Proton elastic scattering cross-sections on F, C and Li from 3 to 7 MeV

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Proton elastic scattering and proton induced γ-ray emission cross-sections on Na from 2 to 5 MeV

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Abstract

Differential cross-sections for proton elastic scattering on sodium and for γ-ray emission from the reactions ^{23}Na(p,p′γ)^{23}Na ($E_\gamma = 440$ keV and $E_\gamma = 1636$ keV) and ^{23}Na(p,α′γ)^{20}Ne ($E_\gamma = 1634$ keV) were measured for proton energies from 2.2 to 5.2 MeV using a 63 μg/cm^2 NaBr target evaporated on a self-supporting thin C film.

The γ-rays were detected by a 38% relative efficiency Ge detector placed at an angle of 135° with respect to the beam direction, while the backscattered protons were collected by a Si surface barrier detector placed at a scattering angle of 150°. Absolute differential cross-sections were obtained with an overall uncertainty estimated to be better than ±6.0% for elastic scattering and ±12% for γ-ray emission, at all the beam energies.

To provide a convincing test of the overall validity of the measured elastic scattering cross-section, thick target benchmark experiments at several proton energies are presented.

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Keywords: Cross-sections; Elastic scattering; PIGE; Proton; Sodium

1. Introduction

Elastic backscattering (BS) and particle induced γ-ray emission (PIGE) techniques with MeV energy proton beams have been extensively used for the analysis of light elements in the materials, both because of large probing depths and high cross-sections due to the nuclear component of the interaction. For the quantitative determination of light elements in the sample, reliable values of the cross-sections for elastic scattering and prompt γ-ray emission have to be known.

Among the light elements, sodium is important for material, earth and environmental sciences, and cultural heritage as well, being a component of glass, minerals, sea spray aerosol particles and pigments. Very few data of interest for application of proton elastic backscattering analysis on sodium were found in the literature and in nuclear databases [1–4]; moreover, all data appear in graphical form in the original references and are anyway limited to 3.5 MeV proton energy. The ^{23}Na(p,p′γ)^{23}Na and ^{23}Na(p,α′γ)^{20}Ne reactions, yielding suitable prompt γ-rays of 440, 1634 and 1636 keV, have been studied in the past in the proton energy range 1.0–4.5 MeV [5–8], but no absolute cross-section data were given, apart in the work from Mateus et al. [8] which is anyway limited to 2.4 MeV proton energy.

Therefore, in this paper we studied the differential cross-sections for proton elastic scattering and proton induced γ-ray emission reactions on sodium in the energy region from 2 to 5 MeV, with the aim of providing basic data for practical applications of BS and PIGE to sodium analysis.

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2. Experimental

The experimental work was conducted at the 5 MV Tandetron accelerator at the CMAM (Centro de Microanálisis de Materiales) in Madrid [9]. The measurements were performed at proton energies from 2.2 to 5.2 MeV with steps ranging from 20 to 5 keV. The accelerator energy was calibrated by using resonances in alpha particle elastic scattering from ^{12}C, ^{14}N, ^{16}O and ^{28}Si and in the (p,γ) reaction on ^{27}Al; after the calibration the bombarding energy is known to better than ±0.1% [10]. The proton beam entered the target chamber after being collimated to dimensions of $2.0 \times 2.0\ \mathrm{mm}^2$ by two sets of rectangular slits located at 0.7 m and 2.7 m upstream from the target.

The target consisted in a 63 μg/cm^2 NaBr film evaporated on a self-supporting thin C foil (about 30 μg/cm^2); the proton energy loss in the NaBr film ranged from about 5 to 3 keV.

The elastic backscattered protons were measured by a silicon surface barrier detector (50 mm^2 area, 500 μm thickness and 12 keV FWHM energy resolution) placed at a laboratory angle of 150°, subtending a solid angle of 2.51 ± 0.04 msr defined by a rectangular collimator placed at 82.8 mm from the target; the spread in the scattering angle due to beam size on the target and detector finite aperture was 1.2°.

