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Measurement of proton inelastic scattering cross sections on fluorine

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ABSTRACT

Differential cross-sections for proton inelastic scattering on fluorine, $^{19}F(p,p')^{19}F$, from the first five excited levels of ^{19}F at 110, 197, 1346, 1459 and 1554 keV were measured for beam energies from 3 to 7 MeV at a scattering angle of 150° using a LiF thin target (50 μg/cm^2) evaporated on a self-supporting C thin film (30 μg/cm^2). Absolute differential cross-sections were calculated with a method not dependent on the absolute values of collected beam charge and detector solid angle. The validity of the measured inelastic scattering cross sections was then tested by successfully reproducing EBS spectra collected from a thick Teflon (CF_2) target. As a practical application of these measured inelastic scattering cross sections in elastic backscattering spectroscopy (EBS), the feasibility of quantitative light element (C, N and O) analysis in aerosol particulate matter samples collected on Teflon by EBS measurements and spectra simulation is demonstrated.

1. Introduction

The knowledge of the cross sections for the inelastic scattering of MeV energy protons on nuclei with low lying nuclear levels (from a few to several hundreds of keV) can be important when performing quantitative analysis of thick multielemental samples with the elastic backscattering spectrometry (EBS) technique to efficiently disentangle overlapping shapes in the spectra due to both elastic and inelastic peaks. In particular, the knowledge of the proton inelastic scattering on fluorine, $^{19}F(p,p_1)^{19}F$ and $^{19}F(p,p_2)^{19}F$, from the first two excited levels of ^{19}F at 110 and 197 keV, respectively, is indeed crucial for reliable EBS analyses of samples containing also nitrogen and oxygen other than fluorine; in fact, the energy of protons elastically backscattered by N and O at the typically used angles between 150° and 170° and for some proton energy ranges is very close to the energy of p_1 and p_2 protons. Thus, given the finite energy resolution of the particle detection systems, the signals are actually undistinguishable and mistakes might happen. A similar situation happens when considering the $^{19}F(p,p_3)^{19}F$, $^{19}F(p,p_4)^{19}F$ and $^{19}F(p,p_5)^{19}F$ inelastic scatterings, from the third to fifth excited levels of ^{19}F at 1346, 1459 and 1554 keV, in the presence of lithium in the sample. In addition, neglecting the presence of the inelastic peaks of fluorine may induce the IBA practitioner to erroneously consider the presence of nitrogen and oxygen in samples where these elements are absent, such as Teflon (CF_2), in order to achieve a simulation of an EBS spectrum, but inferring a wrong sample composition at the same time [1].

Moreover, the lack of inelastic scattering cross sections restricts the direct analysis of fluorine in thick samples by proton EBS up to a depth from the surface corresponding to an energy window of less than 100 keV, thus hampering the large probing depth that, in principle, can be achieved by using proton beams of increasing energy, for instance greater than 3 MeV.

Whereas several papers have been published on the high energy proton elastic scattering on fluorine [2–7], also in recent years to meet the increasing demand of experimental values of elastic backscattering cross sections of high energy protons on light nuclei [8], only a few papers dealing with the inelastic scattering cross sections are presently available in the literature. In the 1970s, Thompson et al. [2] measured the cross section of the $^{19}F(p,p_2)^{19}F$ reaction at 90° in the laboratory frame of reference and in the proton energy interval between 5.5 and 6.8 MeV, while Kuan et al. [3] obtained the (p,p_1), (p,p_3), (p,p_4) and (p,p_5) inelastic scattering cross sections from 5.8 to 5.9 MeV proton energy at a laboratory angle of 168°. Then, in the 1980s, Ouichaoui et al. [4] measured the (p,p_1), (p,p_2), (p,p_3) and (p,p_4) inelastic scattering cross sections from 2.70 to 2.99 MeV proton energy at laboratory angles of 158.3°, 144.6°, 122.3°, 94.65° and 66.8°.

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In order to provide basic data for practical applications of backscattering spectroscopy with high energy protons in fluorine analysis, this paper presents the measurements of the inelastic scattering cross sections for the reactions $^{19}F(p,p_{1,2,3,4,5})^{19}F$, i.e. from the first five excited levels of ^{19}F at 110, 197, 1346, 1459 and 1554 keV, in the proton energy range 3.0–7.0 MeV, at an angle of 150° in the laboratory frame of reference.

2. Experimental

The inelastic scattering cross sections were measured at the 5 MV HVEE Tandetron accelerator of the Centro de Micro-Analisis de Materiales (CMAM) in Madrid (Spain) under the same experimental conditions described in the work of Caciolli et al. [6]. Actually the new cross-section data presented here are obtained from the re-analysis of the particle spectra that led to the previous publication of only the (p,p_0) elastic scattering data in Ref. [6]. Here we only remind that the measurements were carried out in the proton energy range from 3 to 7 MeV, at 25 keV energy steps, using a multilayered C/LiF/Au sample made of a thin LiF film (about 50 μg/cm^2) evaporated on a self-supporting C target (about 30 μg/cm^2) and further coated with a thin Au layer (about 20 μg/cm^2) for beam dose normalization purposes. Proton beam currents were in the range 10–40 nA and each measurement lasted typically 600 or 1200 s. The accelerator energy was calibrated by using resonances in alpha article scattering from ^{12}C, ^{14}N, ^{16}O and ^{28}Si and in the (p, γ) reaction on ^{27}Al [9], and after the calibration the bombarding energy is known to better than 0.1%.

