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MEASURING NUCLEAR EXCITATION ENERGIES AND Q-VALUES WITH A CYCLOTRON–MAGNETIC SPECTROGRAPH SYSTEM*

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Nuclear excitation energies and reaction Q-values have been measured with the M S U. cyclotron–magnetic spectrograph system with uncertainties on the order of 1 keV or less. The method involves a spectrograph calibration procedure which utilizes a combination of momentum-matching and kinematics techniques. The calibration lines used in the present work are independent of any previous spectrograph based on the ^{210}Po(α) energy scale. The present work is also largely independent of Ge(Li) gamma detector measurements, and provides independent consistency checks on previous measurements at the 1 keV uncertainty level. Sample results include checks on the excitation energies of the first excited state of ^{12}C and the third excited state of ^{24}Mg. The excitation energy of the first excited state of ^{11}C and the Q-values for the reactions ^{24}Mg(p,d)^{23}Mg and ^{24}Mg(p,t)^{22}Mg are also presented.

1. Introduction

The importance of highly accurate nuclear excitation energies and nuclear reaction Q-values is well established. For example, nuclear structure studies often require the investigation of the levels of a given nucleus via many different experimental techniques. It is the comparison of the properties of a given level in the different reactions that is most relevant in the testing of nuclear theories. Hence the levels of interest must not only be resolved from neighboring levels but also identified unambiguously. Such ambiguity is currently an often recurring problem in the comparison of direct reaction charged particle spectra with the generally much more accurate γ-ray data on the same nucleus. Accurate excitation energies for high lying levels are also useful and sometimes essential in placing unambiguously cross-over γ-rays in a particular decay scheme.

Precise nuclear reaction Q-values or mass differences are also needed for several reasons in nuclear physics. One very active field, for example, is the search for a deviation from the purely quadratic prediction of the isobaric multiplet mass relationship[1,2]). It is now obvious that this requires masses of ground states and of certain excited states with uncertainties of 1 to 5 keV or less[3,4]). Other uses of accurate Q-values are in studies of nuclear Coulomb energy systematics[5,6]), in extracting precise β-decay matrix elements[7]), and in establishing the mass relationship of Garvey et al [8]) on the proton rich side of the line of nuclear stability.

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The method described in this paper combines momentum matching[9,10]) to determine the beam energy, kinematics to determine the scattering angle, and previously known energy levels to determine the spectrograph calibration. It is possible with the present method to make independent checks of data based on the Po(α) standard as well as checks of measurements made with Ge(Li) gamma detectors The advantages and disadvantages of this method of spectrograph calibration are compared in a later section with the ^{210}Po alpha calibration used, for example, by Browne et al.[11,12]).

2. Description of experimental set-up

The measurements described in this paper utilized 30–40 MeV proton beams of the Michigan State University Cyclotron and an Enge split-pole magnetic spectrograph[13]). Kinematic compensation, as described by Enge[13]), is accomplished by moving the plate holder to a position which compensates for the kinematic variation of energy with angle ($dE/d\theta$) In addition, by focussing the beam spot such that there is the proper amount of linear variation of energy with position on target some compensation for a finite energy spread in the beam can be made. Using this dispersion matching and kinematic compensation it has been possible to obtain direct reaction spectra with line widths of 3–7 keV fwhm with a beam whose energy spread is many times greater[14,15]). In general, however, conditions are optimum for only one reaction in any given run. Hence in the context of the present work where several different calibration reactions from several different mass targets are observed simultaneously certain compromises are necessary.

Neither dispersion matching nor kinematic compensation are essential to the present method of highly precise energy measurements, but do allow increased counting rates for a given experimental resolution. The resolution does affect the accuracy to which centroids of lines can be determined, but, to obtain precisions ~ 1 keV line widths of $\lesssim 30$ keV are adequate if the statistics are good enough. Hence the present method is quite general and is applicable to any accelerator–magnetic spectrograph system.