The γ-radiation was detected by a 61.0 mm × 61.5 mm Ge detector connected to the vacuum of the target chamber, placed at an angle of 135° to the beam axis, 207.5 mm distant from the target and subtending an angle of about 17°. The nominal efficiency and resolution of the detector are 38% and 2.0 keV for 1.33 MeV, respectively.

The current traversing the target was collected in a Faraday cup biased at +190 V, strongly inhibiting the escape of secondary electrons. During the measurements proton beam currents were in the range 20–40 nA, depending on beam energy, in order to keep the count rate low enough to reduce pile-up effects. Dead time corrections were always less than 5% for the γ-ray detector, whereas they were negligible for the particle detector (<0.5%). Each measurement was allowed to continue until obtaining at least 2000 counts in all the elastic scattering and γ-ray peaks.

3. Data analysis and results

At beam energies for which the elastic scattering of protons from Br is Rutherford, the absolute differential cross-section values for elastic scattering at an angle θ, $(\frac{d\sigma}{d\Omega})_{el}(E,\theta)$, and for γ-ray emission at an angle φ, $(\frac{d\sigma}{d\Omega})_{\gamma}(E,\varphi)$, were deduced from the following equations, adopting a procedure not relying on the knowledge of the absolute number of incident protons and the target thickness:

$$\left(\frac{d\sigma}{d\Omega}\right)_{el}(E,\theta) = \left(\frac{d\sigma}{d\Omega}\right)_{R,\,Br}(E,\theta)\cdot\frac{A_{Na}}{A_{Br}}\cdot\frac{1}{r}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\gamma}(E,\varphi) = \left(\frac{d\sigma}{d\Omega}\right)_{R,\,Br}(E,\theta)\cdot\frac{A_{\gamma}}{A_{Br}}\cdot\frac{\Delta\Omega_p}{\Delta\Omega_\gamma\varepsilon_\gamma}\cdot\frac{1}{r}$$

where $(\frac{d\sigma}{d\Omega})_{R,\,Br}(E,\theta)$ is the proton Rutherford cross-section from Br at the mean energy E in the target and scattering angle θ; A_{Na}, A_{Br}, and A_γ are the areas of the proton elastic scattering peaks on sodium and bromine, and the area of the detected γ-ray coming from Na obtained, respectively, from scattered protons and γ-radiation spectra collected simultaneously (see Fig. 1); $\Delta\Omega_\gamma$ and ε_γ are the solid angle and the efficiency of the γ detector, respectively; r is the stoichiometric ratio between the number of Na and Br nuclei in target; $\Delta\Omega_p$ is the solid angle of the particle detector.

Since at incident beam energies higher than 3.0 MeV the p + Br elastic scattering cross-section can not be safely considered Rutherford anymore [11], in this energy range the absolute differential cross-section values were then obtained from the following equations:

$$\left(\frac{d\sigma}{d\Omega}\right)_{el}(E,\theta) = A_{Na}\cdot\frac{1}{\Delta\Omega_p}\cdot\frac{1}{(Nt)_{Na}}\cdot\frac{1}{N_p}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\gamma}(E,\varphi) = A_{\gamma}\cdot\frac{1}{\Delta\Omega_\gamma\varepsilon_\gamma}\cdot\frac{1}{(Nt)_{Na}}\cdot\frac{1}{N_p}$$

