Redetermination of (p,γ) Resonant Energies Used as Fixed Points on the High-Energy Scale

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In order to clear up a discrepancy in the existing absolute measurements of (p,γ) resonances, the proton energies at which strong fluorine and aluminum (p,γ) resonances occur were measured using a 36-in. radius absolute electrostatic analyzer and compared with measurements for the lowest energy fluorine resonance which had been measured previously using a 12-in. absolute electrostatic analyzer. An accuracy of one part in a thousand is claimed for both instruments and the disagreement was found to be less than 1.5 parts in a thousand. Weighted mean values of fluorine resonances, based on two analyzers, were found to be 340.7 $\pm$0.3 kev, 484.3$\pm$0.3 kev, 873.5$\pm$0.7 kev, 1347.7$\pm$1.0 kev, and 1373.7$\pm$0.8 kev. These are compared with the values obtained by other workers in this field, and found to be in good agreement with those of Herb *et al.* and Bondelid *et al.* but discrepancies exist between the present measurements and those of Bumiller *et al.*

1. INTRODUCTION

THE absolute determination of the proton energies at which well-defined nuclear events such as sharp (p,γ) resonances occur can be used to define the high-energy and high-voltage scale, and these determinations are useful calibration points for workers who do not wish to make absolute measurements of the incident particle energies involved in nuclear reactions.

In general, the agreement of absolute determinations of (p,γ) resonances in the energy scale below 500 kev is very good. For example, recent determinations of the energy of the lowest strong resonances in the $F^{19}(p,\alpha,\gamma)O^{16}$ reaction made by Bumiller *et al.*[1] and Bondelid *et al.*[2] are in excellent agreement with earlier determinations made by Morrish,[3] and by one of the present authors.[4]

In the higher energy range, considerable discrepancy exists between the absolute determinations from the various groups. For a very strong resonance in the same fluorine reaction, Herb *et al.*[5] obtained a value of 873.5 $\pm$0.9 kev, Hunt *et al.* a value of 874.5$\pm$0.9 kev, and more recently Bumiller *et al.* and Bondelid *et al.* obtained values of 871.3$\pm$0.4 kev and 872.4$\pm$0.4 kev, respectively. The total spread in the values obtained is of the order of $4/10^3$ and is inconsistent with the accuracy of one part in a thousand or better claimed by each of these groups.

The work described in this paper is an attempt to investigate this discrepancy, and the resonances chosen for this purpose were those in the $F^{19}(p,\alpha,\gamma)O^{16}$ reaction previously measured by one of the authors at 340.4$\pm$0.4 kev, 483.2$\pm$0.5 kev, 874.5$\pm$0.9 kev, 1348$\pm$1.4 kev, and 1375$\pm$1.4 kev, and an extremely narrow resonance in the $Al^{27}(p,\gamma)Si^{28}$ reaction previously measured by Bondelid at 992.4$\pm$0.5 kev, by Bumiller at 990.8$\pm$0.2 kev, and by Herb at 993.3$\pm$1.0 kev.

The inclusion of the lower fluorine resonances is of special interest, since these were initially measured at this Laboratory using a small, 12-in. radius, absolute electrostatic analyzer.[4] Measurements of these resonances using the larger analyzer enable a direct comparison to be made between values obtained using the two instruments.

The use of thin targets in the previous determinations from this Laboratory, while in general the other groups have used thick targets, has been instanced as a possible source of discrepancy and this has been carefully checked in the present work.

2. EXPERIMENTAL PROCEDURE

The beam from a pressurized Van de Graaff accelerator[6] was deflected using an absolute electrostatic analyzer. This was followed by a magnetic deflector to separate out the particles of unwanted mass, and those of the required mass were allowed to fall on calcium fluoride or aluminum targets evaporated on to copper backings. The γ rays were detected by a large sodium iodide crystal and the counts for a given target charge were recorded.

When a charged particle of mass, m, and charge, e, having fallen through a potential difference, E, is passed through a radial electrostatic field between curved electrodes, the energy Ee is given by

$$Ee=Ve\frac{a}{2d(1-\frac{1}{2}eV/m_0c^2)}$$

for symmetric charging of the electrodes, where V is the potential difference across the electrodes, a the geometric mean radius, and d their mean separation.

