AN ABSOLUTE METHOD FOR THE ENERGY CALIBRATION OF CYCLOTRON BEAMS

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ABSTRACT

A procedure for the absolute measurement of the energy of a charged particle beam is described. The method is based on scattering kinematics, in particular the variation with angle of the energy of particles scattered by elastic and inelastic processes from different target nuclei. A determination of the angle at which particles scattered by two different reactions have the same energy allows a precise calculation of the energy of the incident ion beam. The experimental procedure and some preliminary results are reported. The system allows the calibration of cyclotron beams in the range of energies typical of present day commercial accelerators.

INTRODUCTION

The precise knowledge of the energy and of the energy spread of the charged particle beams extracted from a cyclotron is very important, and sometimes mandatory, in a number of applications. A typical case which is worth citing is represented by the collection of nuclear data, which are of interest not only for fundamental nuclear physics, but also for many fields of applied research, such as high purity radionuclide production.

The number of low and medium energy cyclotrons, commercially manufactured and mostly dedicated to applied research (biomedicine, material science, elemental analysis, etc.) is continuously growing. The information on the beam energy as inferred from the accelerator parameters supplied by the builder can sometimes be not sufficiently accurate for specific applications such that mentioned above, so that the cyclotron need be calibrated by a method ensuring an absolute energy determination. It would be advisable that the uncertainty of the measurement be less than the intrinsic energy spread of the beam.

Besides these considerations, the availability of a simple calibration procedure is certainly useful to carry out periodic checks of the reproducibility of the machine parameters. The aim of the present work has been to realize a simple system, reliable and quick to set up, capable of supplying the required information with a few hours data acquisition. The system allows the calibration of extracted beams in the range of particles and energies typical of present day commercial cyclotrons. The paper briefly illustrates the theory, describes the experimental apparatus and reports some preliminary results obtained with the Scanditronix MC40 cyclotron installed at the Ispra Establishment of the J.R.C.

THEORY

Of the several possible procedures which may be used to obtain an absolute measurement of the energy of a particle beam, the so-called "crossover" technique[1-2)] is based on scattering kinematics. It represents an absolute method applicable to a wide range of particles and energies, and it has therefore been chosen for the present work.

When a beam of charged particles of mass M_p and kinetic energy E_i impinges onto a very thin target consisting of two (or more) types of nuclei, the particles undergo a number of competing elastic and inelastic scattering processes. If two nuclear species are present, particles scattered elastically and inelastically by the two different targets have in general different energies, at any given angle ϑ. Charged particle spectrometry shows a number of peaks on a display of a MCA, which can be identified by their known kinematic shifts, even if the data acquisition system is not energy calibrated.

Let us consider particles elastically scattered from a light nucleus of mass M_1 and inelastically scattered from a heavier one of mass M_2, leaving it in a particular excited state with excitation energy E_x. Since there is a specific value of ϑ at which particles from the two processes have the same energy, from a measurement of this "crossover" angle, ϑ_c, the energy of the incident ion beam can be univocally determined by the kinematics. To fully exploit the potential accuracy of this method, it is necessary to take into account the relativistic corrections. The relationship between ϑ_c and kinetic energy T can be expressed by a forth degree polynomial:

$$a_0T^4+a_1T^3+a_2T^2+a_3T+a_4 = 0 \qquad (1)$$

in which:

$$a_0 = 4\sin^2\vartheta_c$$
$$a_1 = 8\xi\sin^2\vartheta_c$$
$$a_2 = 4[(\xi^2-2\eta)\sin^2\vartheta_c+\kappa]$$
$$a_3 = 4\xi(\kappa-2\eta\sin^2\vartheta_c)$$
$$a_4 = \kappa^2+4\eta(\eta-\kappa)$$

and

$\xi = 2M_p - E_r$, $\eta = E_r M_p$, $\kappa = E_r^2 - P_r^2$.

Here P_r, the momentum transferred at crossover, is given by:

$$P_r^2 = \frac{E_x(M_2-M_1+E_x/2)[2M_1M_2+E_x(M_1+M_2+E_x/2)]}{(M_2-M_1)^2} \qquad (2)$$

whilst E_r, the energy transferred at crossover, is:

$$E_r = (M_1^2+P_r^2)^{1/2}-M_1 = [(M_2+E_x)^2+P_r^2]^{1/2}-M_2 \qquad (3)$$

where masses are expressed in energy units. Equation (1) can be solved either analytically or numerically. It has two real solutions: the first is the value of E_i looked for, the second gives the value of E_r.