3. Momentum matching technique

The present work is an extension of the method for energy calibration of the beam analysis system previously developed at MSU by Trentelman and Kashy[9]). That method, referred to as the momentum matching technique, has also been used in nuclear Q-value measurements[4]). This method utilized a short position-sensitive detector at one position in the focal plane of the spectrograph. The broad range feature of the magnet was not needed or used, and the method was also independent of any spectrograph calibration.

To illustrate the momentum matching principle an example of one beam energy determination will be described with the aid of the kinematics illustrated in figs. 1–3 (see also ref. 9). Using a thin carbon target on a formvar backing it is possible to obtain the double momentum crossovers indicated in the figures at one and only one beam energy and one and only one scattering angle for the set of reactions ^{12}C(p, p), ^{12}C(p, d) and of ^{12}C(p, p′) 4.439, ^{1}H(p, p). In other words, once this double crossover is obtained the average beam energy is determined to be 33.964±

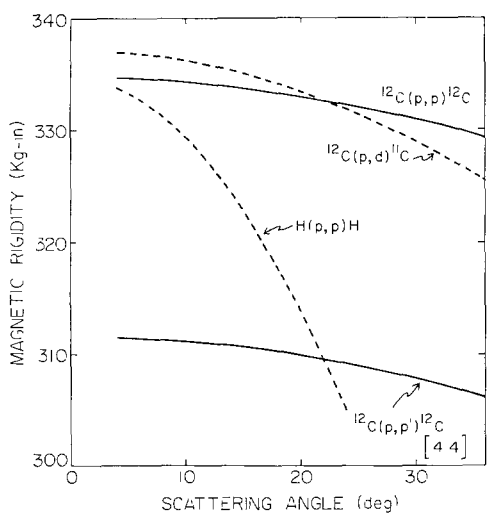

Fig 1 Magnetic rigidities of reaction products as a function of scattering angle at a fixed beam energy of 33.964 MeV

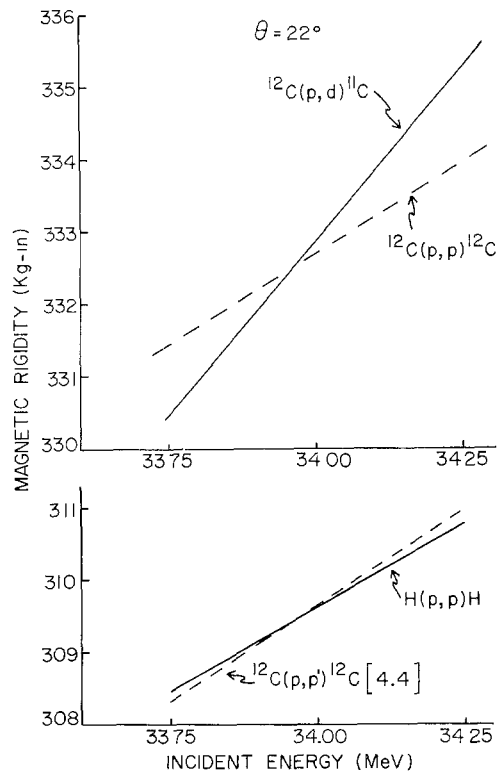

Fig. 2. Magnetic rigidities of reaction products as a function of beam energy at a fixed scattering angle of 22°.

