A proposal about Rutherford Backscattering Spectrometry for a second level master in physics education

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1 Introduction

Most of the techniques for material science are based on quantum mechanics, since matter is studied in terms of interactions with its microscopic components (e.g. atoms, nucleuses and electrons) or aggregates of them (e.g. crystals, phonons). However, due to the strong orientation of the techniques to gain qualitative or quantitative information (doing measurements), they are often interpreted according to semi-classical or classical models (e.g. the effective mass for conduction of a charged particle, the electron gas in a metal, the phonon as a harmonic oscillator). In this sense, the analysis techniques can be introduced in physics education as a bridge between classical physics and quantum mechanics with its applications. Rutheford Backscattering Spectrometry (RBS) is an analysis technique largely used in material science [1] and it constitutes a candidate technique for secondary school level or university students.

The didactical proposal presented below follows our previous experience and research works about the introduction of the analysis techniques into the curriculum of secondary school [2-6] and benefits from our direct involvement in the use of RBS for condensed matter analyses. The aim of the activity is to enable students to deal with simple, not trivial, RBS spectra and to discuss them in an appropriate scientific language. The materials were prepared for a course of the second level master in modern physics "Innovazione Didattica in Fisica e Orientamento" (Didactic Innovation in Physics and Orientation) for teacher training [7].

2 The course structure and contents

The first part of the course, given in distance mode through an appropriate web platform, is sectioned into three periods: introduction to the basic concepts of the technique, analysis and discussion of RBS spectra, and project of didactical paths. In the first period the master students are invited to read two documents about the basic concepts of RBS [3, 4] and discuss them in forum both from disciplinary and from didactical point of view. In the second period they have to solve two tests, the first consisting in the interpretation of elementary RBS spectra, the other proposing more complex ones. In both tests the students have to motivate their choices and can discuss together through web forums. In the last period they are invited singularly to prepare a didactical path aimed at allowing secondary school students to understand the bases of RBS and to interpret elementary non trivial spectra.

After the distance part, the course comprises a didactical part during a one week workshop in presence which was carried out coinciding with a summer school with 50 secondary school students selected by profit within the entire nation.

In the following, the basic concepts as proposed in the first period of the course are synthetically reported and the didactical path proposed in the workshop and experimented with the summer school students is described.

3 The basic concepts of RBS

RBS provides information about the depth distribution of the constituent elements of the first hundreds of nanometers of a sample. It consists in sending a monoenergetic (some MeV) light ion beam (H^+ or He^{++}) towards the sample and measuring number and energy of the ions backscattered along a certain (Fig.1a). Due to the order of magnitude of the energy employed, the process can be considered, with fair approximation, a scattering between unscreened nucleuses and understood in terms of elastic collisions between charged point masses (Fig. 1b). For a didactical approach, the main concepts necessary to interpret a RBS spectrum can be reduced into three main and separate basic topics.

Kinematic factor K, which answers the question: what is the energy of an ion after an elastic collision with a heavier nucleus? Or else, conversely, how can the mass of a target element be evaluated from a measure of the energy of the backscatterd ions? This factor is independent of the beam energy and can be classically calculated imposing the conservation of kinetic energy and momentum. A full expression, according to the geometry of Fig. 1b, can be:

$$K_{M_2} = \frac{E_1}{E_0} = \left(\frac{M_1 \cos\theta + \sqrt{M_2^2 - M_1^2 \sin^2\theta}}{M_1 + M_2} \right)^2 \quad (1)$$

which reduces to

$$K_{M_2} \approx \left(\frac{M_2 - M_1}{M_2 + M_1} \right)^2 \quad (2)$$

in the case of $\theta \to \pi$ which is the condition of maximum mass resolution.

Scattering cross section σ, which answers the question: what is the probability that an incident ion hits the nucleus of a certain element of the sample and be sent along a certain scattering direction? Or else, conversely, haw can the abundance of an element in the sample be evaluated from the fraction of scattered ions? An expression of the scattering cross section is that attributed to Rutherford:

$$\sigma = \left(\frac{Z_1 Z_2 e^2}{4E} \right)^2 \frac{4}{\sin^4 \frac{\theta}{2}} \frac{\left(\sqrt{1 - \left(\frac{M_1}{M_2} \sin\theta \right)^2} + \cos\theta \right)^2}{\sqrt{1 - \left(\frac{M_1}{M_2} \sin\theta \right)^2}} \quad (3)$$

which reduces to

$$\sigma \approx \left(\frac{Z_1 Z_2 e^2}{4E} \right)^2 \left(1 - \left(\frac{M_1}{M_2} \right)^2 \right)^2 \quad (4)$$

in the case of $\theta \to \pi$.

