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An undergraduate course in experimental atomic and molecular physics using an accelerator

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Abstract

We describe experiments, performed as a part of a one-semester experimental course, using the NEC 1.7 MV Pelletron electrostatic accelerator, offered to undergraduate students of physics in Rio de Janeiro. Besides the accelerator, the laboratory includes a source of negative ions by cesium sputtering, a Wien filter and a switching magnet. Experiments include principles of PIXE, time-of-flight mass spectrometry and beam attenuation in the accelerator tube.

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Keywords: Accelerators; Teaching

1. Introduction

Atomic and molecular physics have yielded a collection of concepts that have had an important effect on many domains, including economy and health. For instance, today we have many accelerator-based diagnostic techniques and treatment of diseases as such proton therapy. In addition, medical accelerators can induce short-lived radionuclides in components near the beam and in the air. The use of accelerators in research and industry has widened our understanding of many phenomena, as for example, the complex radiation interactions in the atmosphere leading to ozone layer depletion; they are also important tools for the diagnostics and cure of some diseases, for the elemental analysis of materials, etc. Many papers have been published on the uses of accelerators in teaching [1–7].

2. Course description

The course has 3-h of meeting per week. The meetings are divided into lectures (pre-lab) and laboratory work. Adequate material is introduced during the lectures to give students a basis for performing the assigned experiments. The instructor, who is always uncommitted during the laboratory periods, presents a brief description of the tasks so that students are able to complete them accordingly.

Every student is required to compose a detailed written laboratory report on each experiment, accounting for the work, the results and their interpretation of results. Midterm and final examinations are performed, whose main intention is to assess the capability of the students in summarizing and understanding the experiments.

The lectures include sources of radiation, sources of negative and positive ions, elementary accelerator physics, beam optics (electrostatic lenses, velocity, energy and momentum analyzers), and detection systems (faraday cups, channeltrons, surface barrier detectors, photomultipliers). In a preliminary laboratory, the students are introduced to vacuum techniques.

3. Description of the experiments

The laboratory was originally set for basic studies of atomic and molecular collisions, ionization of atoms, fragmentation of molecules and particle-induced X-ray

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analysis. It has a versatile negative-ion source by cesium sputtering and a 5SDH NEC accelerator.

The experiments selected for the lectures ought to be sufficiently simple, so that they can be accomplished within the circumstances of a class which meets for merely 6 h a week, but is complex enough to challenge the students in their experimental work, data analysis, and theoretical analysis. We describe below practices that meet the course boundary conditions.

3.1. Mass spectrometry using a Wiens filter

The velocity selector is a device, where reciprocally perpendicular electric and magnetic fields are produced, also forming a right angle with the ion flight path. There is a specific velocity v at which the ions experience equal but opposite magnetic and electric forces, which then cancel out and consequently allow the ions to travel in a straight line with a constant velocity. In most velocity selectors, the magnetic field is supplied by a pair of permanent magnets and the electric field is produced by a pair of parallel conductors, set apart by a distance d, between which an electric potential difference V is applied. Even in the non-ideal case of conductor lengths and widths not much larger than the distance d, the electric field lines are parallel enough close to their central region. The $E \times B$ velocity selectors allow the mass and charge state separation of ion beams. Charged particles passing through orthogonal electric (E) and magnetic (B) fields are deflected unless their velocity is given by

$$v = \frac{E}{B} \tag{1}$$

or, using the fact that $E = V/d$,

$$v = \frac{V}{Bd}. \tag{2}$$

One can also scan the mass spectrum of ions entering the filter by varying V. Let us assume that all ions possess a kinetic energy K, obtained after being accelerated from rest by an electric potential V_0. When these ions enter the selector, only ions with a well-defined mass-to-charge ratio will be transmitted. The mass of these transmitted ions is

$$m = \frac{2KB^2d^2}{V^2}. \tag{3}$$

Then a plot of the ion's mass as a function of $1/V^2$ is a straight line as shown in Fig. 1.

