14

Nuclear Instruments and Methods in Physics Research B42 (1989) 389–392
North-Holland, Amsterdam

IMPROVED BEAM-ENERGY CALIBRATION TECHNIQUE FOR HEAVY-ION ACCELERATORS

A.M.J. FERRERO, A. GARCIA *, S. GIL *, A. ETCHEGOYEN, M. Di TADA, A.J. PACHECO **, D. ABRIOLA, D.E. DiGREGORIO **, M. ELGUE, M.C. ETCHEGOYEN **, J.O. FERNÁNDEZ NIELLO **, A.O. MACCHIAVELLI and J.E. TESTONI **

Departamento de Física, TANDAR, Comisión Nacional de Energía Atómica, 1429 Buenos Aires, Argentina

Received 22 September 1988 and in revised form 12 February 1989

A simple technique for beam energy calibration of heavy-ion accelerators is presented. A thin hydrogenous target was bombarded with ^{12}C and ^{19}F, and the energies of the protons knocked out, elastically were measured at several angles using two detectors placed at equal angles on opposite sides of the beam. The use of these two detectors cancels the largest errors due to uncertainties in the angle and position at which the beam hits the target. An application of this energy calibration method to an electrostatic accelerator is described and the calibration constant of the analyzing magnet was obtained with an estimated error of 0.4%.

1. Introduction

A precise knowledge of the absolute beam energy is a crucial requirement in order to perform or compare experiments in many fields of nuclear physics (e.g. near-barrier fusion and nuclear astrophysics studies). This usually implies the calibration of a nuclear-magnetic-resonance (NMR) gaussmeter of an analysing magnet with a given beam-defining slit system. Several techniques are commonly used, such as measurements of compound-nucleus resonance energy [1], nonresonant proton capture reactions [2], or threshold energies [1,3]. These techniques, normally used for calibration of small and medium energy machines, are difficult to apply to larger accelerators [1]. For larger machines, a novel time-of-flight technique and an α-particle reaction-energy technique have been employed as described in ref. [4].

A further method (which is very simple) to calibrate accelerators with beam energies in the range of 3–5 MeV per nucleon was successfully used by Olsen et al. [5] and tested against time-of-flight measurements by Bimbot et al. [6]. This technique involves the bombardment of a thin hydrogenous target with a heavy-ion beam and the detection of the protons knocked out elastically at 0°. However, the need for a reliable energy calibration using α-emitting sources makes this 0° geometry appropriate only for beam energies below 5 MeV per nucleon.

In the present work a method for beam energy calibration not restricted to the range of 3–5 MeV per nucleon is proposed. This method is based on the measurement of recoiling protons over a wide range of angles. Since the energy of the scattered protons varies as the square of the cosine of the detection angle, it is possible to reduce their energies to a region amenable to a reliable energy calibration. A possible drawback of a non-0° geometry, namely, the large error that might arise from the uncertainty in the position and angle at which the beam hits the target was essentially canceled by using two detectors at approximately equal angles on opposite sides of the beam.

The rest of this paper is devoted to the application of this method to the energy calibration of the 20 UD tandem accelerator at Buenos Aires, TANDAR [7], describing both the experimental method and the analysis with particular emphasis on the error assessment.

2. Experimental method

Beams of ^{12}C and ^{19}F of typically 5 nA were obtained from the 20 UD tandem accelerator, TANDAR. The nominal ^{12}C beam energies were 65 and 70 MeV with 4^+, 5^+, and 6^+ charge states while the ^{19}F beam energy was 104 MeV with a 7^+ charge state. Such beam energies and charge states were chosen in order to cover the most common range of work of the analysing-magnet field.

The beams were focussed to produce a 2 mm diameter spot at the aluminized 0.230 mg/cm^2 Mylar target. Recoiling protons were detected at both sides of the beam from 10° to 35° with two symmetrically placed

* Present address: University of Washington, Seattle, USA.
** Member of the Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina.

