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Physics education using beams of ions and electrons

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ABSTRACT

Physics education and public outreach are becoming increasingly important in the activities of physics departments in universities and research centers. In this contribution, we would like to illustrate some didactic paths focused on Ion and electron beam technologies, developed in our research group to create connections with nearby secondary schools. These didactic paths connect curricular topics, like for example the motion of charged particles within electric and magnetic fields, with the production and the use of beams of ions and electrons in several branches of both basic and applied research.

1. Introduction

The involvement in science education in schools, and more generally the interaction with the public, is becoming increasingly important in the ordinary activities of universities and research centers. Research scientists are nowadays aware of the need and advantages of these activities, to improve scientific literacy and trust of science and to increase the workforce in scientific disciplines [1–6]. Universities' educational programs toward high schools have been institutionalized. In Italy for example the "Piano Nazionale Lauree Scientifiche" (PNLS -National Plan for Scientific Degrees) is an initiative of the Italian Ministry of Education, University and Research (MIUR) aiming at establishing collaboration at the local level between schools and universities in educational activities for pupils and of professional development for schoolteachers [7,8]. Also the National Institute for Nuclear Physics (INFN) developed several third mission initiatives, such as Lab2Go, an activity specifically devoted to the recovery of scientific instruments of school laboratories (https://web.infn.it/lab2go/). In the following, we would like to illustrate the physics education activities with ion and electron beams, that have been developed within the context of both the PNLS and Lab2Go in collaboration between our research group on ion-surface interactions and some schools of the region of Calabria.

The interaction of energetic charged particles with matter is the basic process for many fields of basic and applied research, such as nanotechnology, plasma physics, spectroscopy and microscopy of surfaces and nanomaterials, medicine (hadron therapy), and the space research. Educational activities about this physics are therefore well suited to introduce secondary school pupils to topics of active scientific research which are of actual societal relevance. At the same time, the activities are particularly suited for students in the last three years of the secondary school curriculum (age 16–19) because the use of beams of ions and electrons can connect to topics of the school program like, for example, the motion of charged particles in electric and magnetic fields or the basic of quantum mechanics.

The activities we are going to discuss are part of a more extended program aiming at a large involvement of research scientists from our department in physics education activities with schools. The program aimed at recovering disused, and in several cases ancient, instrumentation in laboratories of some schools in the region of Calabria [9–11]. The didactic paths are conceived as work-based learning experiences for the school pupils [9,10]. These experiences are compulsory for all Italian students in the last three years of the secondary education cycle. Work-based learning entails non-formal experiences integrated within the curricular (formal) program and performed in collaboration with an enterprise or an organization, like for example a physics department in a university, for which it is included within its third mission programs. In this sense, these didactic paths are part of our local project within the PNLS. More recently the activity has been included also within Lab2Go. The use of old instruments allows presenting the topics from a historical point of view, which has several advantages in physics education, as pointed out by recent research [12–15]. Here, we present those didactic paths related to the physics of ion and electron beams, to discuss the advantages of this physics in science education and to give ideas of how academic and research groups active in these fields can perform physics education in collaboration with secondary schools.

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2. The project

After the university researchers and the school teachers have identified the instruments in the school laboratories, and these have been eventually restored by the technician of our physics department, the project entails didactic paths comprising of small teaching- learning-sequences [16] of 3–4 units, for a total of about 12–16 h for a group of about 20–30 pupils for each school. One of the goal of the project is a large involvement of researchers, with particular attention to the youngest ones, who are still poorly involved in these activities [4,5]. For this reason, most of the involved researchers are early career scientists (graduate students and post-docs) [9,17]. Along each didactic path the group of school pupils can interact with three or four researchers, and the whole project involved about twenty researcher. The involvement of a large number of researchers ensures a regular turnover, so that this additional work load is not detrimental of their scientific activities.