The absolute accuracy in the calculation of E_i is only a function of the precision with which ϑ_c is experimentally determined, since the uncertainties on the values of the masses M_p, M_1, M_2 and the excitation energy E_x (which represents the reference energy) can be considered negligible.

In practice, the determination of the crossover is achieved by measuring pulse-height spectra at some angles in the proximity of ϑ_c, then plotting the angles of scatter versus channel number and finally interpolating the two sets of data: ϑ_c is given by the intersection of the two curves (see below). The energy of the scattered particle is a parabolic function of $\cos\vartheta$; however, in a narrow angular region around ϑ_c the experimental data can be fitted by a straight line without committing any appreciable error.

EXPERIMENTAL

A simple scattering chamber has been designed and built for carrying out the measurements. It consists of a movable section, which can rotate around a pivot, coupled to the beam line by means of a bellow, as it is shown in Fig. 1. The angular excursion is from -55° to +55°. The target holder is mounted at the end of a collimator (see Fig. 2) inserted into the chamber and rigidly connected to the beam line. The target is positioned at the centre of rotation of the system. A small beam stopper is mounted after the target to prevent undue activation of the chamber by the direct beam and to monitor the current on target. The detector is mounted at the extremity of the movable arm, and can therefore be rotated to detect particles scattered at any given angle ϑ. Its positioning is achieved by a coarse adjustment by 5° step and a fine adjustment obtained via a micrometer (1° displacement corresponds to 14 complete turns, or 700 divisions, of the micrometer). The detector is a plastic scintillator coupled to a Philips XP2972 photomultiplier, an EG&G ORTEC Scintillation Preamplifier Model 113 and an EG&G ORTEC Amplifier Model 572. Data are acquired via the EG&G ORTEC ADCAM Data Acquisition Package, run on a Portable Compaq Personal Computer.

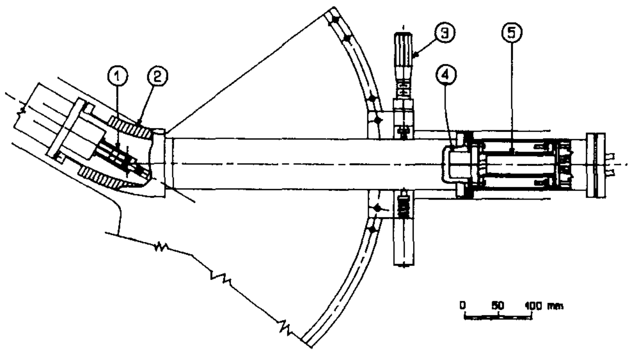

Fig. 1. Plan view of the scattering chamber. 1) Target holder-collimator; 2) bellow; 3) micrometer; 4) lead collimator; 5) photomultiplier.

A special voltage divider chain has been designed for use with the Philips tube XP2972. The chain recommended by the manufacturer and normally used gives some problems when the photomultiplier is mounted into a vacuum chamber where the vacuum value is approximately 10^{-6} torr. In fact the measured current of the chain is nearly 600 μA and the dissipation is high. Therefore, after a few hours, the resolution of the spectrum becomes appreciably worse. A significant improvement is obtained with a specially designed voltage divider chain, using Motorola transistors MPS A92, which has been designed to reduce the current and to stabilize the voltage drop among the dynodes. Furthermore the high value resistors are used with appropriate temperature stability characteristics.

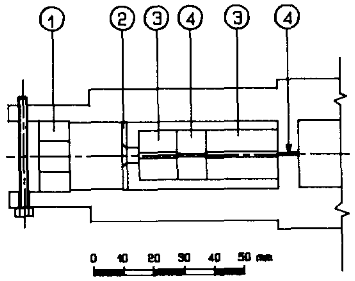

Fig. 2. Cross sectional view of the target collimator. 1) Beam stopper; 2) target; 3) lead; 4) 1 mm diameter collimator.

For the first tests Mylar was chosen as target material, since it is commercially available in calibrated foils of different thicknesses. Mylar is a mixture of hydrogen, carbon and oxygen: the crossover has been determined considering elastic scattering on hydrogen and inelastic scattering on the first excited state of carbon. Scattering contribution from oxygen is of course also present and may sometimes interfere with the measurements. The elastic peaks from oxygen and carbon are nearly coincident and are readily identified at the right end side of the pulse height spectrum. The target thickness should produce an energy spread less than the intrinsic energy spread of the beam (which is of the order of 1%); however, a target too thin would decrease too much the number of interactions and hence the count rate. A target thickness of $\Delta E \approx 100$ keV has been chosen for the present measurements.

