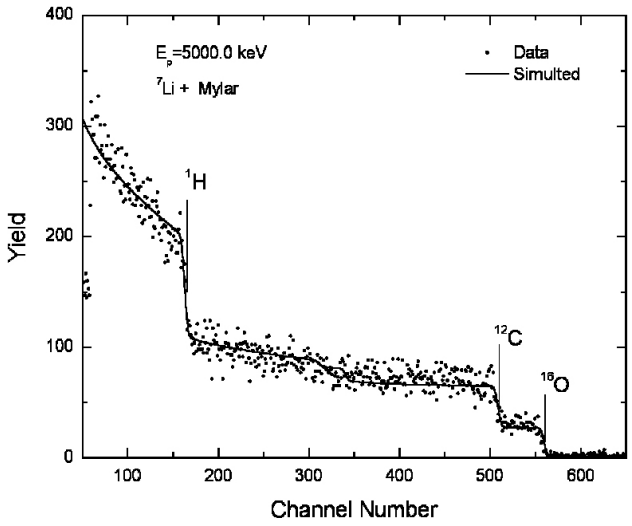

FIGURE 1. Energy spectrum of recoiled particles (at 45^0) from the bombardment of a 3.5 μm mylar film with 5.0 MeV ^{7}Li ions, used as a reference.

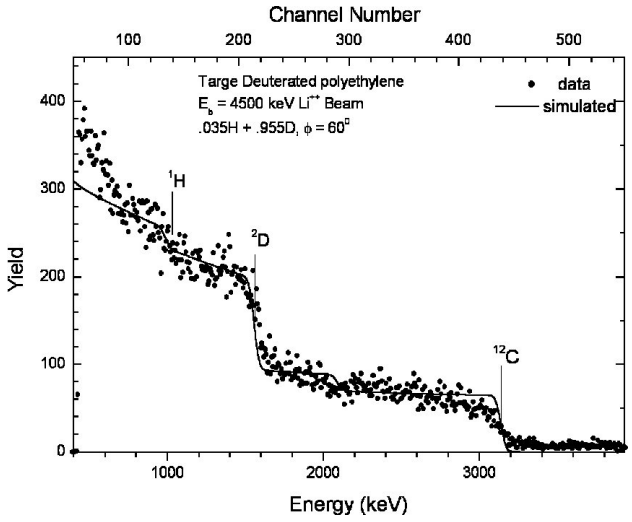

FIGURE 2. Energy spectrum of recoiled particles (at 45^0) from the bombardment of the C_2D_4 polyethylene film with 4.5 MeV ^{7}Li ions.

The result of the fits for the deuterated polyethylene (C_2D_4) target analyzed is consistent with an average hydrogen content of 4% of ^{1}H and 96% of ^{2}H, with an (average) uncertainty of 2.5%

2.2. Setup for the excitation function measurements

The overall setup is similar to the one described in [2]. A squared (5 by 5 cm) Double Sided Strip Detector (DSSD), 1000 μm thick with 16 strips in the front and 16 in the back (256 pixels), is placed behind a large area (900 mm^2) of the circular transmission detector (100 μm thick) at zero degrees, 9 cm away from the target, covering 15.5° in the horizontal and vertical planes. Since the DSSD used in this telescope is plane, each pixel, as defined by the front and back strips, covers a different solid angle. Those in the middle cover 2° in x and y.

Energy calibration was carried out using a ^{241}Am alpha source in a separate run. The usual analysis of the maximum signal in the front and back sets of strips yields the pixel that hits in the DSSD. From there the position and angle of the detected particle can be extracted, for the purpose of angular distribution measurements.

A C_2D_4 target thickness of 1.4 mg/ cm^2 was used. This is obtained by stacking together two self supported foils (900 and 500 μg/cm^2), on a target ladder at the center of the chamber. The use of thick targets allows us to explore a wide range of excitation energy in the nucleus under study (^{14}N in this case), from the maximum attainable with a given beam energy down.

