THE ENERGY CALIBRATION OF THE BUCHAREST FN TANDEM ACCELERATOR

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La acceleratorul tandem din Bucureşti au fost realizate măsurători de calibrare în energie a magnetului analizor prin compararea energiilor particulelor alfa provenite de la o sursă de ^{241}Am cu energiile proiectilelor de ^{4}He retroîmprăştiate pe straturi subțiri de carbon şi aur. Această tehnică nu este limitată de energiile discrete ale rezonanțelor ori de energiile de prag ale reacțiilor nucleare şi poate fi folosită pentru energii variind continuu. Rezultatele obținute sunt în bun acord cu rezultatele din precedentele calibrări şi indică faptul că valoarea constantei magnetului K descreşte cu energia echivalentă a protonilor în intervalul 2 - 4 MeV. Valoarea medie obținută $K=27.742 \pm 0.004$ keV·amu/e^2·MHz^2 este în bun acord cu valoarea medie $K=27.720 \pm 0.003$ keV·amu/e^2·MHz^2 obținută în precedentele măsurători.

An energy calibration of the analysing magnet of the Bucharest tandem has been completed by comparing the energies of alpha particles from a ^{241}Am source with the energies of ^{4}He projectiles back-scattered by thin carbon and gold layers. This technique is not restricted to discrete resonance or thresholds energies but can be used continuously. The results are in good agreement with the results of previous calibrations and showed that the magnet constant K decreases with equivalent proton energy from 2 to 4 MeV. An average value of $K=27.742 \pm 0.004$ keV·amu/e^2·MHz^2 was obtained in reasonable agreement with the previous average value $K=27.720 \pm 0.003$ keV·amu/e^2·MHz^2.

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1. Introduction

Low and medium energy particle accelerators find increasing applications in nuclear and atomic physics researches as well as in many disciplines, such as medicine and biology, material sciences, environmental studies and the study of art works and archaeological artifacts. In particular, the number of accelerators commercially manufactured and mostly dedicated to applied research is steadily growing.

The precise knowledge of the energy and of the energy spread of the charged particle beams extracted from the accelerators is very important and mandatory in many applications. The information on the beam energy as inferred from the accelerator parameters supplied by the manufacturer can sometimes be not sufficient for specific applications. The accelerators need therefore to be calibrated by a method ensuring an absolute energy determination. For very accurate energy calibrations it is usually not enough to calibrate the energy at just one point. The non-linearity in the analysing magnets as well as the variability of other accelerator components may make it necessary to calibrate over a range of energies, and, possibly over a range of ions that are used. Hysteresis effects in the analysing magnet make the procedure for setting of its field very critical if great precision is needed. There are a number of techniques by which a measurement of particle bema energies may be obtained.

Two common techniques for calibrating the analysing magnet of an ion accelerator are the measurement of neutron threshold energies of sharp (p, n) or (α, n) reactions or the use of nuclear (p, γ) or (p, p) reactions having narrow, well known resonances with large cross sections.

Threshold energies have been determined from absolute measurements of the incident particle energy for a number of reactions. Recommended values of threshold energies for calibration purposes have been tabulated by Marion [1]. A convenient method for measuring neutron threshold energies is the observation of the emitted neutrons at 0^0 using a simple neutron detector such as a long counter. This technique can be utilized with (p, n) reactions up to 6 MeV. Above this proton energy the neutron background becomes prohibitively large.

A technique by which a measurement of particle beam energy may be obtained is based on gamma-ray resonances. The $^{27}Al(p, \gamma)^{28}Si$ reaction has been used most frequently, since the resonance width is ~ 80 eV, and the location of the resonance at 991.90 ± 0.04 keV is ideally suited for those machine that are routinely used for Rutherford backscattering spectrometry measurements. Commonly, backscattering is used more than other analysis methods and the

resonances for the (p, p) and (α, α) reactions can be easily used for quick, fairly accurate energy calibrations.

Other investigators have used the precise measurement of gamma ray energies arising from direct capture reactions in high-resolution Ge detectors to measure the beam energy [2]. Time of flight has also been used for calibration purposes [3]. The time-of-flight technique provides a relatively simple method for measuring absolute beam energy if a time-modulated beam of sufficient intensity is available. In contrast with the use of resonances or thresholds, which occur only at specific energies, this technique is useful over a wide range of particle types and energies.