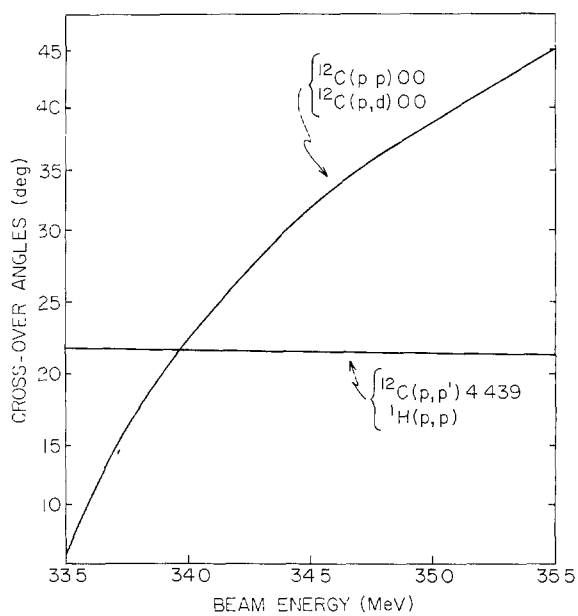

Fig 3. Graphs of the momentum match crossover angles as a function of beam energy for two separate reaction pairs.

0.002 MeV and the lab scattering angle is 22.01° independent of any previous energy or angle calibrations. At this double crossover condition the $^{12}C(p, d)$, $^{12}C(p, p)$ group has a magnetic rigidity of 332.50 ± 0.01 kG·in and is useful in spectrograph calibration at relatively high magnetic fields. The indicated uncertainties are due to the $^{12}C(p, d)$ Q-value uncertainty; the actual experimental uncertainties are larger due to errors in centroid determination, etc. In practice, beam energies determined by this method are believed to be accurate to about ± 5 keV. The double crossover condition is unique because the (p, d) and elastic proton momentum match angle is quite sensitive to the beam energy whereas the $^{12}C(p, p')$ and $^{1}H(p, p)$ crossover angle is approximately independent of beam energy as indicated in fig 3. Because the deuteron mass is twice the proton mass the (p, d) line in fig. 2 moves vertically twice as fast as the proton lines when the beam energy is changed. Actually the $^{1}H(p, p)$ energy crossover has been used previously in beam energy determination (as opposed to angle determination) [16]) but this method required an independent highly accurate knowledge of the scattering angle. As can be seen by the slope of the curve in fig. 3 this crossover in the spectrograph is rather insensitive to the beam energy; an uncertainty of 0.1° in this angle implies an uncertainty of 300 keV in beam energy at 35 MeV.

Using other combinations of reactions, beam energy calibrations have been done at 23, 27, 34 and 40 MeV [17]). These points when combined with precisely known reactions have provided a curve for the effective radius of curvature vs the spectrograph magnetic field as measured by NMR frequency at a given point in the spectrograph focal plane. Thus unknown Q-values and excitation energies can be determined by measuring the magnetic field necessary to bring the groups of interest to this point in the focal plane, i.e. the various particle groups and crossovers are observed on the detector in sequential runs. Small fluctuations in beam energy and beam spot position on target represent the main limit of this method and could result in errors of typically about ± 5 keV in Q-values or excitation energies for single measurements. Of course these errors can be reduced by averaging several series of measurements.

The present paper presents a generalization of the momentum matching method which utilizes the broad range aspect of the spectrograph and improves the ultimate accuracy by a factor of 5 or more by avoiding the uncertainties inherent in sequential measurements. The main difference is that all calibration lines and unknown lines are recorded in a single exposure on nuclear emulsions. The criteria for choice of calibration lines and the details of the data analysis are given in the next section.

4. Spectrograph calibration method

The present method uses the momentum matching concept, kinematics, and previously known energy levels in a single spectrograph exposure to provide all the information necessary to determine the spectrograph calibration coefficients, the beam energy and scattering angle as well as new information on nuclear reaction Q-values and excitation energies. As an example of this technique consider the exposure illustrated schematically in fig. 4. In this exposure a thin ^{24}Mg target on a carbon plus formvar backing was bombarded with 35 MeV protons and the particles detected at 10°.