Stopping cross section ε, which answers the question: what is the average energy loss of the ion if the collision occurs under the surface of the sample? Or else, conversely, how can the in-depth distribution of an element be obtained from the energy spectrum of the scatted ions? The stopping cross section is the superposition of the contributions of various microscopic phenomena and the choice operated in the research is to use experimental curves of energy loss per unit depth *dE/dx* of each element, normalized to the atomic density *N*, as a function of the ion energy:

$$\varepsilon(E) = \frac{1}{N}\frac{dE}{dx}(E) \qquad (5)$$

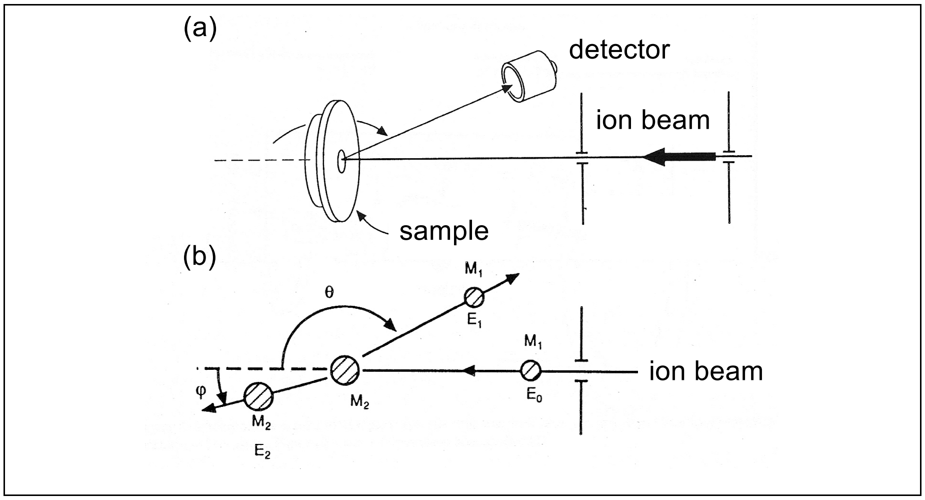

Figure. 1. a) experimental setup in the scattering chamber of a RBS measurement; b) equivalent physical model in a classical mechanics framework.

4 The didactical path

This proposal originates from this approach and relies on these three basic concepts integrating theoretical and experimental activities. It is composed of five phases.

Approach to the technique (1 hour). With the aid of a slide presentation, a picture of how the technique is applied and of the experimental facilities needed is provided, and subsequently the problem of interpreting a RBS spectrum is proposed. At this stage, only the concepts of kinetic factor and scattering cross section are presented.

Experimental and theoretical involvement with kinematic factor and scattering cross section (1 hour). The students, divided in groups of 5 people each, perform various activities in parallel. The first activity insists in the direct experience of the factors and conditions that are involved in the kinematic factor using as a model for the collision between the ion and the target atom two trucks made to collide on a 2 m rail. The students measure the velocities of the projectile truck before and after the collision as a function of the mass of the target truck by means of an on-line measurement system. Thanks to this activity the students can observe that the kinetic factor does not depend on the initial velocity of the projectile and is a monotonic increasing function of the target mass. The second activity consists in the direct experience of the meaning of cross section using as a model for the interaction between the ion and the target atom a small marble made to bounce against a wooden form (available shapes: scalene triangles, circles and ellipses). The students make various throws of the marble with parallel initial trajectories, distant less than the diameter of the marble itself, and construct a histogram of the directions (scattering angles) of the marble after bouncing against the form. Thanks to this activity the students can reflect upon the meaning of cross section as a statistical quantity and can observe that the histogram contains the information on the shape of the form and consequently on the kind of the interaction that occurs. The last activity is the theoretical calculation of the kinematic factor by imposing the conservation of kinetic energy and of momentum in the case of backscattering or in the more general case of Fig. 1b.

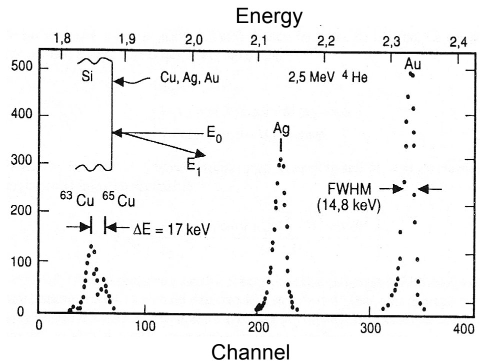

Figure 2a. Backattering yield of a monoatomic layer of Cu, Ag and Au atoms on a Si substrate. Beam energy: 2.5 MeV, scattering angle 170°.