The use of RBS (Rutherford Backscattering Spectrometry) measurements to determine an internal energy calibration offers several advantages, the most obvious being that it is not restricted to discrete resonance energies or thresholds energies but can be used continuously. This technique uses the conventional backscattering spectrometry setup. Two measurements are required. The first are backscattering measurements of two calibration samples. These data defines two linear equations that relate the energy per channel a and the energy intercept b of the system to the beam energy E. The second measurement is of some positive-Q nuclear reaction or the measurement of the α particles from a radioactive source, at the same gain. We obtain a third linear equation. Variations of this technique have been attempted in some earlier reports [4-8]. In these reports the elastic scattering approach was used to calibrate the accelerator energy scale. Another absolute method for the determination of the energy of a charged particle beam which uses a backscattering technique is based on scattering kinematics and exploits the variation with angle of the energy of particles scattered by elastic and inelastic processes [9]. Normally, this method is applied to beam energies above a few MeV.

The FN-tandem in Bucharest was commissioned in March 1973 but its operation was stopped for quite long time periods, due to the strong earthquakes in Romania in the years 1977 (7.2 Richter scale) and 1986 (6.9 Richter scale). To prevent the consequences of similar seismic events in the future, a seismic protection system was designed and installed. Due to sustained efforts made by the Tandem Accelerator team, the accelerator was recommissioned in the second half of 1991. In the past the analysing magnet has been calibrated up to 14.2 MeV equivalent proton energy using both threshold (p, n) and (α, n) and resonance (p, p) reactions. The absolute calibration points used resulted from measurements of both (p, n) and (α, n) thresholds and narrow (p, p) resonances. The calibration measurements were made during several separate experimental runs over a time period from 1975 to 1999. Data were taken on two separate occasions: July 1975-May 1976 and December 1999.

In 2006 a program of modernization and development of the accelerator was started. A new RMN fluxmeter (made by METROLAB, Switzerland) for measuring the magnetic field in the analysing magnet gap was installed. A new calibration of the energy analysing system was needed. A new energy calibration has been completed for ^{4}He beams over the energy range from 4.278 to 5.594 MeV.

The method adopted for calibration of the analysing magnet fields of the Bucharest FN tandem accelerator consists simply of comparing the energies of alpha particles from a radioactive source with the energies of ^{4}He projectiles back-scattered into a silicon detector by thin carbon and gold layers.

A description of the experimental setup will first be presented, followed by the experimental measurement techniques used. Then the analysis and results of the calibration will be given, along with a brief discussion and summary.

2. Energy calibration

The objective of the performed experiments was to determine the beam energy as accurately as possible near 5 MeV where there is a dearth of suitable resonance or threshold calibration energies. The experimental arrangement was that typically used in RBS measurements. Data were taken on two separate occasions: January 2010 and March 2011.

The $^{4}He^{++}$ beam was obtained from a home made injector for helium negative ions. This injector, based on a duoplasmatron ion source allows to use either a short charge exchange channel fed with lithium vapors for providing helium negative ions or a longer channel fed with hydrogen for producing hydrogen negative ions. The change between the two channels is relatively easy. The negative ions of hydrogen or helium are injected in the tandem accelerator through the 20^{0} inflection magnet and then accelerated by the High Voltage Engineering Corporation model FN tandem accelerator before being momentum analysed by the 90^{0} magnet system with radius of curvature 1016 mm. Following this momentum analysing system, a switching magnet bent the beam 30° into a beam line where all energy calibration measurements were performed.

The object and image slits of the analysing magnet were both set at full apertures of 1.0 mm in the dispersive plane. To minimize effects of differential hysteresis, the magnetic field was recycled according to the following procedure before taking measurements. The magnet current was increased smoothly from zero to 280 A and then reduced to zero; this was done three times and then the field was increased to the required value without overshooting. All data were taken in the direction of increasing energy; if it was necessary to reduce energy, the field was recycled.

The field of the 90 ° magnet is measured with a NMR fluxmeter. The relativistic relationship between the energy E of the particle analysed and the magnetic field B is given by the expression

$$E = K_1 B^2 \frac{Z^2}{M}\left(1+\frac{E}{2Mc^2}\right)^{-1} \quad (1)$$

where Z is the effective charge of the particle, M is its mass, and (E/Mc^2) is the ratio of its kinetic energy to rest mass energy. In the present work E is in MeV, Z is in units of the electronic charge, and B is in Tesla (T). The mass M, expressed in nuclidic mass units, is obtained by subtracting the mass of the appropriate number of electrons from the atomic mass, neglecting the electron binding energies.