3.2. Calibration of a switching magnet

The switching magnet selects the momentum of a particle. The deflection of ions in a perpendicular magnetic field is proportional to the particle momentum per unit charge. As the magnetic force is orthogonal to the particle velocity,

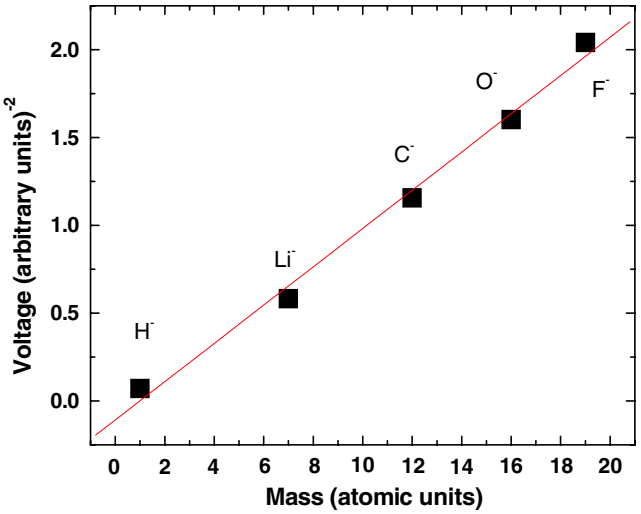

Fig. 1. Mass spectrometry of negative ions from the SNICS source using a Wiens filter.

the velocity module remains constant though its direction changes in response to the sideways deflecting force of the magnetic field. If the particle velocity is v at right angles to B, the particle will experiment a circular movement of radius R at constant speed. The centripetal force mv^2/R is provided by the magnetic force

$$qvB = \frac{mv^2}{R} \tag{4}$$

or, in terms of the particle's kinetic energy

$$B = \sqrt{\frac{mK}{q^2R}}. \tag{5}$$

A plot of the square of the magnetic field as a function of mK/q^2 should then be a straight line, and this is shown to occur in Fig. 2.

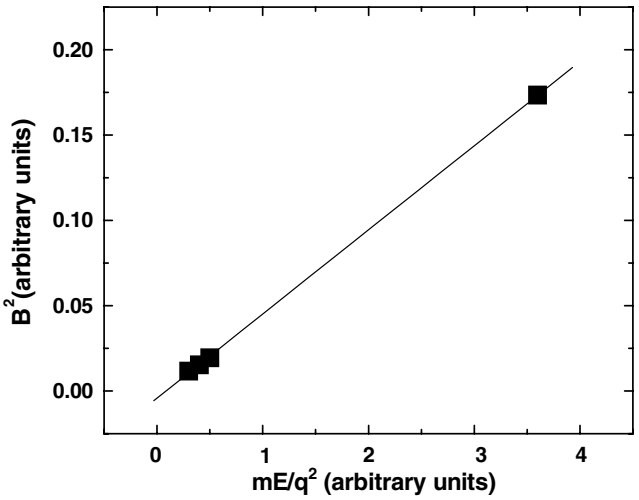

Fig. 2. Calibration of the switching magnet.

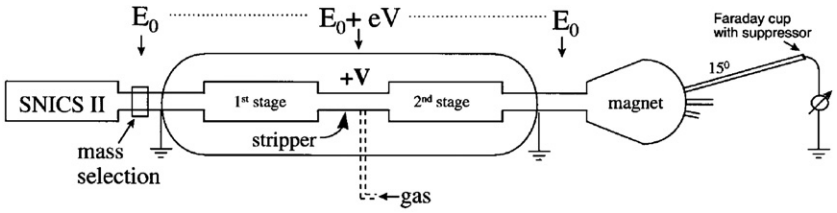

Fig. 3. Schematic diagram of the accelerator.