The first units of the path are performed formally within the regular classes attended by the students and is included in the curricular program. According to the defined path, in this phase pupils study with their teachers topics like the motion of charged particles in electric and magnetic fields, atomic spectra and the Bohr model of the atom or the classical physics of two body collisions. The second phase is the experiment in the lab, both at school and at the university. In many cases we have found both old and recent versions of the same experiment. The more recent versions are generally easier to use and constructed so that the experiment cannot fail. On the other hand, the success of the experiments in our experience is not so straightforward with old instruments. In many cases, the instruments worked, but not properly so that the whole activity resulted in finding suitable conditions for their operation. This situation appears more interesting from the educational and pedagogical point of view because it led the activity toward important conceptual questions about the scientific method, such as the reliability of the data produced during the experiment, the individuation and control of the relevant variables, reproducibility, errors. Moreover, this situation provided opportunities for active and cooperative learning for the pupils, that created a communal learning environment and a peer to peer interaction among all the involved actors, researchers, teachers and pupils [9].

The last phase entails visits at the research laboratories of the university, to observe the application of the physics studied during the path to current research [18–20].

The paths have been designed specifically for each school, depending on the instruments found in the school laboratory. Nevertheless, many instruments are common among many schools and in the following we describe some of the thematic paths that have been developed with these instruments, specifically those related to the importance of electrons and ion beams in both the history of physics and in current basic and applied research.

3. Didactic paths

Fig. 1-3 show discharge tubes dating back to different periods that have been found in most of the schools involved in the project. These are glass tubes of various dimensions and shapes, partially evacuated and with two metal electrodes. When a voltage of some kV is applied between the electrodes, a glow is observed in the walls of the glass tube. The light is produced by rays emanating from the cathode, as revealed by the shadow observed after a Malta Cross placed in front of the cathode (Fig. 1), so that they were called Cathode rays. The tubes are generally called Crookes Tubes, after the English scientist William Crookes who studied the deflection of cathode rays in magnetic fields in 1879. But it was not until 1897 that cathode rays were individuated as electrons in a series of famous experiments by J.J. Thomson [21] who studied the behavior of the cathode rays in uniform electric and magnetic fields. The Thomson experiments can be repeated with the tubes shown in Fig. 2. The tube in Fig. 2a allows the cathode rays to be directed between two metallic parallel plates among which is applied a voltage so that the rays are deflected as revealed by the spot that is produced when they hit the luminescent screen. The rays are deflected toward the positively charged plate, revealing the negative charge of the cathode rays. The setup allows also demonstrating that the deflection is proportional to the voltage applied to the plates and measuring the charge to mass ratio of the electron. Thus, beside the discovery of the electron, the tubes are well suited to study the parabolic motion of a material point. Most of these old tubes are not in line with current safety regulations, because of several factors such as their fragility, the generation of X-rays etc, but there are modern replicas commercially available, such as the tubes in Fig. 2b and Fig. 2c.

Fig. 3 shows a tube similar to that used by Goldstein in 1886, which lead to the discovery of what were called Canal rays. The cathode in this tube is perforated (see Fig. 3a), so that, when a voltage of several kV is applied between the anode and the cathode, luminous rays are seen extending behind the cathode, starting from the channel in the cathode, the reason why they were called channel or canal rays. A series of later experiments performed by W. Wien and J.J. Thomson made clear that canal rays were positively charged, as they deflected toward the