Taking into account the relationship between B and the measured NMR frequency:

$$B = 2.3487 \cdot 10^{-2} \cdot f$$

where B is in Tesla and f is in MHz we obtain

$$E = Kf^2 \frac{Z^2}{M}\left(1+\frac{E}{2Mc^2}\right)^{-1} \quad (2)$$

The relationship of measured NMR frequency to the energy of a particle passing through the magnet should be a constant, the "magnet constant", expressed as

$$K = \frac{ME}{Z^2 f^2}\left(1+\frac{E}{2Mc^2}\right) \quad (3)$$

The magnet constant K may be a weak function of the magnetic field because of saturation and fringing field effects.

One of the samples used for the measurements was a SiC layer ($390x10^{15}$ at/cm^2) sandwiched between a 7 nm Au layer and a 5 μm Al foil. The second sample consisted in a C layer (60 Å) and a Au layer (90 Å) deposited on a polished 1 mm thick Si wafer.

The multilayer structures Au/SiC/Al and Au/C/Si were obtained by Pulsed Laser Deposition (PLD) technique. The PLD method involves the interaction of a laser beam with a target material producing a plume which transports the particles onto a substrate, where a thin film is formed [10]. The basic experimental PLD set-up consists in a laser (YAG:Nd with four harmonics , i.e. 1060 nm, 530 nm, 355 nm, 265 nm), a reaction chamber equipped with a vacuum–system that can goes down to 10^{-6} mbar, a target rotation-translation system and a heater (substrate holder) that can go up to 800°C. The experimental deposition system is presented in Fig.1.

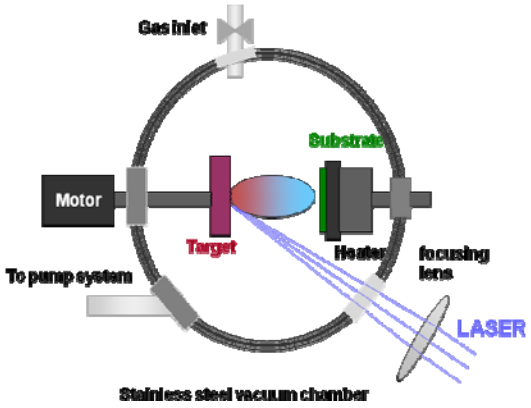

Fig. 1. The deposition chamber scheme

The measurements were performed with a standard backscattering setup presented in Fig. 2, using $^{4}He^{++}$ ion beams from the 9 MV tandem Van de Graaff accelerator at NIPNE. The vacuum was kept at 10^{-6} Torr during the measurements. The ions scattered under 167^{0} laboratory angle were detected by a ion implanted passivated silicon detector with a solid angle of 0.86 msr which was connected to a conventional electronic device. Detector pulses are preamplified, amplified and shaped and sorted by the pulse height analyzer. The gain was continuously monitored with a precision pulser. The energy resolution was 18 keV.

Fig. 2. The scattering chamber mounted on one of the extensions of the Bucharest tandem accelerator (upper part of the figure); the cover of the scattering chamber which contains the stand for the silicon detector and for the sample (lower part of the figure).

The beam energy was calibrated using the α's from ^{241}Am with a modified version of Scott's method [8]. Two measurements were performed. The first are backscattering measurements of two calibration samples (C and Au). Spectra were collected recording also the corresponding NMR frequency. These data defines two linear equations that relate the energy per channel a and the energy intercept b of the system to the beam energy E.

$$E_C = K_C \cdot E = a \cdot N_C + b \tag{4}$$

$$E_{Au} = K_{Au} \cdot E = a \cdot N_{Au} + b \tag{5}$$

where E_C, N_C, K_C and E_{Au}, N_{Au}, K_{Au} are the energy, channel number and the kinematic factor for backscattering from C and Au respectively. If E is not known and is to be determined we must obtain a third equation relating E to a and b. This equation cannot be homogeneous if the set is to have a unique solution.

The third equation is obtained by counting the α particles from the ^{241}Am radioactive source, at the same gain. The radioactive source used contained two alpha emitters ^{239}Pu and ^{241}Am. So the third equation is

$$E_\alpha = a \cdot N_\alpha + b \tag{6}$$

After solving the system of equations the solution is implemented in the code RUMP [11] and the simulated spectrum is compared with experimental spectrum.