The effective radius of curvature ρ of particles in the spectrograph vs distance D from the high ρ end of the focal plane is assumed to satisfy the equation:

$$\rho = \rho_0 + \alpha(D - D_0) + \beta(D - D_0)^2,$$

where D_0 represents the distance from the end of the focal plane about which the expansion is done, ρ_0 is effective the radius of curvature at the distance D_0, and α, β are the linear and quadratic expansion coefficients, respectively. Thus in any given exposure there are five unknowns: ρ_0, α, β, the beam energy E_p, and the scattering angle Θ. The present measurements were all done in the first 32 cm of the high ρ end of the spectrograph focal plane (about 10 MeV proton energy range). Reproducibility and consistency checks at the ± 1 keV level have indicated that it is sufficient to use a ρ-vs-D curve with only a small quadratic term and no higher order terms over this region of the focal plane.

In general the independent determination of these five unknowns would be difficult even with a large number of calibration lines, due to ambiguities or correlations between the various unknowns. For example, the beam energy and angle are often highly correlated because increasing the scattering angle shifts peaks in the same direction as decreasing the beam energy However, if the calibration lines are properly chosen all five unknowns can be determined approximately independently by a single χ^2 minimization. This can be shown qualitatively by reference to the six calibration lines used in the current example shown in fig. 4. Firstly, the energy scale in the region of the elastically scattered protons is mainly determined by the separation of the $^{24}Mg(p, p)$ elastic from

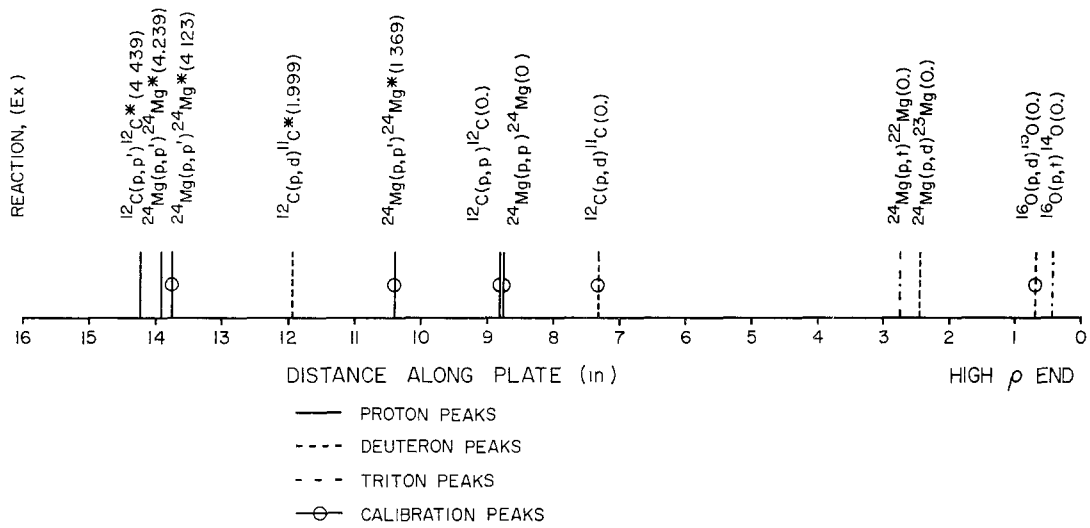

Fig. 4. Plot of the peak positions in the focal plane of the spectrograph for a typical exposure. The peaks used in the spectrograph calibration are so indicated.

the $^{24}Mg(p, p')\,2^+$ first excited state ($E_x = 1.36857 \pm 0.00004$ MeV) [18]). The scattering angle is then determined by the position of the $^1H(p, p)$ peak as well as the separation of the $^{12}C(p, p)$ and $^{24}Mg(p, p)$ elastic peaks since their kinematic shifts are significantly different. The position of the $^{12}C(p, d)$ ($Q = -16.234 \pm 0.001$ MeV) [19]) is then quite sensitive to the beam energy due to the factor of two differences in the variation of magnetic rigidities of the protons and deuterons as the energy is changed. The quadratic term is determined by the $^{24}Mg(p, p')\,4^+$ second excited state ($E_x = 4.1226 \pm 0.00013$) [18]) at one end of the energy scale and the $^{16}O(p, d)\,^{15}O$ ground state ($Q = 13.4393 \pm 0.0008$) [20–22]) at the other end