Measurement of the geometric parameters, a and d, and the deflecting voltages therefore enable precise determinations to be made of the particle energies,

[1] F. Bumiller, H. H. Staub, and H. E. Weaver, Helv. Phys. Acta. **29**, 83 (1956).
[2] R. O. Bondelid and C. A. Kennedy, Phys. Rev. **115**, 1601 (1959).
[3] A. H. Morrish, Phys. Rev. **76**, 1651 (1949).
[4] S. E. Hunt, Proc. Phys. Soc. (London) **A65**, 982 (1952).
[5] R. G. Herb, S. C. Snowden, and O. Sala, Phys. Rev. **75**, 246 (1949).
[6] D. R. Chick and D. P. R. Petrie, Proc. Inst. Elect. Engrs. **B103**, 132 (1958).

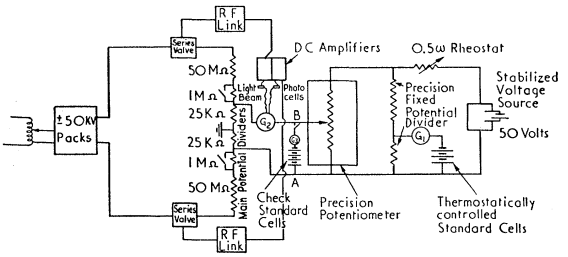

FIG. 1. Stabilizing circuit for ±50 kv deflector supply.

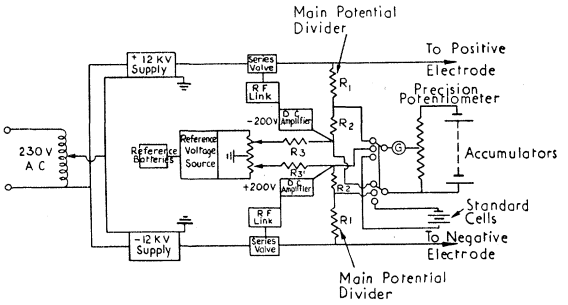

FIG. 2. The ±12 kv stabilized voltage supply.

providing that such factors as fringing fields, the effect of stray magnetic fields, orthogonality of entrance and emergent beams,[2,4,5,7] and the symmetry of the deflecting voltages are carefully measured.[2,4,5,7]

3. THE ELECTROSTATIC ANALYZER

The absolute electrostatic analyzer used for these determinations has been described in detail elsewhere.[7] The mean radius of curvature was 36 in. and the nominal separation of the electrodes $\frac{3}{8}$ in. The electrode separation was initially machined to a precision of 0.0002 in., but due to breakdown of the supporting insulators the deflector bars had to be removed, and when these were replaced with new insulators the variation in the separation along the length of the electrodes was 0.002 in. This was carefully measured using a dynamic air flow technique of sensitivity 0.00002 in. and a weighted mean gap taken as described by Herb.[5] Independent calculations at this Laboratory have shown that the additional errors due to gap nonuniformity are not greater than $1/10^4$.

Other sources of error due to analyzer geometry have been discussed previously and were estimated to be less than $4/10^4$. Bondelid has shown that in the case of the NRL analyzer,[2] deflection of the base-plate when the vacuum was applied to one side only could appreciably alter the electrode separation. This was checked on the present instrument by using dial gauges mounted from one electrode and bearing against the inner surface of the other. No observable deflection occurred when the vacuum chamber was evacuated using dial gauges of sensitivity 0.00005 in. This is no doubt due to the smaller area of the vacuum box, and the 4-in. deep radial webs used to stiffen the 1-in. thick base-plate on which the deflecting electrodes are mounted.

One other source of error not previously considered was the heating of the electrodes due to proton and secondary particle bombardment. Whilst the ratio $R/2d$ is normally independent of ambient temperature fluctuations, heating of the deflector bars only would be expected to change the separation.