Fig. 3 shows a backscattering spectrum for ^{4}He on the Au/SiC/Al sample measured in January 2010. The C peak is strongly enhanced in this spectrum due to the resonance in the cross section near 4.26 MeV. The simulation using RUMP is presented with solid line.

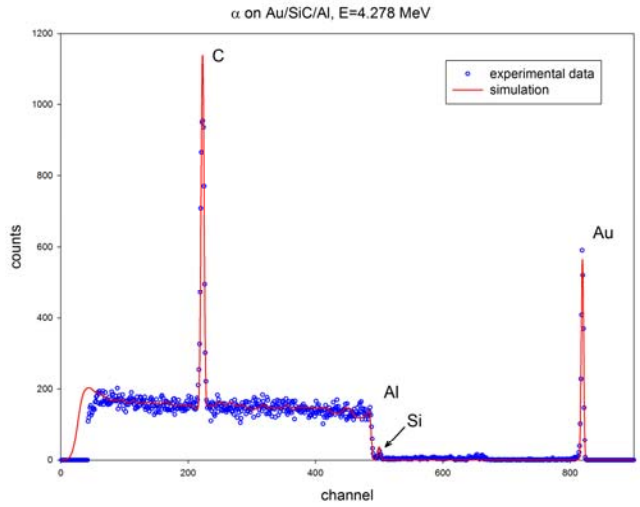

Fig. 3. Experimental spectrum registred for 4.278 MeV incident energy on Au/SiC/Al target. On the figure is marked the scattering on the surface of each layer of the target.

The N_C, N_{Au} channels were determined from the RBS spectrum; the N_α channel was determined from the alpha spectrum of the ^{239}Pu + ^{241}Am source, measured at the same gain as the backscattering spectrum. Solving the equation system a value of E = (4278.0 ± 1.5) keV was obtained for the beam energy. The solution is implemented in the code RUMP. It may be observed from Fig.3 that RUMP simulation is very close to the experimental spectrum.

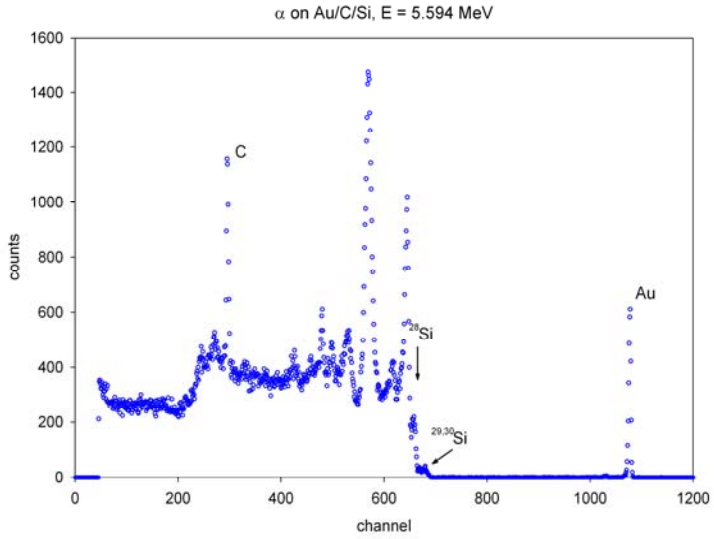

Fig. 4. Experimental spectrum registred for 5.594 MeV incident energy on Au/Si target.

Fig. 4 shows a backscattering spectrum for ^4He on Si/C/Au sample measured in March 2011. The maxima in the spectrum of elastic scattering on Si correspond to resonances in the cross section. In this experiment we measured RBS spectra at 9 energies between 4.4 and 5.6 MeV where some resonances occur in $^{28}Si(^4He, ^4He)^{28}Si$ elastic scattering. Fig.5 shows the spectrum from the ^{239}Pu + ^{241}Am alpha source, measured at the same gain as the backscattering spectra. For the spectrum presented in Fig.3 the N_C, N_{Au} channels were determined; the N_α channel was determined from the alpha spectrum of the ^{239}Pu + ^{241}Am source presented in Fig. 5.