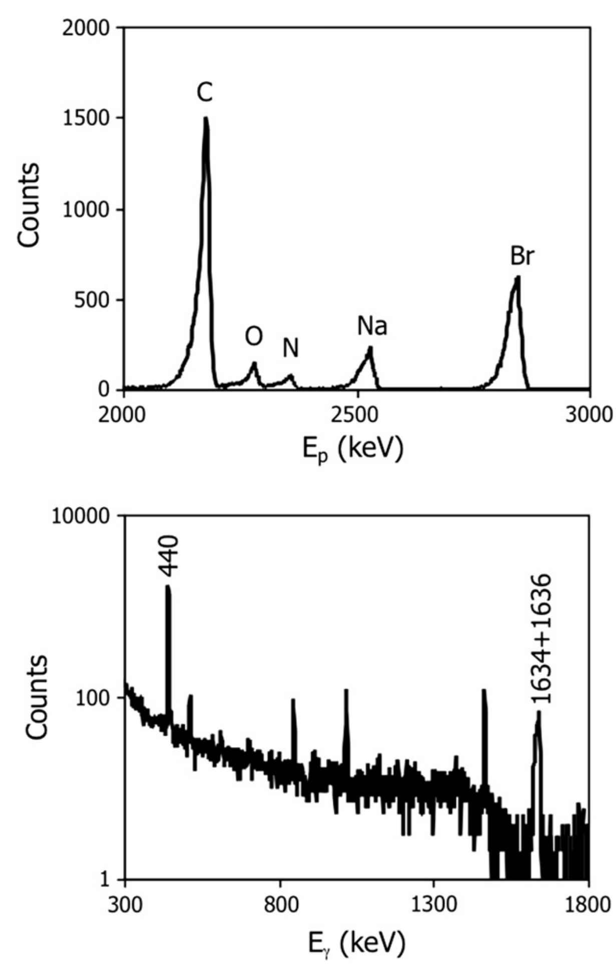

Fig. 1. Proton scattering spectrum obtained at $\theta = 150°$ (top) and γ-radiation spectrum collected at $\phi = 135°$ (bottom) by bombarding the NaBr/C target with 3008 keV protons. Both spectra were collected simultaneously.

where $(Nt)_{Na}$ is the areal density of Na nuclei in the target and N_p is the number of incident protons.

The peak areas have been obtained by fitting with Gaussian functions; the asymmetrical shape of the elastic scattering peaks has been reproduced by a Gaussian function plus an exponential curve connected to its left-hand tail.

The stoichiometric ratio r and the areal density $(Nt)_{Na}$ have been measured by RBS with 2.0 and 2.8 MeV alpha particles, at 150° (the Rutherford scattering cross-sections used here have been corrected for electron screening effect [12]). The target stability was verified by repeating these measurements several times during the runs and no changes (i.e. carbon build-up or selective loss of elements) were observed. Also, reproducibility checks at the same proton energies were performed periodically and the results were always in agreement within the statistical uncertainty.

The product of the γ detector solid angle and efficiency – the absolute efficiency – was determined by means of the relative yields of several γ-ray lines from ^{133}Ba, ^{54}Mn and ^{22}Na radioactive sources (energies between 81 keV and 1.27 MeV) calibrated in activity with an uncertainty of ±5%, placed at the target position. The absolute efficiency of the detector was then obtained from a fit to the experimental points with a three parameter function, $a_2E_\gamma^{-2} + a_1E_\gamma^{-1} + a_0$.

The contributions to the uncertainty in the absolute differential cross-section values are reported in Table 1. By adding the systematic contributions to the statistical errors from the peak areas, it can be estimated an overall uncertainty better than ±6.0% for the elastic scattering, and ±9% and ±12% for the 440 keV and the 1634–1636 keV γ-ray emissions, respectively, at all the beam energies.

The measured differential cross-sections for the p + Na elastic scattering is plotted in Fig. 2; also shown for comparison is the corresponding Rutherford cross-section. No other elastic scattering data are available in similar energy or angular range for direct comparison with the present data.

In Fig. 3 we show the differential cross-sections for the 440 keV radiation and the combined effect of 1634 and 1636 keV γ-rays produced in the ^{23}Na(p,α′γ)^{20}Ne and ^{23}Na(p,p′γ_{2-1})^{23}Na reactions – they were not completely resolved, hence they were summed together. Assuming an isotropic angular distribution of the 440 keV radiation [13], the total cross-section data from Mateus et al. [8] have been scaled down by a factor 4π and compared to our data: in the off resonance regions their values are about 25% greater than ours and the two resonances at 2.285 and 2.339 MeV are better reproduced, since finer energy steps and a thinner target were employed in Mateus' work.