This was a checked by running the analyzer under normal conditions for a period of about two hours, rapidly removing the vacuum box, and measuring the mean separation as a function of cooling time. The first measurement was made three minutes after irradiation had stopped and the gap was found to be slightly wider than when measured cold. The gap width approached its cold value after one hour and the difference between this cold value and the value obtained by extrapolating the separation-time curve back to zero time was 0.00007 in. corresponding to a correction in separation of $2/10^4$.

After prolonged use a dark deposit was formed on the parts of the inner surface of the electrodes adjacent to the beam. Although the thickness of this deposit was less than 0.0001 in., it was thought that if this were of imperfectly conducting material it could develop surface charges and affect the accuracy of the results. About half-way through the present series of measurements the deposit was removed using very fine emery cloth, the electrode separation was remeasured and further resonance determinations made. There was no significant difference between the two sets of measurements. A similar result has been reported by Herb.[5]

4. THE DEFLECTOR VOLTAGE SUPPLIES

The first series of measurements were made using the deflecting voltage supply described by Hunt and Firth.[7] This is shown schematically in Fig. 1. One possible source of error not previously considered was that due to mechanical drift of galvanometers G_1 and G_2. If this occurred, small currents would be required to give zero readings and any undetected out of balance currents would produce errors in the final voltage estimate. In order to check this, a second bank of standard cells and a sensitive galvanometer were connected between points A and B in Fig. 1 and the potentiometer adjusted for zero current in G_3. Sufficient cells were used in this second bank to correspond to an output voltage near that corresponding to the resonant energy being measured. Estimates of the deflector voltage with reference to the two sets of standard cells were found to be in agreement to $1/10^4$ in most cases, indicating that mechanical drifts in the zeros of G_1 and G_2 were negligible.

In a second set of measurements the stabilized voltage supply originally used in conjunction with the small electrostatic analyzer was employed. This is shown in Fig. 2. The voltage limit of this supply was ±12 kv so

[7] S. E. Hunt and K. Firth, Phys. Rev. **99**, 786 (1955).

TABLE I. Absolute values for (p,γ) resonances obtained in the present work.

Previous values	340.4[a]			483.2[a]			874.5[b]		$Al^{27}(p\gamma)Si^{28}$ 992.4[c]	1348[b]	1375[b]
	M_1	M_2	M_3	M_1	M_2	M_3					
Present values using ±12 kv voltage supply	340.9 ±0.1	340.9 ±0.06	340.8 ±0.06	484.7 ±0.06	484.5 ±0.05		873.8 ±0.12		993.7 ±0.06	...	...
	340.8(7)±0.05			484.6(0)±0.07							
							M_1	M_2			
Present values using ±50 kv voltage supply	341.1[d]	340.9 ±0.10	340.9 ±0.10	484.7[d]	484.6 ±0.10	484.7 ±0.2	874.1 ±0.15	873.8[e]	994.3 ±0.15	1348.4 ±0.3	1374.4 ±0.6
		340.9(7)±0.1			484.6(7)±0.15						
Mean absolute values (unweighted)		340.9(2)±0.10			484.6(3)±0.15		873.9(5) ±0.2		994.0 ±0.3	1348.4 ±0.3	1374.4 ±0.6
Mean half-widths		2.6 kev			1.5 kev		4.2 kev		<0.4 kev	4.2 kev	12 kev

[a] See reference 4.
[b] See reference 7.
[c] See reference 2.
[d] Three measurements only.
[e] One measurement only.

that the two higher energy fluorine resonances could not be measured.

5. LINEARITY OF ENERGY SCALE

Since one of the main objects of this work was to find any discrepancy between the previous low-energy resonance determinations using the small electrostatic analyzer and the higher energy resonance determinations using the large electrostatic analyzer, it was essential to check very carefully that the energy scale was linear. The variation of the high-voltage potential divider ratios with applied voltage was measured. No detectable variation was found in those employed on the first deflector voltage supply; those of the smaller deflector voltage supply varied by three parts in ten thousand over the voltage range of interest. The potential divider ratios increased reproducibly as the voltage was increased, so that the appropriate correction could therefore be applied to the resonance measurements.