The width of the peaks in the pulse height spectrum is the sum of several factors: 1) energy spread of the beam; 2) geometry: acceptance of the target collimator, finite target thickness, target to detector distance and detector collimation; 3) intrinsic spread due to the detector. The uncertainties due to geometry should be such that their sum does not exceed the contribution given by the intrinsic spread, whilst the energy spread of the beam of course represents an unavoidable lower limit.

The uncertainty introduced by finite target thickness is due to the fact that particles follow different trajectories in crossing the foil and therefore undergo different energy losses. The energy spread introduced is a function of angle of scatter: it varies from 2% of the energy loss for $\vartheta = 10°$ to about 50% of the energy loss for $\vartheta = 50°$.

The collimation of the target and the detector should be such that the uncertainty due to the geometry is sufficiently small. In both cases a 1 mm collimator was used. With a target to detector distance of 500 mm (which has been chosen in order to keep the scattering chamber sufficiently compact), the angular uncertainty is given by arctg(1/500) = 0.11°. The horizontal and vertical emittances of the proton beam extracted from the Ispra cyclotron are both about 40 mm·mrad. The target collimator has been chosen so that its acceptance is about half the beam emittance: a collimator with a length of 40 mm and a diameter of 1 mm has therefore been used. The angular acceptance is thus 1.4° and constitutes the principal factor affecting the peak width. To improve the signal to noise ratio, without worsening the angular resolution, use has been made of a slit collimator in front of the detector (1 mm x 10 mm), perpendicular to the detector movement (i.e., vertical in the present case).

The detector used was a NE 102A plastic scintillator with a diameter of 10 mm and height of 12 mm (determined by the maximum range of the particles to be detected). A test made with a NaI detector showed an improvement in the resolution, but the background due to gamma radiation was significantly worse.

The various contributions mentioned add up to produce a finite width of the peaks appearing in the pulse height spectrum. The experimental FWHM is about 7% with the NE 102A scintillator. With the NaI crystal the FWHM was about 3% and it can be easily shown that it is mainly due to the geometry. The precision on the experimental value of ϑ_c is thus determined by the accuracy by which the centroids of the peaks can be identified. In practice, a few thousands second data acquisition provides a statistics sufficient to establish their position within one or two channels. If necessary, this can be achieved by means of appropriate fitting procedures.

RESULTS AND DISCUSSION

Preliminary results obtained for 18 MeV protons confirmed the validity of the present technique. From the value of the nominal energy inferred from the cyclotron settings, a first guess of ϑ_c (which can be obtained from the tables reported in ref. 2) allows the choice of the angular region at which measurements should be carried out. For the present case this corresponds to an interval centred at about 30°.

Althought the symmetry of the chamber has been checked in advance, nevertheless the finite size of the target collimator and the divergence of the beam introduce an unavoidable asymmetry in the system. It is therefore necessary to perform right and left measurements with respect to the direction of the incident particles. The crossover angle is given by the average value of the right and left determinations; these have in turn been obtained by interpolating data from measurements performed at four different angles. The acquisition time was 2000 seconds for each measurement, but since the scattering cross section varies with energy and angle, the time necessary to reach a sufficient statistics may in effect vary from one experimental condition to another. Preliminary measurements made with 26 MeV (nominal) protons showed a marked decrease in the statistics for angles around 20°.

Fig. 3 shows a typical spectrum obtained for nominal 18 MeV protons. The graph in Fig. 4 reports the data for left and right measurements. The average value of ϑ_c is 30.91°, corresponding to $E_i = 18.21$ MeV.

The values of the masses of nuclei and their excitation energies were taken from ref. 3-5. The error in the determination of the centroids of the peaks is typically one or two channels, which in turn signifies an error of a few tens keV on the value of E_i. This uncertainty is small compared with the intrinsic energy spread of the beam.

A major problem encountered has been that of reducing the background radiation (neutrons + gammas). This aspect is particularly critical due to the short target to detector distance, since the main contribution to background comes from the beam lost on the target collimator and the stopper placed just after the target. A significant reduction of the background radiation has been achieved by adding lead shielding in front of both target and detector collimators. Another improvement has been obtained by positioning the chamber as close as achievable to the quadrupoles, in order to better focus the beam through the target collimator. The photomultiplier has been shielded from the stray magnetic field by inserting the whole detector+PM assembly inside a tube of μmetal.