A 20 MeV ^{12}C beam was delivered to the chamber with typical current of 10^7 particles per second. With such a low flux no significant damage was inflicted to the targets, that it remained fixed, along irradiation.

Particle identification was performed by the standard energy loss (E-ΔE) technique. In this way protons, deuterons, and alpha particles could be identified.

3. Simultaneous measurement of the excitation functions for the (d,d) and (d,p) reactions

In the off line analysis, protons and deuterons are properly identified, and the pixels from the detector are arranged into concentric "rings" two degrees wide, where zero degrees is the center of the DSSD detector, which coincides with the beam direction.

Energy losses of the incoming beam particles and the reaction products are treated as described in [1]. The calibrated energy detected for protons and deuterons is corrected by losses in their way out of the target to obtain their primary energy, using the same computer code as before. Here again, energy and angular straggling can be neglected. In this way, we produce energy spectra for protons and deuterons, which are the differential energy and angular distributions in the laboratory frame. It is also straight forward to produce the same functions in the center of mass reference system. This is done simultaneously for both reactions: ^{2}H(^{12}C,d)^{12}C, and ^{2}H(^{12}C,p)^{13}C.

Figures 3 and 4 show the excitation functions at 165° obtained for the ^{2}H(^{12}C,d)^{12}C, and ^{2}H(^{12}C,p)^{13}C reactions, respectively. They show a typical resonant behavior. Data is represented by dots. The solid line is the result of R-Matrix calculations including information of energy, and the width of all relevant states in ^{14}N in the 11.7 - 13.0 MeV excitation energy region. The most striking feature of the data, in Figs. 3 and 4, is the strong excitation of the states of J^π: 4^-, 3^- and 4^+, 3^-. Both sets, data and theory follow each other closely throughout the excitation functions in the measured energy range. On Table I, we give the quantum numbers of the resonances (excited states in ^{14}N) used in the calculations. Column 1 gives the energy of the resonance in the center of mass, column 2 gives the excitation energy in ^{14}N, column 3

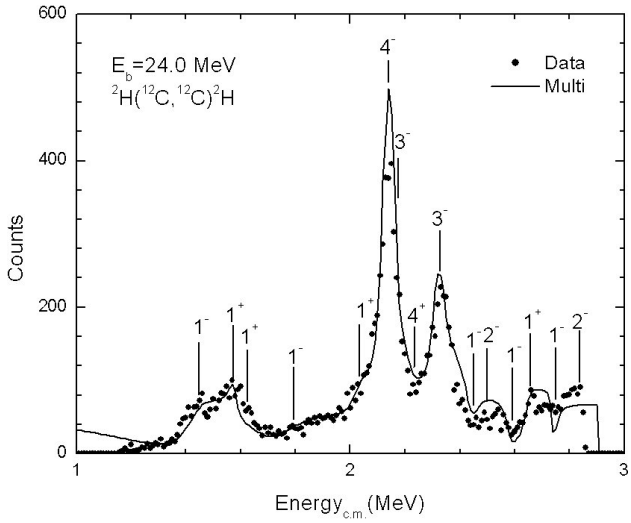

FIGURE 3. Energy spectrum of recoiled particles (at 45^0) from the bombardment of the C_2D_4 polyethylene film with 4.5 MeV ^{7}Li ions.