As a more general check the lower resonances were observed using the Mass 1, Mass 2, and Mass 3 components of the incident beam. For a linear scale resonances were expected to occur at measured energies of E, $E(2+1/1840)$, and $E(3+2/1840)$, respectively. This was found to be true in the statistical accuracy of observations which was about $\pm 3/10^4$. Measurements made using the beams of different masses are listed separately in Table I.

6. TARGET TECHNIQUES

If a beam loses a small amount of energy ΔE transversing a target, the peak in the resonance curve will be observed at an energy[8] $E'=E_0+\Delta E/2$, where E_0 is the true resonant energy. Thin-target yield curves were taken for which ΔE, calculated from the amount of material evaporated and the stopping power curves, was between 0.3 and 0.5 kev at 1 Mev, and the appropriate correction was made at each energy.

In order to check the correction the target was rotated through 60° with respect to the incident beam, making its effective thickness $2\Delta E$. The resultant displacement $\Delta E/2$ between the two curves was in good agreement with the calculated thickness (Fig. 3).

Measurements were also carried out using targets of thickness ΔE appreciably greater than the natural half-width of the resonances. In this case the resonant energy is taken as that corresponding to half the maximum yield. The values obtained were not significantly different from those obtained using thin targets. Typical curves for the aluminum resonance observed from thick and thin targets are shown in Fig. 4.

Throughout the irradiations all targets were heated to a minimum temperature of 200°C and were mounted near to a liquid air trap in order to prevent the build-up of carbon films on the target surface. The absence of systematic drifts in resonance values, and the agreement of the displacement of the values when target was rotated confirmed that no appreciable carbon build up occurred. This was certainly less than 0.2 kev during the eight or nine hours for which a target was irradiated.

7. RESULTS

The results are shown in Table I. Each value quoted is the mean of about 10 determinations and the errors quoted are the standard deviations of the mean values.

In each set of results half the values were obtained with the analyzer rotated through an angle of 180° about a vertical axis to correct for possible nonorthogonality of the incident beam to the entrance plane of the analyzer.

It will be seen that the values for the higher fluorine resonances are in good agreement with those obtained by Hunt[7] using the same electrostatic analyzer. The correction found previously due to the heating up of the deflector electrodes and a slight underestimate of

[8] R. K. Tangen, Norske Videnskat. Selskab, Skrifter No. 1. (1946).

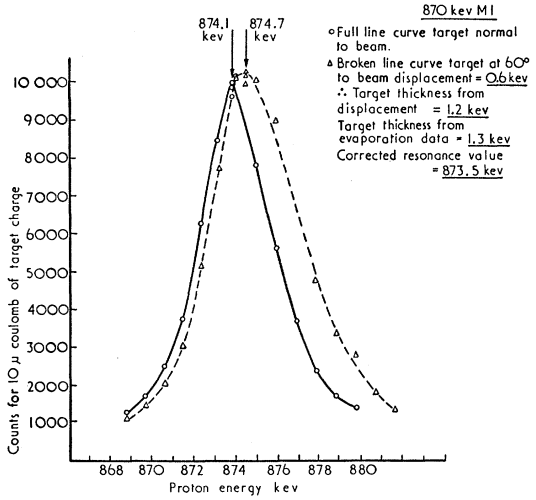

FIG. 3. Displacement of a thin resonance on rotating target through 60°.

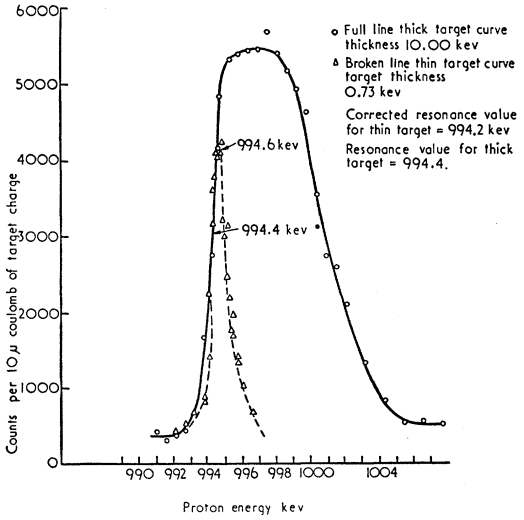

FIG. 4. Thick- and thin-target yield curves for aluminum.

the effect of electrostatic fringing fields would be expected to reduce Hunt's earlier values by 3/10[4].