It is possible to find a unique solution via an iterative process by proceeding qualitatively as described above Starting with nominal values for all parameters, corrections are made sequentially to improve the overall agreement between the actual and calculated peak positions. The solution is reached via a χ^2 search procedure starting with a separate equation for the magnetic rigidity of each calibration line. The nominal magnetic rigidity $(B\rho)_0^i$ of calibration line "i" is determined by reaction kinematics at the nominal beam energy E_0 and the nominal scattering angle Θ_0. The actual magnetic rigidity $B\rho^i$ of that peak at the true beam energy

$$E = E_0 + \Delta E,$$

and true scattering angle

$$\Theta = \Theta_0 + \Delta\Theta,$$

is given by the expansion:

$$B\rho^i = (B\rho)_0^i + \frac{\partial B\rho^i}{\partial E}\Delta E + \frac{\partial B\rho^i}{\partial \Theta}\Delta\Theta.$$

The magnetic rigidity is also related to the actual distance D^i of the peak from the end of the focal plane:

$$B\rho^i = B[\rho_0 + \alpha(D^i - D_0) + \beta(D^i - D_0)^2],$$

with ρ_0, α, β being the unknowns of the spectrograph calibration. Thus for each calibration line there is an equation with five unknowns:

$$-\frac{\partial B\rho^i}{\partial E}\Delta E - \frac{\partial B\rho^i}{\partial \Theta}\Delta\Theta + \alpha B(D^i - D_0) +$$

$$+ \beta B(D^i - D_0)^2 + B\rho_0 = (B\rho)_0^i.$$

With five or more appropriately chosen calibration lines the optimum values of the five unknowns can be found via a χ^2 minimization procedure. The choice of calibration lines is related to the coefficients $(\partial B\rho/\partial E)^i$ and $(\partial B\rho/\partial\Theta)^i$. For various excited states resulting from the same reaction the corresponding coefficients are approximately equal [see the $^{12}C(p, p)$ and $^{12}C(p, p')$ curves on figs. 1 and 2]. For the same nuclear reaction from various mass targets the angular coefficients vary while the energy coefficients are approximately equal [see the $^{12}C(p, p)$ and $^1H(p, p)$ curves on figs. 1 and 2]. In general, both coefficients vary for different outgoing particles with the energy coefficient for deuterons being approximately twice that of protons [see the $^{12}C(p, p)$ and $^{12}C(p, d)$ curves on figs. 1 and 2].

TABLE 1

Typical calibration parameters resulting from a χ^2 fit on the lines indicated in fig. 4 plus $^1H(p, p)^1H$ Nominal beam energy· 33.940 MeV, nominal scattering angle: 15°.

Fit	Parameters	Standard deviations	Correlation coefficients				
			E	Θ	α	β	ρ_0
ΔE	+6.2 keV	0.1 keV	1.00	0.27	0.01	0 48	0.67
$\Delta\Theta$	0.17°	0.04°		1.00	0.26	0.66	−0.36
α	−0 40280	1.0×10^{-5}			1.00	0.55	−0.20
β	+0.000100 in^{-1}	8.3×10^{-6} in^{-1}				1 00	−0 23
ρ_0	32.360 in	7. $\times10^{-5}$ in					1.00

In practice, the centroid positions of the chosen calibration lines and the nominal beam energy and scattering angle are input to a χ^2 minimization program. Centroid positions of unknown lines and a list of possible nuclear reactions are also input. The program performs a least squares fit to determine the spectrograph calibration coefficients, a correction to the nominal beam energy, and a correction to the nominal scattering angle. The fit parameters and their standard deviations are calculated along with the resulting χ^2 and correlation coefficients between the fit parameters. An inappropriate choice of calibration lines can produce correlation coefficients near 1.0 indicating that the corresponding unknowns were not determined independently. The correlation coefficients are, therefore, useful in determining the significance of the various fit parameters. Sample parameters resulting from a fit on the exposure of the type indicated in fig. 4 are given in table 1.