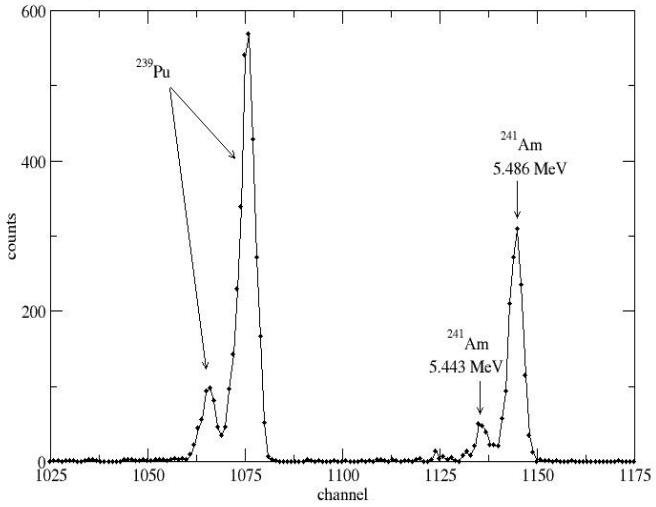

Fig. 5. The pulse height spectrum of the alpha source. The full line is just for guiding the eye.

Solving the equation system a value of E = (5594.0 ± 1.8) keV was obtained for the beam energy. The solution was implemented in the code RUMP. The positions of the C and Au peaks were reproduced. To analize the rest of the spectra collected recording also the corresponding NMR frequency we maintained the energy calibration of the spectra and tried different beam energies until the best reproduction for the positions of C and Au peaks was obtained.

In Fig. 6 we present a plot of our measured beam energies versus squares of the corresponding NMR frequencies. The solid line represents the best linear fit to the experimental points. Assuming that no correction due to relativistic effects is performed this is a good linear fit. Note that the relativistic correction is small any way.

Using the measured beam energies and NMR frequencies the magnet constant, K for each beam energy was calculated using the usual relativistically correct expression. The results are presented in Table I. The results of the previous measurements are also included.

A plot of K values versus equivalent proton energy is presented in Fig. 7. The magnet constant decreases with equivalent proton energy from 2 to 4 MeV. This is most probably a result of the rapid onset of saturation of the iron at the entrance and exit edges of the pole faces. As the saturation increases, a higher field is required over the reminder of the orbit and at the NMR probe position to maintain the same average field over the trajectory. Other similar studies have shown the same effect [12, 13, 14, 15].

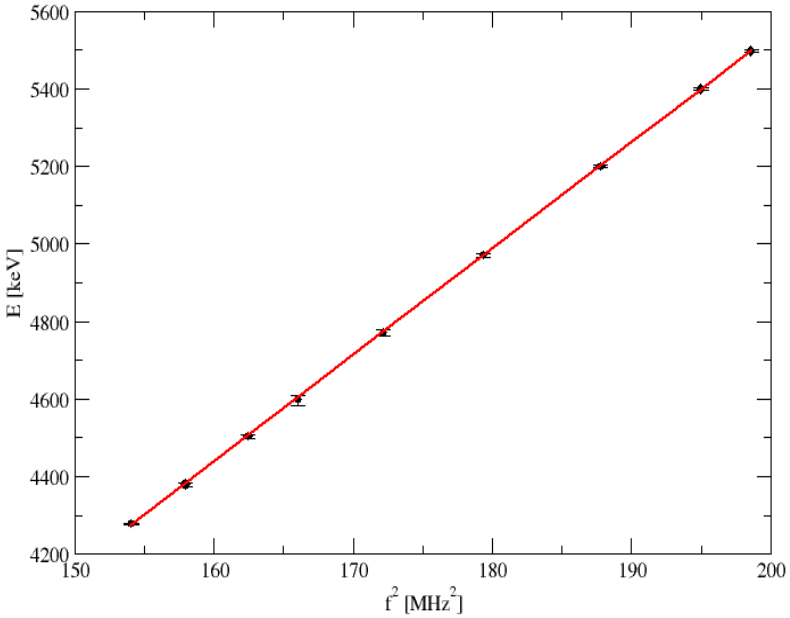

Fig. 6. Incident energies determined with the presented calibration method as a function of the NMR frequencies.

Table 1

Incident energies, corresponding frequencies measured with the NMR probe and the calculated calibration constants. The data marked with * are from previous measurements.