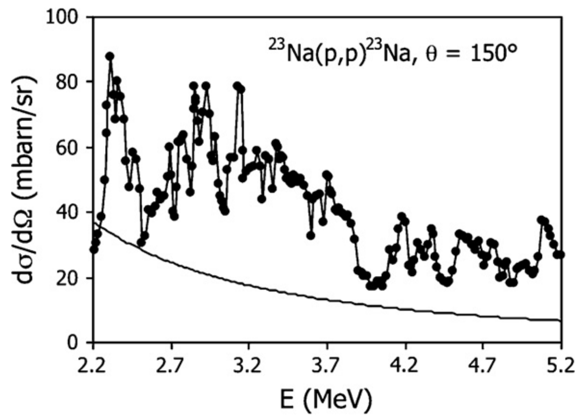

Fig. 2. Differential cross-section values of proton elastic scattering on ^{23}Na as a function of proton energy, at a laboratory scattering angle of 150°. The line represents the Rutherford cross-section.

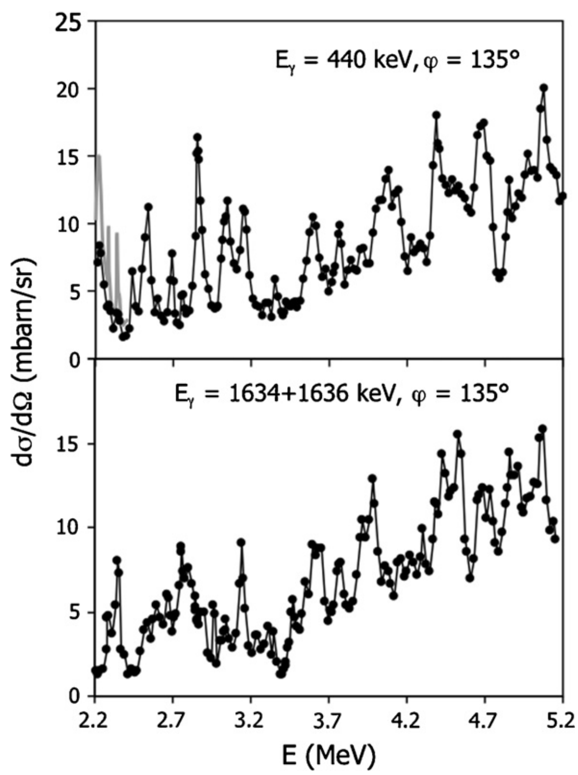

Fig. 3. Differential cross-sections values for the production of 440 keV γ-ray from the ^{23}Na(p,p′γ)^{23}Na reaction (top), and 1634 and 1636 keV γ-rays from the reactions ^{23}Na(p,α′γ)^{20}Ne and ^{23}Na(p,p′γ_{2-1})^{23}Na, respectively (bottom), as a function of proton energy, at a laboratory angle of 135°. The grey line represent the ^{23}Na(p,p′γ)^{23}Na cross-section data from Mateus et al. [8].

Table 1
Estimated uncertainties affecting the absolute differential cross-section values (1 standard deviation)

Quantity	Uncertainty
Elastic scattering peak area, A_{Na}, A_{Br}	<1.0%
γ-radiation peak area, A_γ	<2.0%
p + Br Rutherford cross-section, $(\frac{d\sigma}{d\Omega})_{R,\,Br}$	1.1%
Stoichiometric ratio, r	2.0%
Na areal density, $(Nt)_{Na}$	5.0%
Particle detector solid angle, $\Delta\Omega_p$	1.6%
γ-ray detector absolute efficiency, $\Delta\Omega_\gamma\varepsilon_\gamma$	6.5% @ 440 keV 10% @ 1636 keV
Number of incident protons, N_p	1.0%

Both elastic scattering and γ-ray emission cross-sections are characterised by many resonances and structures, corresponding to the levels of the compound nucleus ^{24}Mg [13]. Obviously, due to the finite steps of the measurements, often exceeding the proton energy loss in the target, some resonances might not be well reproduced.

The present data are available from the authors upon request; the whole data set will be anyway uploaded in the IBANDL nuclear database from IAEA [1], for practical use in ion beam analysis by BS and PIGE with protons.