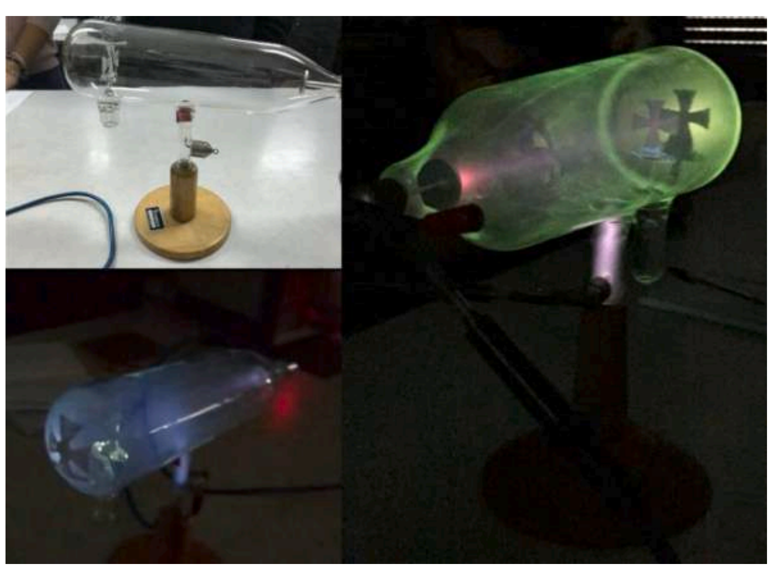

Fig. 1. Some Maltese cross Crookes Tubes. The color of the glow is due to the different glasses.

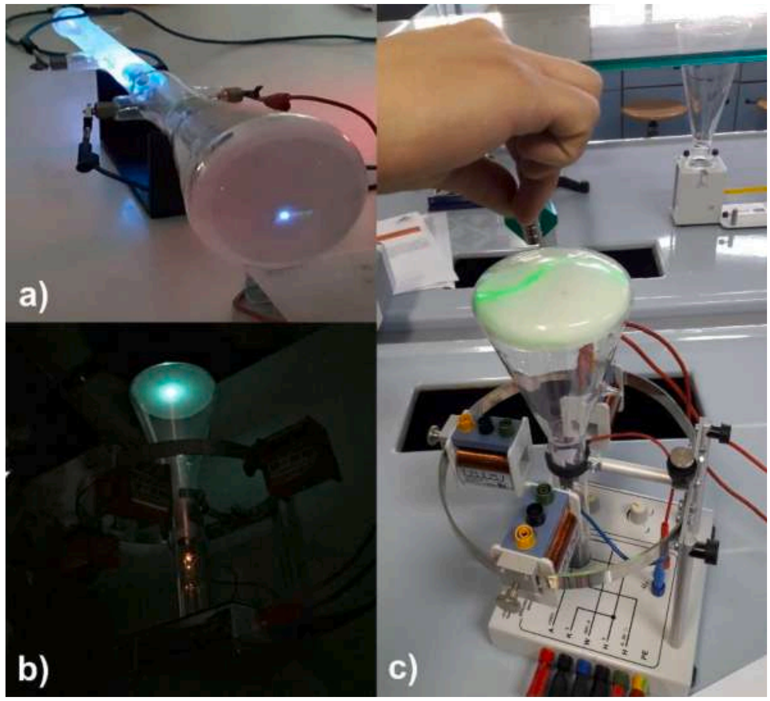

Fig. 2. Some Braun tube that allow studying the behavior of cathode rays in uniform electric and magnetic fields.

Fig. 3. A Canal rays tube. Notice the perforated cathode in the middle of the tube.

negative electrode when passing through parallel plates. Unlike cathode rays, the charge to mass ratio for canal rays depended on the gas species in the tube, being the largest for hydrogen. This led to the discovery of the proton and it is the basic idea of the development of mass spectrometry in the subsequent two or three decades [22].

This experimental part, mostly related to the history of physics and to curricular school topics, is followed by a visit to university laboratories. At university, students have first the occasion to perform experiments with the didactic vacuum system in Fig. 4a, to familiarize with modern vacuum equipment. The system is also equipped with an electron gun, that allow students to produce a beam and measure the current on a metal sample mounted on the manipulator. The main part of the trip to university is a visit to research laboratories where students can observe how the physics of ions and electrons is applied to current research topics. For example the chamber in Fig. 4b is one of the most used with schools. The chamber dates back to the '70s and is equipped with both an ion and an electron gun and two electrostatic analyzer for ion and electron spectroscopy. In Fig. 4b it is evident the old ion gun (Atomika-A-Dida) that dates back to the '70s. The ion gun it is still working and used for studies of ion and electron spectroscopy of surfaces [19].

