Nuclear Instruments and Methods in Physics Research B 290 (2012) 72–78

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Differential cross-section measurements of the d + ^{19}F reaction channels for NRA purposes

V. Paneta [a,b,*], M. Kokkoris [b], A. Lagoyannis [a], V. Rakopoulos [b]

[a] Tandem Accelerator Laboratory, Institute of Nuclear Physics, N.C.S.R. "Demokritos", Aghia Paraskevi, 15310 Athens, Greece
[b] Department of Physics, National Technical University of Athens, Zografou Campus, 15780 Athens, Greece

ARTICLE INFO

Article history:
Received 9 July 2012
Received in revised form 12 August 2012
Available online 30 August 2012

Keywords:
Differential cross section
Fluorine
Nuclear Reaction Analysis

ABSTRACT

Differential cross-section measurements of the ^{19}F(d,p$_{0-1}$)^{20}F and ^{19}F(d,α_{0-3})^{17}O reactions have been performed in the projectile energy region $E_{d,lab}$ = 1800–3000 keV in steps of 25 keV and for detection angles 150° and 170° using thin LiF and CaF_2 targets. To validate the obtained results, benchmarking measurements were performed, using a CaF_2 pellet and a thick, mirror-polished BaF_2 target at various beam energies. The results are also compared to data from literature, when available, and all the observed discrepancies are discussed.

1. Introduction

The quantitative determination of fluorine in various samples is of great importance for material science as well as for medical, biological and environmental studies. The main problem concerning the depth profiling of ^{19}F is that, since it is highly reactive, it is usually present in relatively complex matrices along with several medium- or high-Z elements. Among Ion Beam Analysis (IBA) methods, Elastic Backscattering Spectroscopy (EBS) and Nuclear Reaction Analysis (NRA) can quantify the abundance of individual light isotopes in complex samples, and can simultaneously provide depth profiling data. Particle Induced Gamma-ray Emission (PIGE) can provide the most accurate quantitative depth profiling data. PIGE is generally considered as the most appropriate IBA technique for the determination of fluorine profile concentrations, due to the existence of several, narrow and strong resonances [1,2] in the p + ^{19}F system (e.g. the relatively narrow, Γ = 4.5 keV resonance at E_p = 872.11 keV of the ^{19}F(p,$\alpha\gamma$)^{16}O reaction, or the strong resonance of the ^{19}F(p,pγ) reaction at E_p = 197 keV). Pioneer works in PIGE with deuterons as the probing beam also exist in the literature [3,4]. It has to be noted, however, that PIGE measurements are quite time-consuming, isotope-specific, and they require the use of HPGe detectors. As far as NRA is concerned, ^{19}F(α,p)^{22}Ne (Q = 1673 keV, [5–9]) and ^{19}F(p,α)^{16}O (Q = 8114 keV) reactions have been successfully employed in the past for fluorine depth profiling. A list of relevant works concerning the latter reaction, along with EBS references, has recently been published [10]. Alternatively, one can employ the ^{19}F(d,p)^{20}F (Q = 4377 keV) or the ^{19}F(d,α)^{17}O (Q = 10032 keV) reactions. d-NRA (i.e. NRA with deuterons as the probing beam), despite the generally lower depth resolution with respect to PIGE, presents distinct advantages such as: a) the simultaneous excitation of most light elements (e.g. B, O, N, C, F, Al, Mg and S) usually co–existing in complex matrices, either as main constituents or as impurities, and (b) the enhanced sensitivity and accuracy, mainly due to the generally large cross sections of the deuteron-induced nuclear reactions. These advantages are, of course, offered at the expense of background interference in certain cases (e.g. peak overlaps, 3-body reaction kinematics). Also, certain radiation safety precautions are mandatory due to the emitted neutrons from (d,n) reactions (on the target elements and structural materials), and/or deuteron breakup (for deuteron beam energies above 2.2 MeV). As far as d-NRA is concerned, differential cross-section data for the ^{19}F(d,α_0)^{17}O, ^{19}F(d,p$_0$)^{20}F and ^{19}F(d,p$_1$)^{20}F reactions have been reported in literature [11–13] in the past.

Nevertheless, the existing d-NRA differential cross-section datasets, necessary for the accurate determination of fluorine depth profiles are unfortunately inadequate and discrepant in many cases, thus limiting the applicability of the technique. More specifically, previous studies of the ^{19}F(d,p)^{20}F and ^{19}F(d,α)^{17}O reactions, that have been performed within the energy range E_d = 800–2500 keV for the former reaction [11] and within the energy range E_d = 710–2500 keV for the latter one [12,13] for only one backward angle at 150°, differ not only in the order of magnitude of the determined absolute differential cross-section values, but also in the shape of the corresponding excitation functions.

* Corresponding author at: Tandem Accelerator Laboratory, Institute of Nuclear Physics, N.C.S.R. "Demokritos", Aghia Paraskevi, 15310 Athens, Greece.
E-mail address: vpaneta@inp.demokritos.gr (V. Paneta).

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http://dx.doi.org/10.1016/j.nimb.2012.08.015

The present study aims at contributing in this field, by resolving the discrepancies of the previous studies of the d + ^{19}F reaction channels and by adding new differential cross-section data in literature. In the present work, differential cross sections of the first two proton groups of the ^{19}F(d,p)^{20}F reaction and of the first four groups of α-particle emission of the ^{19}F(d,α)^{17}O reaction were measured. The reactions have been studied in the deuteron energy range of 1800–3000 keV in steps of 25 keV for the detection angles of 150° and 170°. The obtained data were validated through benchmarking experiments using a CaF_2 pellet and a thick, mirror-polished BaF_2 target and are also compared to existing data from literature, when present.