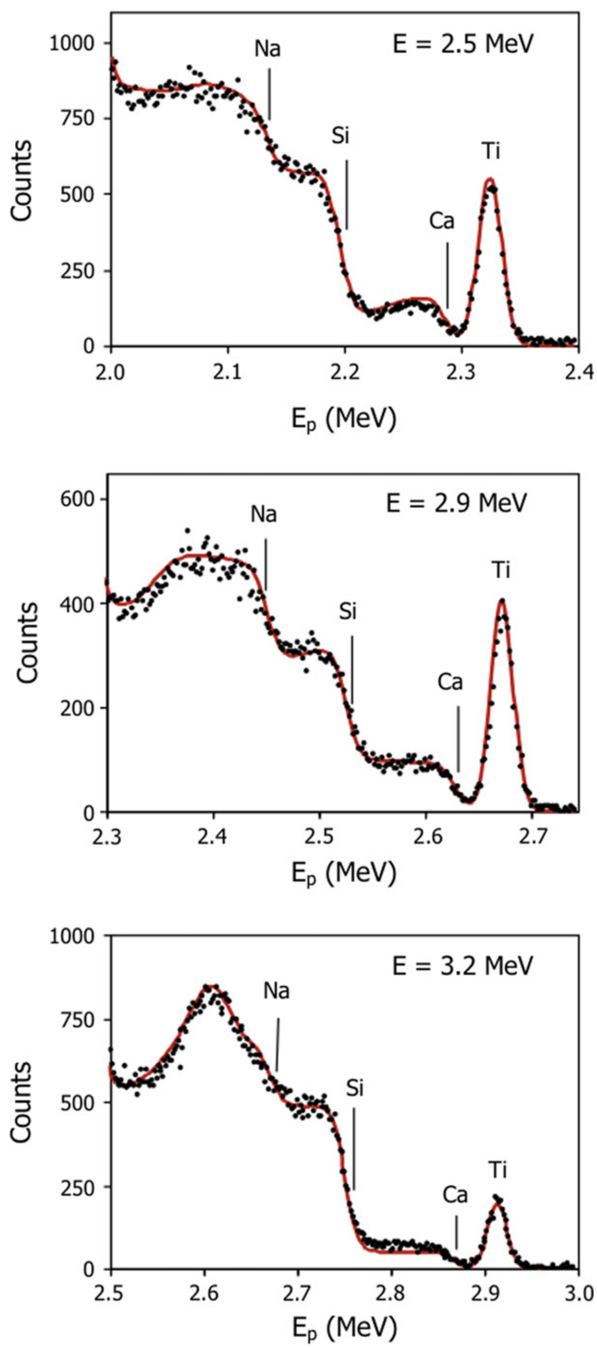

Fig. 4. Backscattering spectra of protons on a Au/Ti/glass sample containing Na together with SIMNRA simulations for several proton energies, at a scattering angle of 150°. The O and Au signals are not shown purposely to better detail the spectra region around Na signal.

4. Benchmark experiment

To provide a convincing test of the overall validity of the measured elastic scattering cross-section, thick target benchmark experiments at several proton energies were performed. The measurements were carried out at the 3 MV Tandetron accelerator of INFN-LABEC laboratory in Florence, using a scattering chamber [14] equipped with a silicon PIN diode detector (300 μm thickness, 100 mm^2 area and 17 keV FWHM energy resolution) placed at 150° scattering angle, 61 mm apart from the sample and subtending a 4.3 msr solid angle. The target was a commercial glass sample (Ca 4%, Si 30%, Na 11%, O 55%), coated with evaporated thin Ti (75 nm) and Au (145 nm) layers, the latter for dose normalisation; the target composition was determined by RBS analysis with 2.0 MeV alpha particles. For the benchmark experiments proton beams of 2.5, 2.9 and 3.2 MeV energy were used, with intensities of 5 nA and the measurements lasted 600–900 s.

The experimental backscattering spectra together with SIMNRA simulations [15] obtained using SRIM 2003 stopping powers [16] and the measured p + Na elastic scattering cross-section, as well as the available non-Rutherford cross-sections for the elastic scattering of protons on the other target elements [17–20], are shown in Fig. 4. The overall agreement is good (although some discrepancies occur for Ca signal at 3.2 MeV proton energy due to the lack of non-Rutherford cross-section values in this energy range), assuring the reliability of the measured p + Na elastic scattering cross-section data.

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