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Energy calibration of a small accelerator using proton induced X-ray emission and ion backscattering

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ABSTRACT. A new method for the energy calibration of a small accelerator (producing proton beams with energies below 1 MeV) is presented. The procedure makes use of proton induced X-ray emission (PIXE) and backscattering of the proton beam impinging on thin film standards, and is based on the energy dependence of X-ray production cross sections. A comparison with the energy calibration obtained through the nuclear resonance $^{19}F(p,\alpha\gamma)^{16}O$ is carried out, and it is found that the agreement between both methods is fair.

RESUMEN. Se presenta un nuevo método para calibrar en energía a un acelerador pequeño (que produzca haces de protones con energías menores de 1 MeV). El procedimiento hace uso de la emisión de rayos X inducidos por protones (PIXE) y la retrodispersión de los protones del haz que inciden sobre películas delgadas patrones. El método se basa en la dependencia de la sección de producción de rayos X con la energía de los protones incidentes. Se realiza una comparación con la calibración en energía obtenida por medio de la resonancia nuclear $^{19}F(p,\alpha\gamma)^{16}O$ y se encuentra que hay una concordancia aceptable entre los dos métodos.

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1. INTRODUCTION

The increasing importance of particle accelerators in many fields [1] has created a need for accurate and simple methods for their beam energy calibrations. By far, the most common method used is the detection of nuclear resonances with different projectile-target combinations, occurring at very well determined ion-beam energies [2]. However, in several instances the application of this method is difficult, due to limitations in the experimental set-up. Because of this, procedures based on phenomena different to nuclear resonances have been developed in order to determine the beam energy [3–5]. The better knowledge of the ionization cross sections of atoms by proton impact gained during the last years [6] allows its use in the energy calibration. In this paper, a new method for small accelerator energy calibration is introduced, founded on the energy dependence of X-ray production cross sections by proton impact. Also the development of new small X-ray detectors that can be used in many kinds of experimental arrangements, will support the use of the proposed method.

2. METHOD

When a proton beam of energy E impinges on a thin uniform film of thickness Nt, in units of atoms/area, the number $N_{\rm X}$ of X-ray photons from a particular line reaching a detector with absolute efficiency ϵ is given by [7]

$$N_{\rm X} = Q\epsilon\sigma_{\rm X}(E)\,Nt, \tag{1}$$

where Q is the total number of protons hitting the target, and $\sigma_{\rm X}(E)$ is the X-ray production cross section, which is a function of the incident proton energy E. Because the charge collection is usually difficult to measure accurately, the backscattered protons are used in order to eliminate the quantity Q. The number $N_{\rm R}$ of protons backscattered by the film, impinging on a particle detector is [8]:

$$N_{\rm R} = \Omega_{\rm R} Q\sigma_{\rm R}(E)Nt, \tag{2}$$

in which $\Omega_{\rm R}$ is the detector solid angle, and $\sigma_{\rm R}(E)$ is the well known Rutherford's scattering cross section [8]. Using Eqs. (1) and (2), it is possible to obtain for $N_{\rm X}$:

$$N_{\rm X} = \epsilon\frac{N_{\rm R}\sigma_{\rm X}(E)}{\Omega_{\rm R}\sigma_{\rm R}(E)}. \tag{3}$$

Now, if films of two different elements, labeled A and B, are irradiated, the ratio of the number photons in an X-ray line from A, to those produced by element B is, from Eq. (3),

$$\frac{N_{\rm X,A}}{N_{\rm X,B}} = \frac{\epsilon_{\rm A} N_{\rm R,A}\sigma_{\rm X,A}\sigma_{\rm R,B}}{\epsilon_{\rm B} N_{\rm R,B}\sigma_{\rm X,B}\sigma_{\rm R,A}}, \tag{4}$$

where the subscripts A and B refer to the respective element.