3.3. Beam attenuation in the accelerator tube

The accelerator has a cylindrical gas stripper 1 cm in diameter and 47 cm in length placed at the high-voltage terminal, between the two accelerator tubes (around 2 m each) (Fig. 3), and pumped by two 500 l/s turbomolecular pumps located at each extremity of the tandem. The stripper gas, N_2, can be fed in from the exterior of the accelerator through an electronically controlled needle valve. We explore the fact that the beam energy is low at the exit of the ion source and at the momentum-analyzing magnet and high at the collision chamber (the tandem gas stripper). The low-energy negative-ion beam from the ion source is first accelerated and then collides with the N_2 gas target. After the collision, the negative-ion beam is decelerated and selected by a magnet. Finally, the attenuated current is measured. The anion beam is attenuated as the pressure in the gas cell is varied (a typical beam attenuation curve is shown in Fig. 4). The measured anion current, I, is plotted against the parameter pressure (P) dependent $\pi(P)$, defined as the product of the gas density in the collision cell and its effective length. The detachment cross-section (σ) is obtained by adjusting an exponential decay function to the attenuated current

$$I = I_0 e^{-\sigma\pi}. \quad (6)$$

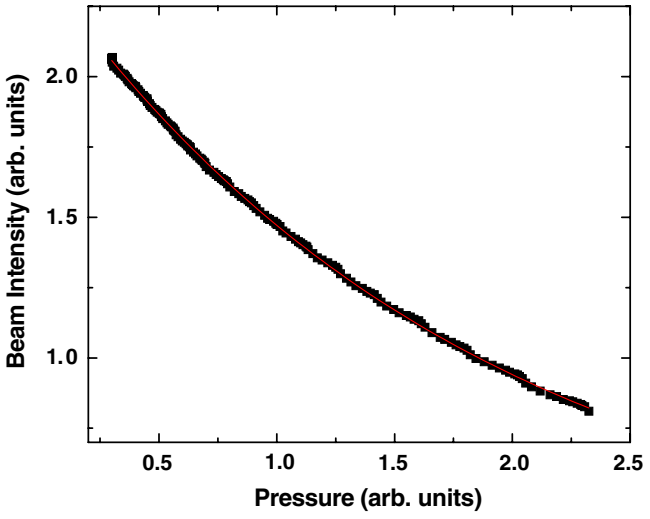

Fig. 4. Typical beam attenuation curve for a 400 keV Cl beam. The solid line is the exponential fit to the data, from which the value of the detachment cross-section is obtained.

A method was developed to obtain $\pi(P)$ from the pressure at the tandem exit, using an auxiliary experiment with an H^- beam and the well known charge-changing cross-sections for hydrogen [8].

3.4. Time-of-flight mass spectrometry

Time-of-flight mass spectrometry is a widely employed method to acquire information about the structures of molecules. This technique is brought in this course as a practice that focuses on the identification of the molecular ion from experimental data. After correctly identifying the atomic or molecular ion, the students ascertain other information that can be deduced from the molecular ion.

Students are given a pre-laboratory lecture on the radiation interactions with matter and mass spectrometry relevant to this experiment. Due to time and space limitations, the students are usually divided in two groups of five students (ten is a typical number of students attending this course per semester).

A tightly collimated monoenergetic proton beam with energies around a few MeV or less is delivered by a 1.7 MV Tandem accelerator. The beam is charge analyzed by an electric field placed just before crossing, at right angles, an effusive jet of the sample molecules. The emergent beam is recorded by a channeltron detector house in a detection chamber downstream of the gas cell. The atomic and molecular ion fragments ejected due to the interaction with the incident beam are accelerated by a two-stage electric field and detected by another channeltron detector. The time-of-flight spectrometer, running in the coincidence mode, is started by the detection of the proton beam and stopped by the ionic fragments. The experimentally obtained mass spectra are calibrated using a rare gas target and compared to those available at the National Institute of Standards and Technology (NIST) Web Book [9]. Fig. 5 shows a mass spectra of the formic acid molecule by a 2.0 MeV proton impact.