The program also calculates the Q-values and excitation energies for all of the unknown peaks for the list of possible reactions given in the input. In the present work, for example, the excitation energies of the first excited states of ^{12}C and ^{11}C were included in the list of unknowns.

TABLE 2

Types of measurements which can be made, with indication of typical uncertainties to be expected

	Typical uncertainties to be expected with 35 MeV proton beam
I. Excitation energies	
A. Inelastic scattering with calibration lines from same nucleus.	0 4 keV at 4 MeV excitation
B. Inelastic scattering with calibration lines from different mass nucleus.	0.5 keV at 4 MeV excitation
C. Reaction other than inelastic scattering with no calibration lines from same residual nucleus.	0.6 keV at 4 MeV excitation
II. Reaction Q-values	
A. Reference Q-value from same reaction on different nucleus.	0.8 keV + reference Q-value uncertainty
B. Reference Q-value from different reaction, different outgoing particles.	1.0 keV + reference Q-value uncertainty

5. Sample results

Types of measurements using this technique are illustrated in this section with sample numerical results. Since the different types of measurements have different sensitivities to the beam energy, scattering angle, etc., they are listed in table 2 in order of increasing experimental uncertainty. The excitation energy uncertainties include typical contributions of ≈ 0.1 keV from known calibration lines up to ≈ 4 MeV. In the case of Q-value measurements there are very few appropriate reference Q-values known to 1 keV or better so it is the relative Q-value which is best measured by this method. The possibility of making such Q-value measurements absolute is discussed in a later section. The uncertainties listed in table 2 are obtainable by averaging 2 or 3 experimental runs and could be reduced further by averaging a larger set of data.

The easiest kind of measurement is type I.A from table 2. An example of this type is the measurement of the excitation energy of the third excited state (2^+) of ^{24}Mg. The first excited state (2^+) and second excited state (4^+) are both well known calibration

lines with published uncertainties of 0.04 and 0.13 keV respectively[18]). We have determined the third excited state to be 115.6 ± 0.4 keV higher than the second excited state, this result being quite insensitive to the exact beam energy or scattering angle. Hence we obtain an excitation energy of the second 2^+ state of ^{24}Mg of 4238.3 ± 0.4 keV which is in good agreement with the value 4238.7 ± 0.4 keV obtained by Meyer et al.[23]) via the ^{23}Na(p, γ) reaction.

A measurement of the second type is the comparison of the excitation energy of the first excited state of ^{12}C with that of the second excited state of ^{24}Mg. Our results are compared with those from two other types of measurements in table 3. The present result is in good agreement with those of the Ge(Li) measurements, but is slightly lower than the value determined by Stocker et al.[12]). The later spectrograph measurements were based on the energy of ^{210}Po (α) decay, whereas the present work used as standards the excitation energies of the first 2^+ and 4^+ levels of ^{24}Mg. These levels of ^{24}Mg are known relative to a primary standard, the ^{198}Hg 412 keV γ-ray, via an iron-free spectrometer measurement[18]). The current work is, therefore, independent of any previous Ge(Li) γ-ray measurements even though it refers back to the same primary standard.

A result of the third type is illustrated by the determination of the excitation energy of the first excited state of ^{11}C. Since the (p, d) reaction is involved, there is greater sensitivity to kinematics and target thickness effects than for the (p, p′) reactions. The present result for this $1/2^-$ state in ^{11}C is $E_x = 1999.7 \pm 0.5$ keV compared to the previous value of 1995 ± 3 keV[24]), and represents an average of several determinations since this state has been seen as an impurity in many experimental runs. This state now provides an accurate momentum match point for a proton beam energy determination of about 38 MeV.

