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## Book of Short Contributions

Editors:

G. Djordjevic, Lj. Nesic and G. Senjanovic

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# Rutherford Backscattering Spectrometry: A Laboratory Didactic Path about the Basic Interpretation Models

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Each time a new physical phenomenon is understood in depth, new techniques of analysis are produced, which employ the fresh knowledge to start new researches in unexplored field. 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. molecules, 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 etc.). In this sense, the analysis techniques can be introduced in physics education as a bridge between classical physics and quantum mechanics with its applications. Moreover, these techniques offer an opportunity to introduce stimulating topics of modern physics which in most cases constitute also a synthesis of various topics traditionally taught in separate contexts (mechanics, thermodynamics, electromagnetism etc).

Rutheford Backscattering Spectrometry (RBS) is an analysis technique largely used in material science [1] and it constitutes a candidate technique for secondary school level students. It can be entirely understood and interpreted in terms of classical models and the teacher is free to deal with each concept also in terms of quantum mechanics. Moreover RBS can be an exciting subject for students since they can feel the experience, as in the research field, of interpreting a spectrum and obtaining structural and elemental information about an actual sample applying physical concepts and models.

The didactic proposal that will be presented follows previous experience and research works about the introduction of the analysis techniques into the curriculum of secondary school [2-8] and benefits from a 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 [9] and, subsequently, employed in various occasions of student involvement in modern physics and hands-on minds-on activities.

**Cultural elements of RBS.**

RBS is a research technique considered to be a fundamental tool for several analyses in several fields of solid state physics [1]. It provides information about the depth distribution of the constituent elements of the first hundreds nanometers of a sample. It consists in sending a mono-energetic (some $MeV$) light ion beam (principally $H^+$ and $He^{++}$) towards the sample and measuring number and energy of the ions backscattered along a certain direction relative to the impinging beam (Fig.1a). A simple calculation shows that the minimum distance reached by a $He^{++}$ ion ($Z = 2$) with energy $E = 2MeV$ in a head-on collision with an $Ag$ atom ($Z = 47$) at rest is smaller than the radius of the inner $Ag$ electrons ($\frac{2Ze^2}{E} = 6.8 \times 10^{-5} nm$ vs. $\frac{a_0}{Z} = 1.1 \times 10^{-3} nm$, with $e$ the elementary and $a_0$ the Bohr radius) indicating that the process can be considered, with fair approximation, a Rutherford scattering between unscreened nucleuses. Therefore, besides the treatment in terms of elementary particle within the framework and the formalism of quantum mechanics, it is almost perfectly equivalent to interpret the process within the classical mechanics in terms of elastic collisions between charged point masses (Fig. 1b).

For a didactical approach, the main concepts needed to interpret a RBS spectrum can be reduced to three main and separate basic ideas. Each one will be introduced as a physical quantity and, at the same time, interpreted as a parameter providing information on the target.

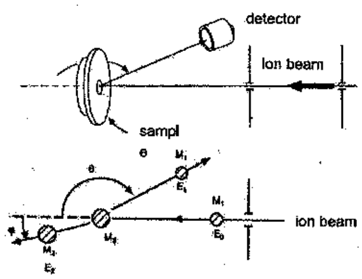


Figure 1: a) experimental setup in the scattering chamber of a RBS measurement; b) equivalent physical model in a classical mechanics framework.

1) *Kinematic factor K*, as answer the following question: what is the energy of an ion after an elastic collision with a heavier nucleus? Or alternatively, how can an observer evaluate the mass of a target element from a measure of the energy of the backscattered ions? This factor is independent of the beam energy (provided that the process remains a Rutherford scattering, and that inelastic events - at too low energy - or nuclear interactions - at too high energy - occur) and can be classically calculated assuming the conservation of kinetic energy and momentum. A full expression, according to the geometry of (Fig. 1b), can be

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

which reduces to $K_{M_2} = \left(\frac{M_2 - M_1}{M_2 + M_1}\right)^2$ in the case of $\theta \to \pi$ which is the condition of maximum mass resolution.

2) *Scattering cross section* $\sigma$, answering to this 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 how can the abundance of an element in the sample be evaluated from the fraction of scattered ions (or its scattering efficiency)? An expression of the scattering cross section, in the same hypotheses of the kinematic factor, is the one attributed to Rutherford:

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

with $\sigma \approx \left(\frac{Z_1 Z_2 e^2}{4E}\right)^2 \left(1 - (\frac{M_1}{M_2})^2\right)^2$ in the case of $\theta \to \pi$.

3) *Stopping cross section* $\varepsilon$, answering the question: what is the average energy loss of the ion due to its penetration into the matter? Or how can the in-depth distribution of an element be obtained from the energy spectrum of the scattered ions? In other words, how can we convert the energy scale of the collected ions after the scattering into a depth scale?

The stopping cross section is the superposition of the contributions of various microscopic phenomena whose efficiency depends on the energy of the ion, therefore various theoretical expression of this quantity can be calculated depending on the mechanism of the energy loss considered relevant according to the ion energy. Due to this difficulty, the choice operated in the research is to use experimental curves of energy loss per unit depth $\frac{dE}{dx}$ measured from pure element targets, normalized to the element atomic density $N$, as a function of the ion energy $\varepsilon(E) = \frac{1}{N}\frac{dE}{dx}(E)$.

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[9] 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 and organised in three areas: mathematics, physics and chemistry. In the field of PLS, 9 Research Units in Physics Education worked together to produce the Master "Innovazione Didattica in Fisica e Orientamento" (IDIFO) (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.