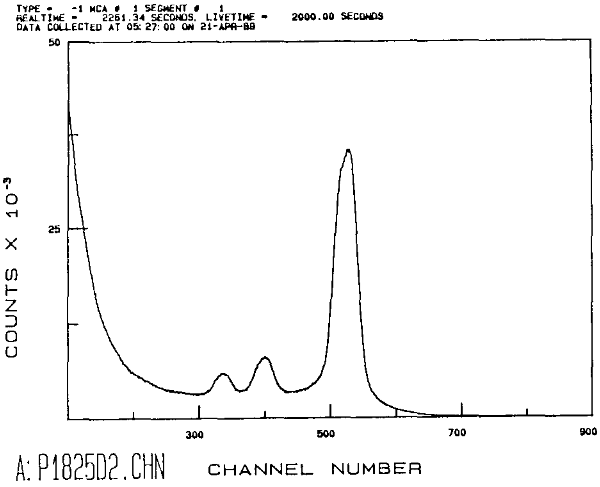

Fig. 3. Pulse height spectrum at $\vartheta = 25°$ right for nominal 18 MeV protons.

As stated earlier, a plastic scintillator was used instead of a NaI crystal because even if the resolution of the latter is better of about a factor 2, the former is less sensitive to gamma radiation, which represents the dominant contribution to background.

CONCLUSIONS

Preliminary results have shown that the system here described constitutes a reliable method to carry out absolute measurements of the energy of a charged particle beam. The angular excursion of the chamber allows the determination of proton energies from about 8 MeV up to several tens MeV, a range which is typical of present day commercial cyclotrons. By a proper choice of the reference nuclei (i.e., target composition) this energy interval can be widened.

Similar measurements can be performed for heavier ions. However, if the target does not contain a nucleus

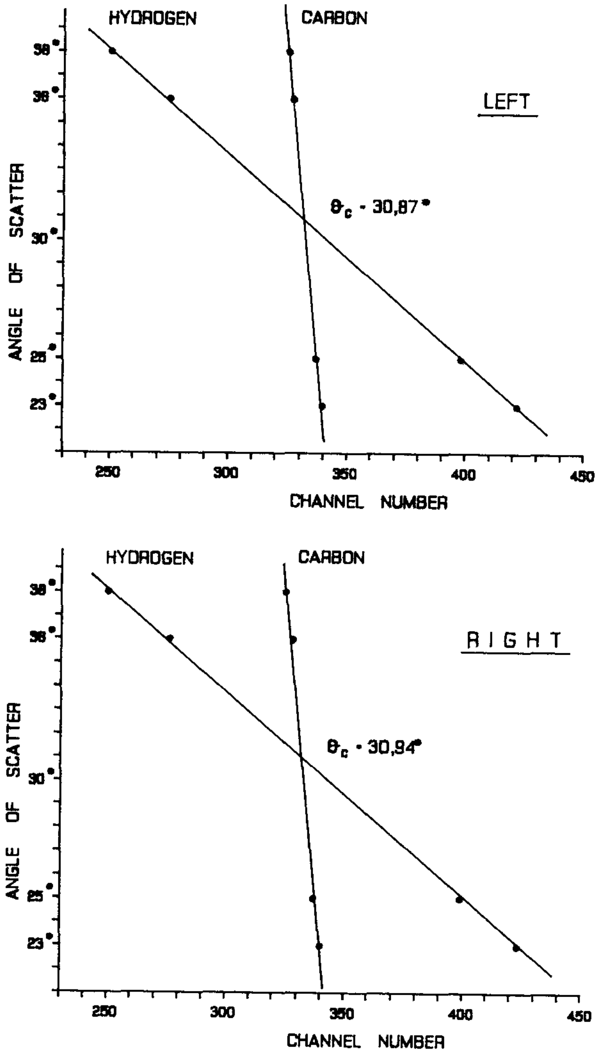

Fig. 4. Determination of right and left crossover angles.

identical to the incident particle (the "light" nucleus), scattering, and therefore crossover, is limited to a restricted angular region. In this case the system resolution is a more critical factor which should be carefully considered.

Measurements at the Ispra Cyclotron Laboratory will be carried out in the near future for a number of energies for protons, deuterons and alphas. Comparison of the results with the nominal energy of the beam as set from the cyclotron parameters will allow the determination of correction factors in the case the two sets of data show significant differences. Further developments to improve the resolution of the system are planned, including the use of a target of different composition (such as polyethylene, to avoid scattering contribution from oxygen) and tests with solid state detectors.

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