The Q-value of the ^{24}Mg(p, d) reaction has been measured to be -14.3075 ± 0.0015 MeV via the present method. The 1971 mass table value of -14.3059 ± 0.0026 MeV [19]) was inferred from a loop involving ^{23}Na(p, n)^{23}Mg, ^{23}Na(n, γ)^{24}Na, ^{24}Na(β^-)^{24}Mg and other less direct measurements. Thus the present measurement helps to confirm the consistency of these earlier measurements. The dominant calibration line in the present measurement was the ^{16}O(p, d) ground state transition which has a recently determined Q-value of -13.4393 ± 0.0008 MeV [20–22]).

The ^{24}Mg(p, t) ^{22}Mg ground state transition was also observed in the present work and was determined to have a Q-value of -21.1983 ± 0.0015 MeV which is 10.5 keV less negative than the 1971 mass table value of -21.2088 ± 0.0090 MeV [19]). However, the mass excess of ^{22}Mg inferred from the present measurement is -0.394 ± 2 keV which is in agreement with the value -391 ± 11 keV obtained from a previous ^{20}Ne(^{3}He, n) Q-value measurement[25]). There were two convenient reference lines for the present measurement, both the ^{16}O(p, d) and ^{16}O(p, t) ground state transitions. These lines were internally consistent with the published masses of ^{15}O and ^{14}O to within ± 1 keV [19–22]). Because of their importance in the determination a β-decay coupling constants[7]) mass measurements of other $T_z = -1$ nuclei in the s–d shell are currently in progress[26]).

TABLE 3

The excitation energy of the first excited state of ^{12}C measured via three different experimental methods.

Excitation energy (keV)	Technique	Standards	Ref.
4439.2 ± 0.5	Spectrograph	^{24}Mg 4122.66 keV level	Present
4442.2 ± 1.5	Spectrograph	^{210}Po α source	12
4439.5 ± 0.3	Ge(Li) γ detector	^{56}Co γ calibration	a

[a] The weighted average of 4439.0 ± 1 (ref. 21), 4439.12 ± 0.31 (ref. 34) and 4440.2 ± 0.5 (ref. 35).
Nuclear recoil energy corrections have been made.

6. Sources of uncertainties

The sizes of the uncertainties associated with measurements of the types given in the previous section will vary somewhat from case to case depending on the strength of the particular line in question, the distance from relevant calibration lines, target thickness uncertainties, experimental resolution, etc. The errors are generally larger in relative Q-value measurements between dissimilar reactions and smaller in excitation energy measurements in inelastic scattering. However, some indication of the various contributions to the overall experimental uncertainties can be given for typical cases and this is done in table 4 for 35 MeV protons and a 100 μg/cm^2 target.

Of the various sources of error listed in table 4 the least understood at the present time is the ρ-vs-D curve. The standard ^{210}Po α-particle calibration is not used in this spectrograph for several reasons: Firstly, with our combination of high resolution and low dispersion it is necessary to determine centroids to an accuracy of 0.02 mm or better. To do this conveniently would

TABLE 4

Approximate contributions to experimental uncertainties.

	E_x in (p,p′)	Q-values
I. Internal errors[a]		
A. Statistical		
1 Beam energy uncertainty (1 10 000).	<0.1 keV at 4 MeV	≈ 0.3 keV
2 Scattering angle uncertainty (0.1°).	~ 0.1 keV at 4 MeV	≈ 0.3 keV
3. Peak centroid uncertainty.	$\lesssim 0.3$ keV	≈ 0.3 keV
B. Systematic		
1. Target thickness corrections	≈ 0	≈ 0.3 keV
2. Uncertainties in ρ vs D curve.	≈ 0.2–1 keV	≈ 0.3 keV
3. Asymmetric peaks	≈ 0	<0.3 keV
II. External errors		
Calibration line uncertainties	$\lesssim 0.1$ keV up to 4 MeV excitation	≈ 1 keV

[a] The numbers correspond to averaging two runs and could be reduced by averaging a larger number of runs at different fields, beam energies, etc.