3.5. PIXE

The technique of particle-induced X-ray emission (PIXE) analysis has become a well-developed analytical tool [6]. The accelerator's external-PIXE beam line, in which protons are extracted into air, after crossing a thin aluminum window, is employed in this experiment. Students are given a pre-laboratory lecture on the radiation

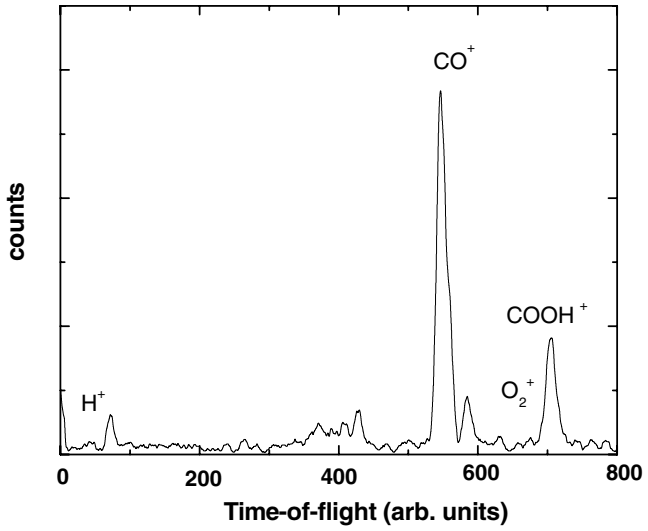

Fig. 5. A time-of-flight mass spectra of formic acid ionized a by 2.0 MeV p^+ impact.

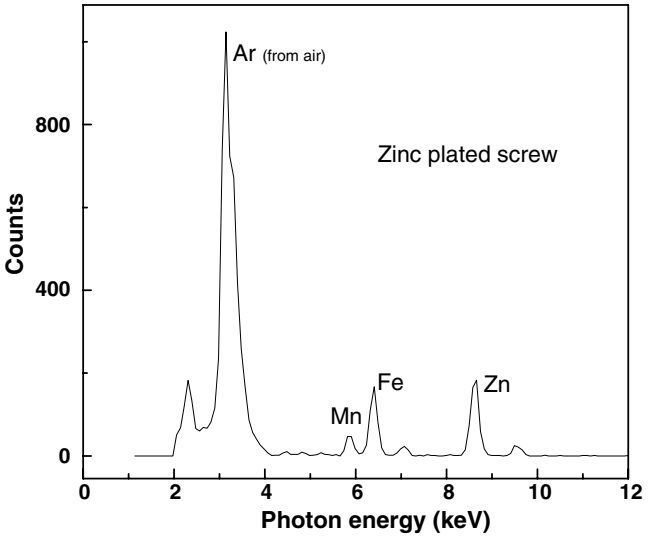

Fig. 6. PIXE spectrum of a zinc plated screw.

interactions, which are able to create atomic inner-shell vacancies, and the relaxation processes which follow them – Auger electron emission, and characteristic X-rays fluorescence. In the PIXE technique, the characteristic X-rays are measured and used to determine the elemental composition of a sample. Students use a Si-PIN photon detector, associated electronics and a multi-channel analyzer (MCA) card inserted in an ordinary micro-computer. Samples of different materials are exposed to the proton beam and their X-rays spectra shown on screen, using the MCA software. Students learn how to perform a preliminary energy calibration of the spectra, using IAEA (International Atomic Energy Agency) radioactive sources, and then identify the unknown sample elements through their tabulated characteristic X-rays energies. Fig. 6 shows a PIXE spectrum of a zinc plated screw induced by a 2.0 MeV proton beam.

4. Summary

The atomic physics group of the Federal University of Rio de Janeiro has developed an accelerator-based undergraduate course in atomic and molecular physics using a 1.7 MV Pelletron accelerator. To the authors knowledge, there is no other similar course in the South Hemisphere. This course is an attempt to avoid the common, and in our view mistaken trend, of highly structured experimental classes where the students are not exposed to the techniques in a hands-on approach. Some students point out how uninteresting the extremely structured laboratories are – to the authors this seems to be one of the major reasons for them decide to for a career in theoretical work.

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