The scattered protons were detected by a silicon surface barrier detector (~12 keV FWHM energy resolution) positioned at 150° and subtending a 2.51 msr solid angle. As an example, in Fig. 1 a proton scattering spectrum collected at 3.80 MeV is shown.

3. Data analysis and results

The absolute differential cross-section values for the $^{19}F(p,p_i)^{19}F$ inelastic scattering reactions (i = 1–5) at proton energy E and at the scattering angle of 150°, $(d\sigma/d\Omega)_{inel}(E)$, were calculated with a method not dependent on the absolute values of collected beam charge and detector solid angle; this method is based on the normalization to Rutherford backscattering from the Au layer, according to the following equation:

$$(d\sigma/d\Omega)_{inel}(E) = (d\sigma/d\Omega)_{R,Au}(E_{Au}) \cdot (A_{inel}/A_{Au}) \cdot (Nt_{Au}/Nt_F)$$

where $(d\sigma/d\Omega)_{R,Au}(E_{Au})$ is the proton Rutherford cross-section from Au at the energy E_{Au} (in the energy region of the present experiment the backscattering of protons on Au nuclei is purely Coulomb and the electron screening effect is negligible); A_{inel} and A_{Au} are the areas of the i-th proton inelastic scattering peak on fluorine and of the proton elastic scattering peak on gold, respectively, obtained from a backscattering spectrum; Nt_{Au} and Nt_F are the area density of gold and fluorine in the sample as obtained by 1.8 MeV alpha particle RBS measurements of the sample [6]. Mean proton energies, E_{Au} and E, in Au and LiF targets respectively were calculated taking into account the energy loss in the different layers; since the energy straggling is negligible its effect on the accuracy of cross-section measurements has not been accounted for.

The uncertainty in the inelastic scattering cross sections is estimated to be around 6–10%, taking into account the counting statistics and the peak area determination of A_{inel} and A_{Au} (overall 5–10%), the Rutherford cross-section on Au (1%, from the uncertainties in the proton beam energy and in the particle detector scattering angle) and the systematic error in determining the Nt_{Au}/Nt_F atomic ratio (1%).

When the inelastic scattering peak is partially overlapped with other interfering reaction or elastic peaks due to other target elements, namely from $^7Li(p,p)^7Li$, $^7Li(p,p_1)^7Li$, $^{16}O(p,p)^{16}O$ (oxygen comes from the LiF oxidation layer) and $^{19}F(p,\alpha')^{19}F$, as in the example shown in Fig. 1 for the $^{19}F(p,p_1)^{19}F$ peak, the area of interest is determined by fitting with gaussian functions with fixed FWHM. In case where the deconvolution by fit can not be achieved due to the almost complete overlapping, the inelastic peak area is obtained subtracting from the total peak area the interfering peak area calculated as follows. First a constant concentration of the interfering element is assumed (such hypothesis, especially for the oxygen content, has been indeed verified by repetition of measurements at the same beam energy). Then considering that the relevant cross sections for the reactions on the interfering elements as available from IBANDL [10] are loosely varying with the proton energy and no resonances appear over the limited energy range where peaks overlapping occurs, the variation of the interfering peak yield (e.g. counts per number of incident protons that, with the used normalization procedure, is expressed actually as counts per Au peak area and per squared proton energy) with the proton beam energy, $Y_{interf.el}(E)$, can been approximated by a linear or polynomial fit. Finally the interfering peak area has been calculated from the interfering element yield obtained interpolating the yield values at lower and higher proton beam energies where no overlapping occurs using the linear or polynomial equation mentioned above, according to the following formula:

$$A_{inel}(E) = A_{tot}(E) - Y_{interf.el}(E) \cdot (E^2_{Au}/A_{Au}(E_{Au}))$$

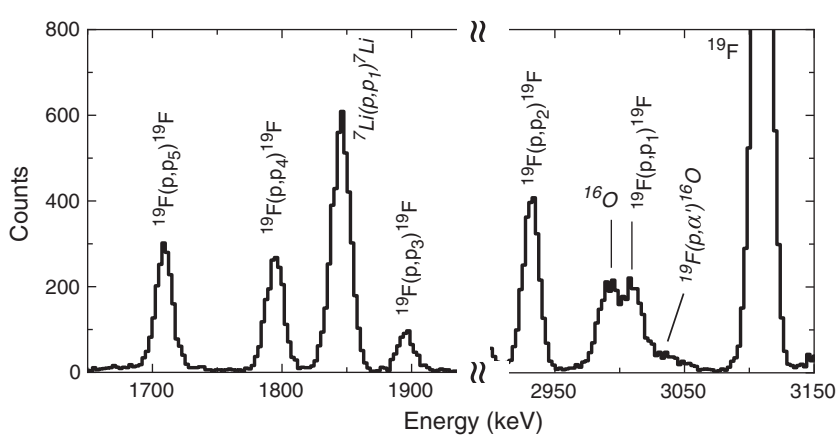

Fig. 1. Details of the proton scattering spectrum (only the regions around the inelastic scattering peaks are shown) obtained at 150° scattering angle by bombarding the C/LiF/Au target with 3.80 MeV protons. The peaks labelled by the isotope name only refer to the elastic scattering.