1500 μm Si detectors each with an angular acceptance of 0.75°. These two detectors moved independently on the lower and upper turn-tables of the scattering chamber. The detector angles were set remotely with an angle encoder of 0.01° step. Both detectors having the *same* arbitrary 0°-reference angle, optically determined within 0.05° accuracy. This high accuracy is important since if the scattering angle has a $\Delta\theta$ error for one of the above-mentioned detectors (due to, e.g., uncertainty in the position and angle at which the beam hits the target), the error for the other detector will be $-\Delta\theta$ within 0.05° accuracy. This fact will be important in the evaluation of the systematic errors as will be discussed later.

Both detectors were calibrated with an α-particle source consisting of ^{239}Pu, ^{241}Am, and ^{244}Cm with energies ranging between 5.1 and 5.8 MeV. In order to obtain further calibration points at higher energies the following method was employed [8]: an auxiliary ^{209}Bi target was bombarded with a 70 MeV ^{12}C beam and the evaporation residues were stopped in an aluminum catcher foil. Alpha particles emitted by these residues were collected by the detectors. The ^{209}Bi foil was placed (see fig. 1) on the lower turn-table, 10° off the detector and behind it so that, when placed at the beam, i.e. 180°; the scattered particles from ^{209}Bi were not detected. The catcher had a 1 cm hole bore in its centre to let the beam through and it was placed at 8 cm from the ^{209}Bi target. The α-particles emitted in the decay of the evaporation residues have the following energies: 6.77 MeV from the decay of ^{213}Fr, 8.43 MeV from ^{214}Fr, 9.21 MeV from ^{218}Ac, and 9.65 MeV from ^{217}Ac [9]. These α-energies were corrected [10] due to the energy loss in the catcher and in the detector gold layer. The recoil nucleus penetration in the catcher ranged from 108 to 190 μg/cm^2 depending on the position at which the fusion reaction took place in the target. A mean penetration of 149 μg/cm^2 was considered in order to evaluate the α-particle energy loss on leaving the catcher. This linear interpolation to 149 μg/cm^2 was shown to be accurate enough by detailed energy-range law calculations.

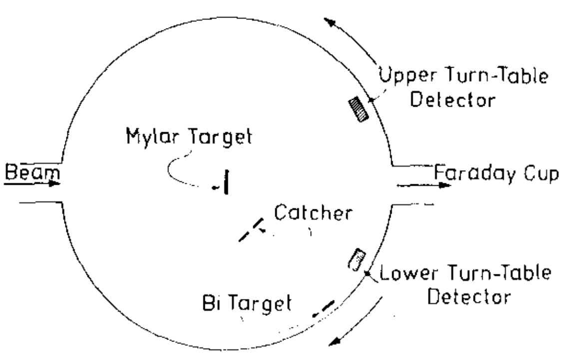

Fig. 1. Layout of the scattering chamber. For energy calibration of the solid-state detectors, the ^{209}Bi foil is placed at 180°.

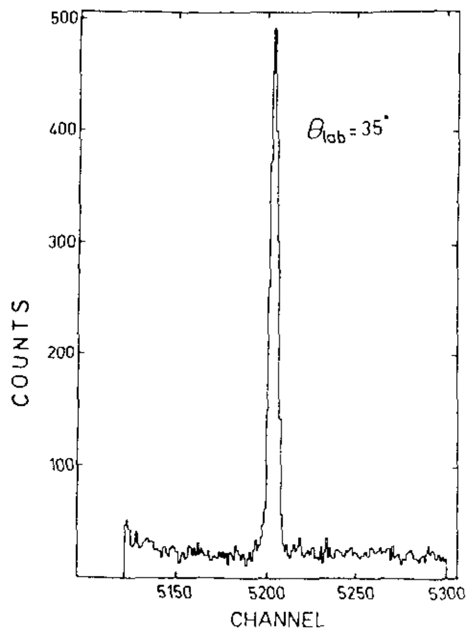

Fig. 2. Energy spectrum of the recoiling protons obtained with the 65 MeV ^{12}C beam at $\theta_{lab} = 35°$.