2. Experimental setup and 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 $E_{d,lab}$ = 1800–3000 keV in steps of 25 keV were led to a cylindrical scattering chamber of medium dimensions (R ~ 20 cm). The energy of the deuteron beam entering the scattering chamber was determined by nuclear magnetic resonance measurements (NMR) with an estimated ripple of ~0.12–0.16%, as verified by the 991.89 keV resonance of the ^{27}Al(p,γ)^{28}Si reaction at the beginning and at the end of the experiment, using a HPGe detector (of 80% relative efficiency). The excellent linearity of the magnet for the energy range under investigation has been examined in the past by implementing the ^{16}O(d,n)^{17}F reaction ($E_{threshold}$ = 1829 keV) and the strong and narrow resonances of the ^{32}S(p,p′)^{32}S reaction up to ~4 MeV. The reported deuteron energy, for each measurement, corresponds to the half of the target's thickness (according to the usual convention), after its proper correction according to the results of the accelerator calibration. The energy loss and the energy straggling in the target in all cases were calculated using the computer code SRIM 2012 [14].

The deuteron beam was collimated to a ~2 × 2 mm^2 spot onto the target, while the vacuum was kept constant at ~5 × 10^{-7} Torr. The beam's current on the target did not exceed 60 nA during all measurements, in order to avoid any possible deterioration of the fluorine concentration, through excessive heating. For the differential cross-section measurements two thin targets were used, a well-characterized, isotopically enriched LiF target (^{6}Li enrichment 94%) and a CaF_2 one, which enabled us to resolve ambiguities, when peak overlaps in the d + ^{6}Li and d + ^{19}F exit channels appeared in the spectra. The LiF target used, consisted of a thin carbon foil of 52 ± 2 μg/cm^2 thickness, a LiF layer of (1017 ± 40)×10^{15} at/cm^2, that was evaporated onto the carbon foil and additionally of a thin gold layer of (61 ± 4)×10^{15} at/cm^2, that was evaporated onto the LiF layer. The CaF_2 target was produced in the same way as the LiF one. More specifically, a CaF_2 layer of (875 ± 35)×10^{15} at/cm^2 was evaporated onto a similar carbon foil and then additionally a similar gold layer was evaporated onto the CaF_2 layer. The gold layer on both targets was used for protection against wear and humidity absorption and for the indirect determination of the (Q∗Ω) product as well, since the scattered deuterons from gold follow Rutherford's formula for the deuteron energy range studied. Thus, differential cross sections could be measured relatively to the Rutherford differential cross sections for ^{197}Au(d,d$_0$)^{197}Au, as described in the following paragraph. The thickness of the gold layer was determined by performing X–ray Fluorescence (XRF) analysis using the in-house developed portable XRF setup of the Institute of Nuclear Physics of NCSR "Demokritos", while the thickness of the LiF and the CaF_2 layer was determined with additional measurements with accelerated protons at 1600 keV. Then, the thickness of fluorine was estimated with the use of the evaluated differential cross sections from SigmaCalc calculations [15] for proton elastic scattering on ^{19}F, which is described in detail in [10].

The detection system consisted of two silicon surface barrier (SSB) detectors (thickness of 1000 μm) placed at a distance of ~7 cm from the target, at 150° and 170°, along with the corresponding electronics. The spectra from both detectors were simultaneously recorded for each energy step. No absorber foils were placed in front of the detectors, whereas the angular uncertainty was reduced to ~ ± 1°, with the use of orthogonal slits (~4 × 8 mm^2) in front of the detectors.

A CaF_2 pellet and a thick, commercial and mirror-polished BaF_2 target were used for the validation of the obtained differential cross sections. The SIMNRA code [16] was used for the simulation

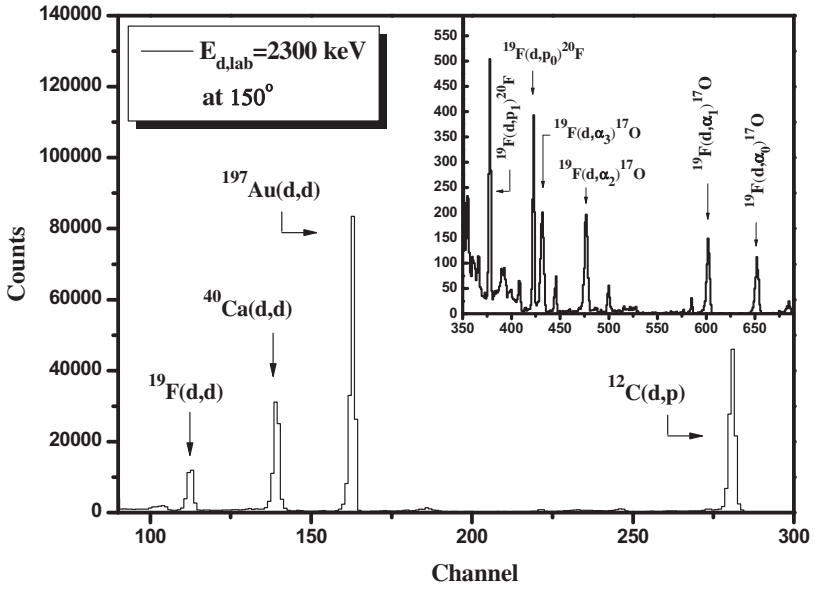

Fig. 1. Typical experimental spectrum of the thin CaF_2 target, taken at 150° and for $E_{d,lab}$ = 2300 keV, along with the corresponding peak identification. The high energy part of the spectrum is presented in detail in the inset.