E ± ΔE keV	f ± Δf MHz	K ± ΔK keV·amu/e^2·MHz^2	ME/Z MeV·amu/e^2
4278 ± 2	12.412	27.803 ± 0.010	4.279
4380 ± 5	12.567	27.768 ± 0.028	4.383
4504 ± 5	12.745	27.763 ± 0.028	4.507
4597 ± 13	12.886	27.720 ± 0.078	4.600
4770 ± 8	13.122	27.738 ± 0.048	4.773
4970 ± 6	13.393	27.744 ± 0.035	4.973
5200 ± 3	13.703	27.730 ± 0.014	5.203
5400 ± 2	13.964	27.731 ± 0.010	5.403
5498 ± 2	14.093	27.720 ± 0.011	5.501
5594 ± 2	14.216	27.715 ± 0.009	5.598
*2168 ± 1	8.861 ± 0.003	27.860 ± 0.033	2.168
*5802 ± 1	14.5428 ± 0.0006	27.720 ± 0.003	5.802
*11340 ± 1	20.2450 ± 0.0005	27.724 ± 0.009	11.341
*14230.7 ± 0.2	22.81971 ± 0.009	27.730 ± 0.009	14.231

For higher equivalent proton energies the value of K remains constant down to about 4 MeV. We were calculating an average value for K by the method

of least-squares. All data from our measurements were included in the average. A value of K=27.742 ± 0.004 keV·amu/e^2·MHz^2 was obtained. This value is in agreement with the average value K=27.720 ± 0.003 keV·amu/e^2·MHz^2 obtained from previous measurements.

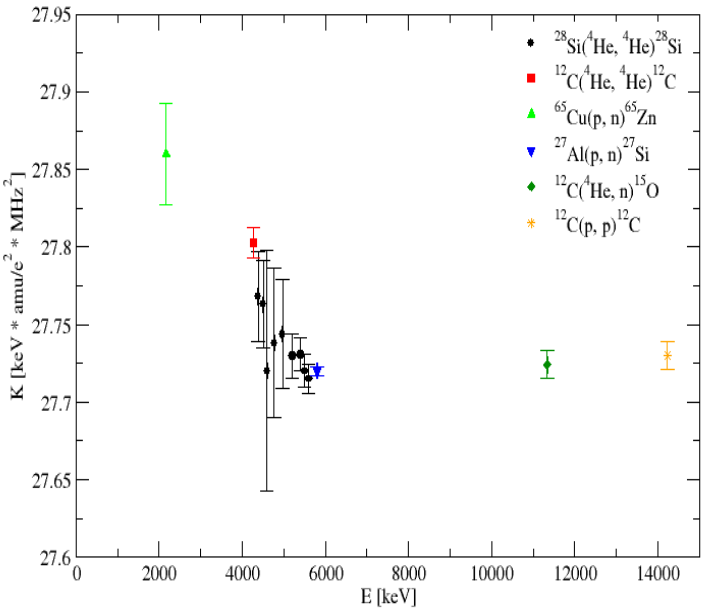

Fig. 7. Analysing magnet calibration constant versus equivalent proton energy. With red and black symbols are represented calibration points obtained during the latest measurements.

3. Conclusions

The backscattering technique described in this paper provides a relatively simple method for calibration of accelerators such as the Bucharest FN tandem accelerator in the energy region around 5 MeV. The calibration of the analysing system was completed for equivalent proton energy spanning the range 4.265 to 5.594 MeV. This yields a new calibration of the magnet analysing system with a minimum of systematic errors. In fact, the method is reliable for incident ^{4}He energies higher than that studied here.

This approach has the advantage that it can be applied continuously at any beam energy, without the need for the interpolation between nuclear resonance energies or (p, n) thresholds energies. Several particle spectra can be collected at different beam bombarding energy relatively fast. The results obtained in our measurements are consistent with previous results based on the T=3/2 resonance in ^{12}C + p reactions and thresholds measurements in (p, n) and (α, n) reactions.

The calibration obtained for the Bucharest FN tandem accelerator determines analysed beam energies to better than 0.3%, provided the analysing slits are set sufficiently narrow and the magnet is recycled to minimize differential hysteresis. For equivalent proton energy from 2 to 4 MeV the magnet constant decreases, most probably as a result of the rapid onset of saturation of the iron at the entrance and exit edges of the pole faces. A similar effect was observed in the analysing systems of several other laboratories. The calibration is linear for fields up to 0.33 T. We intend to extend the measurements to higher magnetic fields.

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