This calibration was performed on line since the relevant lifetimes are of the order of few minutes.

A typical proton spectrum is shown in fig. 2. This corresponds to the 65 MeV ^{12}C beam.

3. Determination of *K*

The aim of the experiment is to determine the constant K which relates the beam energy E_0 and the NMR frequency of the analysing magnet [3], i.e.:

$$K = \frac{A_0 E_0}{(qf)^2}\left[1 + \frac{E_0}{2M_0c^2}\right], \tag{1}$$

where q, A_0 and M_0 are the charge state, mass number, and mass of the accelerated ion, respectively and f the NMR frequency. The beam energy before entering the target, E_0, can be determined from the proton energy after leaving the target, E_p, from:

$$E_0 - \delta E_0 = (E_p + \delta E_p)\frac{(M_0 + M_p)^2}{4M_0M_p}\frac{1}{\cos^2\theta}, \tag{2}$$

where M_p is the mass of the proton and θ is the scattering angle. The energies lost by the projectile and the proton in the target, δE_0 and δE_p, were estimated [10] by assuming that the reaction takes place, on average, at the middle of the target. It was also taken into account that δE_p depends on the scattering angle θ due to different path lengths within the target.

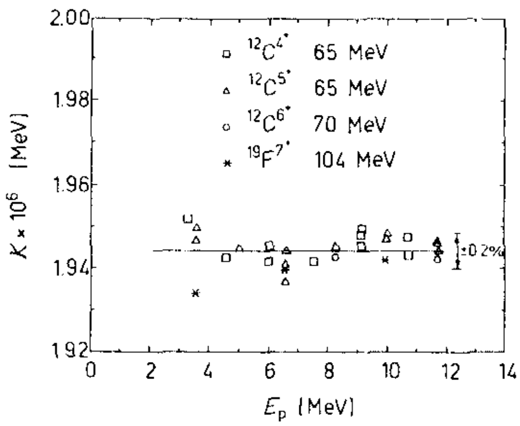

Fig. 3. K-values as a function of the proton energies. Each value is the average over the two detectors symmetrically placed on both sides of the beam. The quoted energies are the nominal bombarding energies. The full line is the average K-value which is 1.944×10^{-6} MeV s^2 and the shown $\pm 0.2\%$ value corresponds to the standard deviation as explained in the text.

The evaluated K-values as a function of the proton energies are shown in fig. 3. Eqs. (1) and (2) were used for the 27 experimental points corresponding to different scattering angles for each of the beams and energies already mentioned. Each of the K-values in the figure is the average between the two values obtained with the symmetrically placed detectors at both sides of the beam.

The errors can be divided into random and systematic errors. The standard deviation of the K-values was evaluated from the formula $s^2 = \Sigma(\bar{K} - K)^2/(N - 1)$ rather than from the quadratic summation of the relevant random errors, i.e., uncertainties in the determination of the proton-peak centroid, nonuniform target thickness and fluctuations in the turn-table positions. The standard deviation was 0.2% and therefore the statistical error of the mean K-value, $s/\sqrt{N}$, is approximately $\pm 0.04\%$. This error is negligible compared with the systematic errors, as will be shown.

The systematic error was assessed from the propagation relation:

$$\frac{\Delta(E_0 - \delta E_0)}{E_0} \cong \frac{\Delta(E_p + \delta E_p)}{E_p} + 2\frac{\Delta(\cos\theta)}{\cos\theta} \tag{3}$$

therefore,

$$\frac{\Delta K}{K} \cong \frac{\Delta E_0}{E_0}$$
$$\cong \frac{\Delta E_p}{E_p} + \frac{\Delta(\delta E_0)}{E_0} + \frac{\Delta(\delta E_p)}{E_p} + 2\frac{\Delta(\cos\theta)}{\cos\theta}, \tag{4}$$

where the second term of the right hand side of eq. (1) was neglected because of the present energy range, and $\Delta f/f$ is negligible. The different contributions in expression (4) were determined as follows:
$\Delta E_p/E_p \cong \pm 0.2\%$ due to the uncertainty from the α-particle energy calibration; $\Delta(\delta E_0)/E_0$, $\Delta(\delta E_p)/E_p \cong \pm 0.05\%$ each, assuming a $\pm 20\%$ error in the target thickness; $2\Delta(\cos\theta)/\cos\theta \cong \pm 0.1\%$ assuming a $\Delta\theta \cong \pm 0.05°$, i.e., the difference in the 0° reference angle of the detectors.