Multiplying both sides by $(N_{\rm R,B}/N_{\rm R,A})(\epsilon_{\rm B}/\epsilon_{\rm A})$, the result is

$$\frac{N_{\rm X,A}N_{\rm R,B}\epsilon_{\rm B}}{N_{\rm X,B}N_{\rm R,A}\epsilon_{\rm A}} = \frac{\sigma_{\rm X,A}\sigma_{\rm R,B}}{\sigma_{\rm X,B}\sigma_{\rm R,A}}. \tag{5}$$

Moreover, looking at the dependence of $\sigma_{\rm R}(E)$ with proton energy, projectile and target masses and atomic numbers, and scattering angle, it is possible to approximate the ratio $\sigma_{\rm R,A}(E)/\sigma_{\rm R,B}(E)$ with a high degree of accuracy as $(Z_{\rm A}/Z_{\rm B})^2$. Thus, the final expression is

$$\frac{N_{\rm X,A}N_{\rm R,B}\epsilon_{\rm B}}{N_{\rm X,B}N_{\rm R,A}\epsilon_{\rm A}} = \frac{\sigma_{\rm X,A}Z_{\rm B}^2}{\sigma_{\rm X,B}Z_{\rm A}^2}. \tag{6}$$

The left hand side contains quantities that can be obtained experimentally, while the right hand one contains terms known from theory or tables. Comparing the ratio obtained experimentally with the right side of Eq. (6) the proton beam energy can be determined. In order to apply this method the use of the K_α X-ray lines is recommended because their

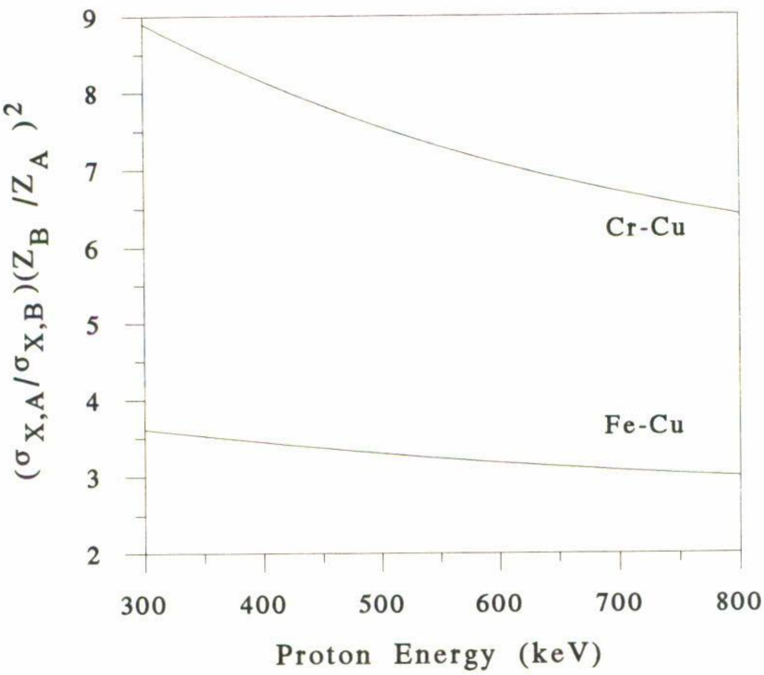

FIGURE 1. The ratio of Eq. (5) (right hand side) as a function of the proton beam incident energy, for two combinations of elemental films, Cr-Cu and Fe-Cu.

production cross sections are well determined with uncertainties below 5% [6]. Also, this method is better if the proton energy is lower than 1 MeV, because the X-Ray production cross sections varies strongly with the energy. The X-Ray production cross sections for the K_α lines are determined by the relation $\sigma_X(E) = \sigma_I(E)w_K f_\alpha$, where $\sigma_I(E)$ is the ionization cross section of the K shell, w_K is the fluorescence of the K shell and f_α is the K_β/K_α branching ratio. Figure 1 shows the behavior of the second term as a function of proton energy, for two combinations of targets A and B, namely Cr-Cu and Cu-Fe, and for the K_α lines of each element. The curves were computed using the X-ray ionization cross sections presented by Paul and Sacher [9], the fluorescence yields by Krause [10], and the K_β/K_α branching ratios of Khan and Karimi [11]. An energy dependence is clearly seen, so it can be concluded that a beam energy calibration is possible when the left hand side in Eq. (6) is determined experimentally. Also, as the slope of the Cr-Cu ratio is higher than that of the Fe-Cu one, a better accuracy should be attained using the first one. Additionally, it is possible to note that the method is more sensitive at lower proton energies, although in this region corrections due to ion stopping should be applied, thus reducing the accuracy of the method.