require an α source 0.3 mm wide with a resolution of about 1 keV. Secondly, since the Enge split-pole spectrograph[13]) and others such as the $Q3D$ magnets[27]) are multiple pole face double-focussing magnets, saturation effects are likely to be important, particularly since the magnetic rigidity of the Po(α) is far smaller than those of typical reaction particles with 35 MeV protons. Finally, a ρ-vs-D curve obtained with α-particles requires a series of magnetic field changes in placing the alpha group at different positions on the focal plane, and thus requires some untested assumptions on magnetic field scaling. The variations (with magnetic field) in the shape of the ρ-vs-D curve have not yet been measured for the Enge split pole. Since such measurements may reduce the residual uncertainties in the present experiments they are planned for the near future at M.S.U.

7. Choice of calibration lines and comparison with other energy standards

Most previous spectrograph work has used the ^{210}Po α-decay energy as a calibration standard. This energy is known to an absolute accuracy of about 100 parts per million[11]). On the other hand, the primary standards for most gamma-ray measurements, are either the 412 keV transition from the decay of ^{198}Au which is known to an absolute accuracy of about 18 parts per million or the 59 keV W K_{α_1} X-ray which is known to an absolute accuracy of about 14 parts per million (see, for example, the discussion of these standards in ref. 28). Secondary gamma ray standards have been established up to 2.75 MeV via conversion electron momentum ratio measurements in iron free spectrometers[18])

In an independent check of one of these secondary standards against the Po (α) scale Stocker et al.[12]) found the scales to be consistent to within the accuracy of their comparison ($\pm$400 parts per million).

For reasons such as the ones mentioned in the previous section the present work is not referred to the Po (α) absolute energy scale. Instead, the present excitation energies have used the first 2^+ and 4^+ levels of ^{24}Mg as calibration lines since these are included in the set of secondary standards mentioned above. In fact the 4^+ 4.12 MeV energy level of ^{24}Mg is the highest energy level measured via such direct techniques. In this sense the present method determines excitation energies in a way which is independent of any Ge(Li) detector gamma measurement, and makes independent checks of such work. Our check of the excitation energy of the first excited state of ^{12}C is such a case, and the agreement is indeed excellent (see table 3).

The ^{11}C mass used in our beam energy determinations is also independent of Ge(Li) gamma ray measurements, but is less directly tied to an absolute scale. This mass (relative to ^{12}C) was determined via an absolute ^{11}B(p, n)^{11}C threshold measurement ($\pm$1 keV)[29]) combined with the ^{11}B–^{12}C mass spectrographic measurement ($\pm$0.3 keV) of Smith[30]).

Most Q-value measurements, such as those of the ^{24}Mg(p, d) and ^{24}Mg(p, t) reactions are not determined independent of Ge(Li) gamma measurements. It is possible in special cases, however, to use only reference lines which have been determined by direct mass spectroscopy. For example, the ^{11}B–^{10}B mass difference has been measured to $\pm$0.4 keV by Smith[30]) and the corresponding ^{11}B(p, d) ^{10}B Q-value is $-9.2314\pm$ 0.0004 MeV. This provides an accurate beam energy momentum match point at about 18 MeV proton energy and a good Q-value reference line for other similar Q-values The ^{10}B–^{11}B mass difference has also been measured to $\pm$2 keV relative to the Po alpha energy scale[31]) and to $\pm$1 keV via (n, γ) with Ge(Li) detectors[32]) and all three measurements are in agreement at this level of accuracy.

Finally, it should be possible in the future to base the

present types of measurements on the new time-of-flight energy scale currently being developed at the Munich MP tandem Van de Graaff[33]). If appropriate Q-values and excitation energies are measured with the Munich system and then used as standards with the present spectrograph calibration method, the result would be a very precise and flexible system with an energy scale based mostly on frequency and distance measurements and independent of previous gamma-ray, charged-particle, and mass spectroscopic work.

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