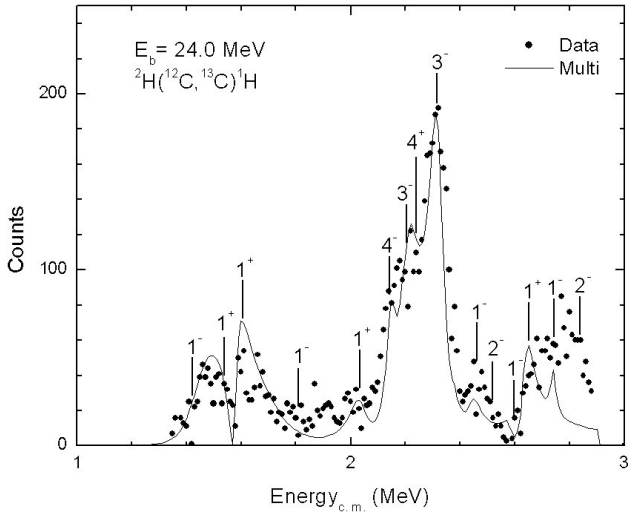

FIGURE 4. Excitation function obtained for the ^{2}H(^{12}C,p)^{13}C reaction.

TABLE I.

Ecm (MeV)	Ex (MeV)	J^{π}	Γ (keV)
1.43	11.702	1^-	140
1.545	11.817	1^+	175
1.60	11.872	1^+	105
1.80	12.072	1^-	320
2.05	12.322	1^+	100
2.139	12.411	4^-	55
2.148	12.420	3^-	45
2.210	12.482	4^+	75
2.321	12.593	3^-	64
2.45	12.722	1^-	60
2.50	12.772	2^-	50
2.68	12.952	1^+	75
2.70	12.972	1^-	20
2.75	13.022	2^-	45

gives the spin and parity of the state and the width, is given in the last column.

It is worth noting that parameters in Table I do not reproduce exactly those published in Ref. 5. Our R-Matrix calculations required some adjustment of those ones in order to better fit our measured excitation functions. In particular, the spin and parity assignments of the four higher spin states, our stronger peaks, either select one of the already suggested values or disagree with them. Since the shape of the excitation functions are very sensitive to the choice of the spin and parity of the state, we are also ruling out other possibilities.

As can be seen from Figs. 3 and 4, the use of inverse kinematics, a heavy projectile, on thick deuterated targets, produces high quality deuteron-induced excitation functions in a compact and fast fashion.

4. Conclusions

Deuterated polyethylene (C_2D_4) targets can usually be manufactured using a long-proved technique in a wide range of thickness: from some tenths up to 900 μg/cm^2. These targets are suitable for the study of inverse kinematics nuclear reactions involving deuterons. The concentrations of hydrogen isotopes, thickness and profile, can be measured precisely for each target, allowing to properly take into account those features in the design of experiments and the analysis of data.

Inverse kinematics focuses all information forward in a laboratory reference frame. A relatively small detector (25 cm^2) is enough to cover a large fraction of the total solid angle in the center of mass system. The granularity obtained through the use of DSSDs is ideal, since it allows construction of angular distributions and to study excitation functions in reactions induced by Hydrogen Isotopes. We have done this before using proton (^{1}H) targets, and in this work, we demonstrate that the quality of the information obtained in deuteron induced reactions is as high as that recorded before in the literature.

A close fit to the data is accomplished using R-Matrix calculations. The gross features of the data can be explained mainly through the use of four high spin states in ^{14}N. A definitive spin and parity assignment for those four states follows this work.

This technique can be confidently used in the near future to study unknown excitation functions induced by deuterons. Of special interest are the coming studies using radioactive species (neutron rich), taking advantage of the new beams being produced at the Oak Ridge National Laboratory, Holifield Radioactive Ion Beam Facility.

Acknowledgements

Research at the Oak Ridge National Laboratory was supported by the U.S. Department of Energy under Contract No. DE-AC05-00OR22725 with UT-Battelle, LLC and under Contract No. DE-AC05-76OR000333 between the U.S. Department of Energy and Oak Ridge Associated Universities. This work was also supported in part by CONACYT (Mexico) through contracts: 1103-E9102, F036-E9109, G0010-E and DGAPAUNAM: IN114896. We like to thank P. Villaseñor, and D. G. Linarte B. operators of the tandem at ININ, K. López, and F. Jaimes, operators of the Pelletron at IFUNAM, and the operator's crew at HRIBF at ORNL, for their assistance and delivery of all the different beams needed for this work.

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