3. EXPERIMENT

In order to test experimentally the feasibility of the method proposed above, thin films of Cr (46.8 $\mu g/cm^2$) and Cu (45 $\mu g/cm^2$) evaporated on 3.5 μm thick Mylar substrates were

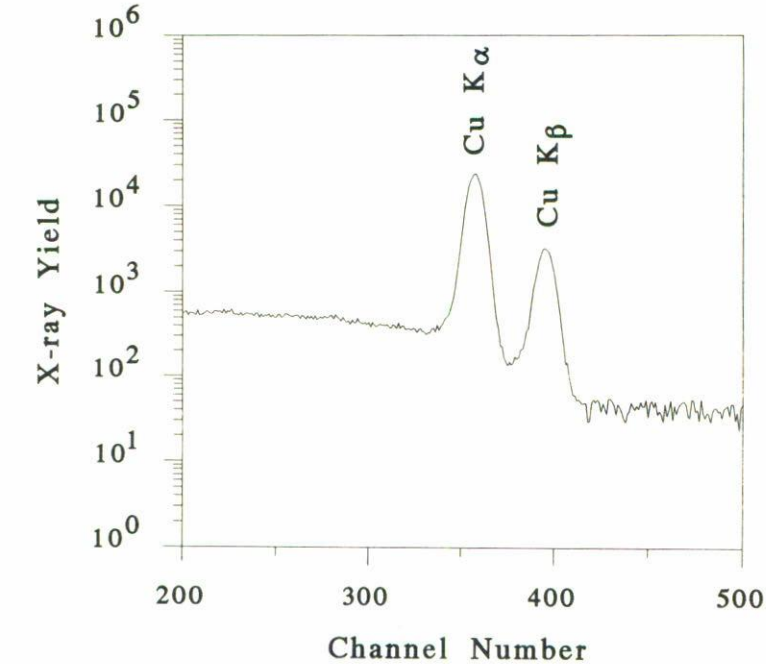

FIGURE 2. Typical K_α and K_β X-ray spectrum of Cu induced by proton impact obtained in the multichannel analyzer using a Si(Li) detector.

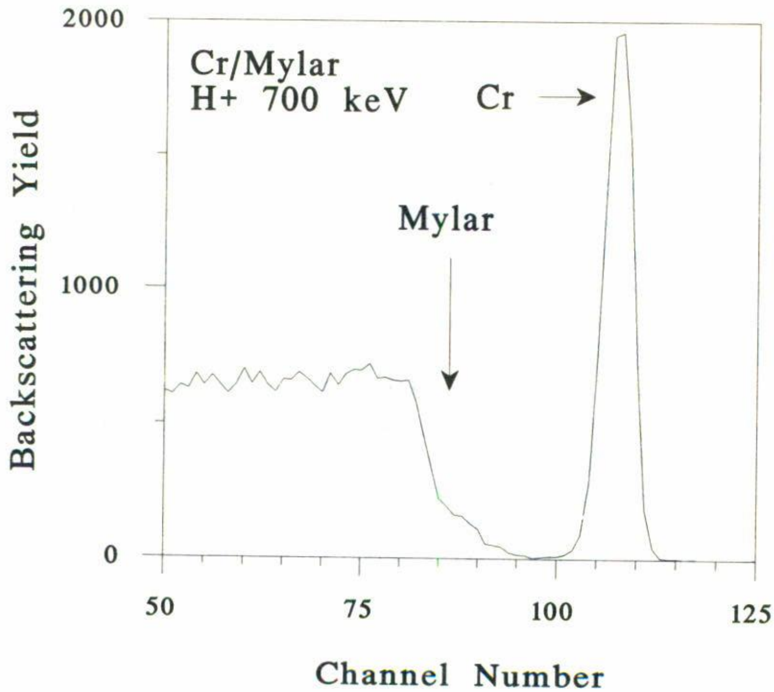

FIGURE 3. Proton backscattering spectrum from a Cr film deposited onto a Mylar substrate. The incident beam energy is 700 keV.