With this chamber, we organized spectroscopy workshops for the school students. Since it is not possible to perform real hands-on activities with equipment that, though old, are still used for research, these workshops have been performed under the strict guidance of the

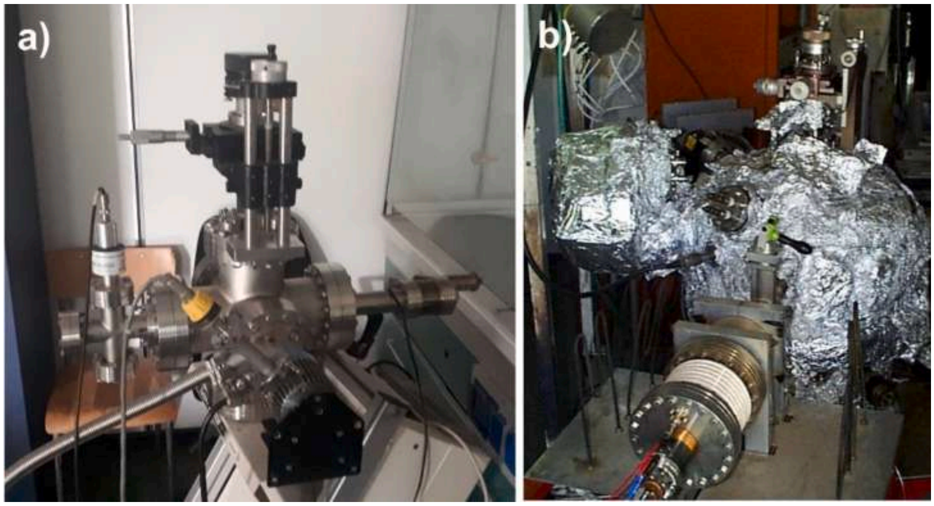

Fig. 4. a) Didactic vacuum chamber; b) an old UHV chamber at the physics department of University of Calabria. Notice the ion gun and the Hemispherical Electrostatic Analyzer (HEA).

university staff, while students were mostly observer. This activity however allows students to connect the physics classes and the experiments they had performed during the didactic path with the production and the use of ion and electron beams in current research performed at university. The ion gun in Fig. 4b allows to show the production of a beam of noble gas ions, through the ionization of the gas by the impact of electrons (produced by the current flowing in a Tungsten filament) accelerated by a discharge voltage of some tenth of an eV. The beam is accelerated up to 15 keV and focused into a Faraday cup situated in the sample position. The Faraday cup and the sample are mounted on a manipulator with five degrees of freedoom, three translational and two rotational. The interaction of the beam with the sample results in the emission of electrons, ions and photons. The chamber is equipped with two hemispherical energy analyzer (HEA) for the spectroscopic detection of both positive and negative charged particles. One of these HEA is mounted externally, while the second with small angular acceptance for angle-resolved studies, is mounted on a goniometer inside the chamber. Students can therefore observe the acquisition of electron and ion spectra and can discuss with researchers the identification of phenomena occurred during the interaction of the ion beam with the surface through their characteristic spectral signatures. Even more important, the interaction with the researchers give also the opportunity to discuss the motivation, the applications and the societal implications of the research.

In this way, starting from the study of curricular topics of the school programs, school students' reflections are guided to the issue of acceptable methods of knowledge production through the direct application of the experimental methods in cooperation with their teachers and with university researchers. The interaction with researchers allow also to further connect the didactic activity to actual research topics and their societal implications.

4. Conclusions

The activity with schools we have discussed shows how the physics of ion beams can allow for a close connection of actual research topics with school curricula, the history of physics and with every-day life. The activities provide an example of a physics education activity that favor a large involvement of researchers, mostly young ones, in a collaborative interaction with school teachers and pupils. The activities can be easily adapted and replicated and we judge they can be of interest for many ion beam laboratories in research centers and universities worldwide, to respond to the increasing demand of interaction of research environments with schools and the general public.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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