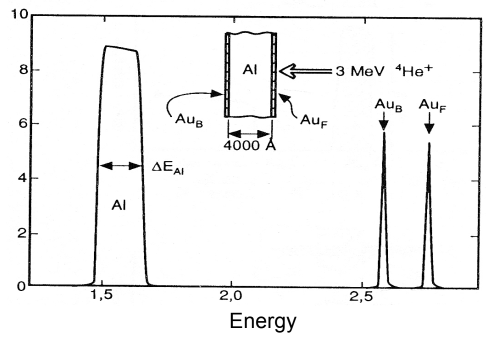

Figure 2b. Backattering yield of a 40 nm Al film with monoatomic layers of Au at the two sides. Beam energy: 3.0 MeV, scattering angle 170°.

Discussion of the results obtained by the various groups and introduction of the scattering and stopping cross sections (30 minutes). The students, during a guided plenary session, present and discuss their results. They observe that backscattering occurs only if the target is heavier than the projectile and that the kinetic factor does non depend on the initial velocity (and energy) of the projectile and is a monotonic increasing function of the target mass. Moreover the students are induced to reflect upon the meaning of a statistical quantity such as the cross section and can observe that the angular distribution of the trajectories after the collision contains the information on the shape of the form and consequently on kind of interaction that occurs.
After the discussion, the mathematical expression of the Rutheford backscattering cross section is presented. In this case it is not necessary that the students calculate it, but it is important, however that they are guided to recognize its behaviour with the target atom mass and the projectile energy. The last concept - stopping cross section - is introduced by recalling the model of sliding friction in mechanics. The similarity is that the stopping cross section ε acts as the friction coefficient and the atomic density N as the normal force between sliding surfaces. Such analogy holds up well in the case of RBS, since the technique is applied to thin film at or near the surface. Especially in this case, where the analytical expression is not available, it is important that the student know the behaviour of the stopping cross section with the target atom mass, that is in general monotonically increasing, with oscillations mostly due to the different electronic density distributions in the various atomic orbitals.
Problem solving (2.5 hours). As a synthesis of the whole information obtained, the two experimental RBS spectra of Fig. 2 are discussed and interpreted (30 minutes).
The first one (Fig. 2a) shows the monotonic character of the kinematic factor and of the scattering cross section with the target mass. The other spectrum (Fig. 2b) shows the influence of the stopping of a 400 nm Al film. Finally, a list of elementary RBS spectra is assigned to the students who are requested to interpret them and to give reasons for their

choices and conclusions in 1 hour. The spectra of two films of elements A and B are given as references, then the list proposes four complex spectra of the two films superimposed with different thicknesses. The activity ends with a plenary discussion of the student results (1 hour).

5 Conclusions

The effort of this work has been oriented to the individuation and the understanding of a minimal set of physical concepts to be presented in an elementary form and, accordingly, to the design of didactical paths for secondary school students.
In the didactical path proposed during the workshop in presence, these concepts have been accompanied by a physical model drawn from classical physics; this ensures to recognize known topics learnt in various physical contexts, to rearrange knowledge, and to experience new contexts of application. The didactical path comprises phases of experimental/practical activities as well as phases of work implying deeper reflection. The entire activity requires 5 hours, which is a sufficient time for introducing well all the physical concepts, but is not exceedingly long, so as to enable the students to follow the whole thread of the topic. As a matter of fact the various concepts are introduced in different ways: practically and in strict analogy with a known physical quantity (stopping cross section), starting from experience (kinematic factor and scattering cross section), theoretically (kinematic factor).

References.

[1] Chu W-K, Mayer J W, Nicolet M-A 1978 *Backscattering Spectrometry* (New York: Academic Press)
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[4] Corni F, Michelini M, Santi L, Soramel F, Stefanel A 1995 *Proc. GIREP (Udine)* p 192
[5] Corni F 2001 *Proc. GIREP (Udine)* p 363
[6] Corni F, Michelini M, 2006 Eur. J. Phys. **27** (2006) 793
[7] Italy's main response to the fall in motivation with regard to scientific studies has been the Progetto Lauree Scientifiche (PLS) (Scientific Degree Project), promoted by the Science Faculties of Italian Universities. Within PLS, 9 Research Units in Physics Education worked to produce the Master "Innovazione Didattica in Fisica e Orientamento" (Master in Didactic Innovation in Physics and Orientation), aimed at the in-service training of teachers on the themes of modern physics, as a result of research carried out in this field.