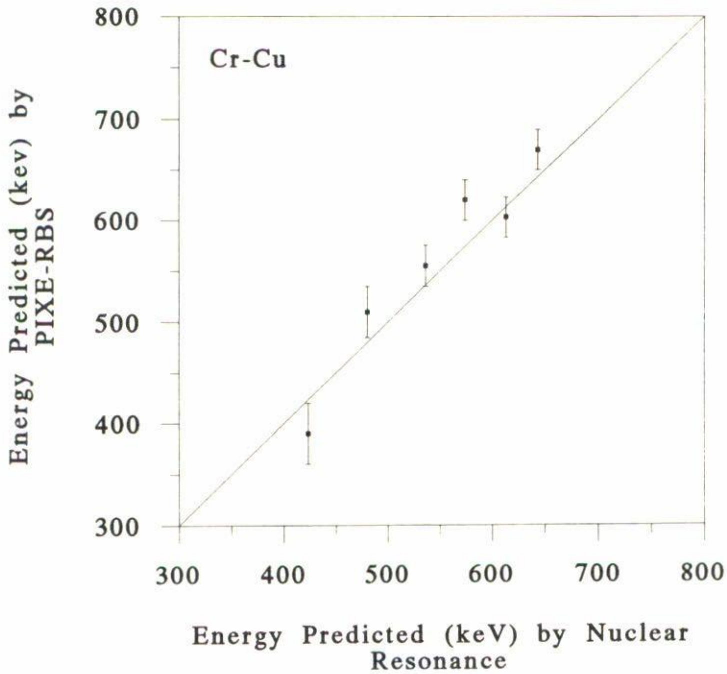

FIGURE 4. Comparison of proton beam energies obtained with the $^{19}F(p,\alpha\gamma)^{16}O$ nuclear resonances at 340, 483.6, 596.8 and 671.6 keV, with those obtained through the method proposed in this work. The line represents the values for which the energies predicted by both procedures are equal.

irradiated with proton beams of energies ranging between 400 and 700 keV. The beam was produced by the 700 kV Van de Graaff accelerator at the Instituto de Física, U.N.A.M. The beam energies were determined previously using the $^{19}F(p,\alpha\gamma)^{16}O$ nuclear resonances at energies 483.6, 596.8, and 671.6 keV. A Si(Li) detector placed 90° from the proton beam incident direction, and at 45° from the target normal was used to measure the K_α X-ray lines of Cr and Cu. The efficiency of the Si(Li) detector was obtained through calibrated radioactive point sources of ^{54}Mn, ^{57}Co and ^{241}Am, while its resolution was 170 eV at 5.9 keV [12]. A surface barrier detector was set 150° from the beam incident direction, to determine the number of backscattered ions. The signals produced in the two detectors were collected in two multichannel analyzers. Computer codes AXIL [13] and RUMP [14] were used to determine from the spectra the number of the X-ray photons detected and the protons backscattered by the metallic film. In Fig. 2 a typical Cu X-ray spectrum obtained is shown, while Fig. 3 presents a backscattering spectrum for 700 keV protons impinging on a Cr film deposited onto a Mylar substrate. In the backscattering spectrum it is seen that the signal coming from the Cr film can be readily separated from the substrate contribution. Finally, Fig. 4 displays the comparison between the beam energies obtained with the nuclear resonances and those calculated with the method proposed in this work.

4. DISCUSSIONS

Looking at Fig. 4. it can be said that the agreement is fair, because the scattering of the experimental points around the line of equal results is not small. The possible reason for this is an anomalous behavior of the Si(Li) detector in the low energy part of the X-ray peaks, which did not allow an appropriate integration of the peak areas [12,15–17]. Moreover, there is a strong influence of the efficiency ratio for both X-ray lines, thus making necessary a very accurate determination of the detector efficiency curve, which was attained in this case. However, once these problems are overcome, the method must give reliable beam energy calibrations. Also, the method has the advantage of being easily applicable to a large number of PIXE experimental arrangements, as it requires instrumentation usually present in those devices.

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