The straight summation of these errors, which is an upper limit of the final relative error, gives $\Delta K/K \cong \pm 0.4\%$. This figure is the same to those obtained with time-of-flight and 0° proton-recoil methods.

The importance of measuring over an angular range is emphasized since systematic errors could be detected in this way. Calculations were performed with a variation of either the target thickness or $\Delta\theta$ slightly above the quoted systematic uncertainties. Both types of errors have a greater influence at lower proton energies, i.e., at larger angles, giving rise to a deviation from the mean K-value which is represented by the horizontal line in fig. 3.

The importance of measuring with two detectors and averaging the K-values seemed to be crucial in order to avoid large errors. This was assessed by plotting the K-values obtained from each detector independently as a function of E_p in a similar fashion as shown in fig. 3. It was observed that, depending on the focussing of the beam on the target, the K-values from each detector lay on different curves with the difference strongly varying with angle. This large uncertainty, as large as $\pm 1\%$, arises from a systematic error in the assumed scattering angle.

As a final comment, it is worthwhile to mention that no systematic change in the K-values was observed throughout the experiment, indicating that there was no significant target evaporation.

4. Summary and conclusions

A versatile and simple energy calibration method for heavy-ion accelerators allowing a variety of beam energies not restricted to a 3–5 MeV per nucleon range has been detailed. This method is based on the measurements of recoiling-proton energies at several angles with two detectors symmetrically placed at both sides of the beam. In this way random errors are minimized, leaving the systematic errors as the main source of uncertainty. In this respect, the uncertainty from the α-particle energy calibration remains the most important one. In the particular application here described, namely, the energy calibration of the 20 UD tandem accelerator TANDAR, special emphasis was paid to the α-particle calibrations by using a standard long-lived triple α-source and several short-lived α-sources produced on line by bombarding ^{209}Bi with 70 MeV ^{12}C beams. Finally, the calibration constant K, defined in eq. (1), was obtained within a $\pm 0.4\%$.

References

[1] T. Freye, H. Lorenz-Wirzba, B. Cleff, H.P. Trauveter and C. Rolfs, Z. Phys. A281 (1977) 211.
[2] J.B. Marion, Rev. Mod. Phys. 38 (1966) 660.
[3] V. Rotberg, D. Pereira, M.N. Rao, N. Veta and O. Sala, Revista Brasileira de Fisica, vol. 6 (1976).
[4] D.K. Olsen, K.A. Erb, C.M. Jones, W.T. Milner, D.C. Weiser and N.F. Ziegler, Nucl. Instr. and Meth. A254 (1987) 1.
[5] D.K. Olsen, N.H. Merril, S.F. Biagi, W.R. Phillips and A.R. Barnet, Nucl. Instr. and Meth. 114 (1974) 615.
[6] R. Bimbot, D. Gardes, H. Geissel and K.H. Schmidt, Z. Phys. A286 (1978) 327.
[7] N. Fazzini, H. González, E. Pérez Ferreira, S. Tau, A. Tersigni and E. Ventura, Nucl. Instr. and Meth. A244 (1985) 20.
[8] M.E. Debray, M. Davidson, A.J. Kreiner, J. Davidson, G. Falcone, D. Hojman and D. Santos, submitted to Phys. Rev. C.
[9] Table for Isotopes, eds. C.M. Lederer and V.S. Shirley (1978).
[10] L.C. Northcliffe and R.F. Schilling, Nucl. Data Tables A7 (1970) 233.