The values obtained for the lower fluorine resonances are appreciably higher than those obtained using the small electrostatic analyzer previously described.[4] In particular, the 340.4-kev resonance then reported is remeasured in the present work at 340.9 kev, a discrepancy of almost 1.5 parts in a thousand. The stabilized voltage source used for about half of the present determinations was the same as that used in the earlier determinations so that any systematic error in this source should be common to both sets of readings. Even taking this into account the difference between the two determinations is not statistically significant. Nevertheless very extensive checks were made on the geometrical measurements of the large electrostatic analyzer and the accuracy of the deflector voltage measurements. These failed to reveal any errors in excess of the quoted uncertainties.

The half-widths of the resonances are shown in Table I. Those estimated from thick targets as the energy interval between one-quarter and three-quarters of the maximum yield, and those estimated from the thin-target curves where Γ_0, the true half-width, is equal to[8] $(\Gamma_m{}^2-\Delta E^2)^{\frac{1}{2}}$ (Γ_m being the measured half-width and ΔE the target thickness), were in good agreement. The value given for the $Al^{27}(p,\gamma)Si^{28}$ resonance is an upper limit since the observed half-width could have been due entirely to the energy spread of the incident beam.

8. DISCUSSION OF RESULTS

The linearity of the voltage scale for the present determinations has been established to about one part in three thousand. It is therefore possible to use the present measurements as relative ones to extend the voltage scale established using the small electrostatic analyzer (based on the determination of the lowest fluorine resonance at 340.4±0.4 kev) without adding appreciably to the uncertainties. These values are given in Table II: the errors quoted are the one part in a thousand error of the initial 340.4 determination (which had been rounded off to 0.4) plus the standard deviation of the mean results at each resonance in the present measurements.

The absolute measurements are also given in Table II, with the estimated total error which was obtained by adding the estimated systematic error to the standard deviation of the mean results in Table I.

In view of the discrepancy between the two sets of results, the best values which can be quoted from this Laboratory are their mean values weighted inversely as

TABLE II. A comparison of weighted mean values with those of other workers.

Present absolute values	340.9±0.3	484.6±0.5	873.9(5)±0.8	994.0±1.0	1348.4±1.2	1374.4±1.5
Values based on previously measured value of 340.4±0.4 kev	340.4±0.4	483.8±0.6	872.6±1.1	992.5±1.2	1346.4±1.6	1372.4±1.9
Weighted mean values	340.7±0.3	484.3±0.4	873.5±0.7	993.5±0.8	1347.7±1.0	1373.7±1.2
Bondelid and Kennedy	340.5±0.3	483.6±0.3	872.5±0.4	992.4±0.5	···	···
Bumiller, Staub, and Weaver	340.5±0.3	···	871.3±0.4	990.8±0.2	1345.5±1.0[a]	1373.4±0.7[a]
Herb, Snowden, and Sala	···	···	873.5±0.9	993.3±1.0	···	···

[a] Private communication.

the square of the quoted errors. These are shown in Table II, together with the values obtained by other workers for comparison.

Bondelid's values are very closely similar to the values which we obtained relative to the 340.4-kev resonance determination and are consequently approximately one part in a thousand lower than our best mean values. The constancy of the discrepancy is consistent with both scales being linear to a few parts in ten thousand.

Comparison with Bumiller and Staub's results shows that their values are $0.6/10^3$ lower than ours for the lowest energy and about $0.8/10^3$ lower at the higher energies, but $2.6/10^3$ lower for intermediate energies. This is not consistent with both scales being accurately linear.

The agreement between our mean values and Herb's values in the medium energy range is good to two parts in ten thousand.

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Energy Loss and Effective Charge of Heavy Ions in Aluminum*

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Heavy-ion beams of fixed initial energy ($E^0/m \approx 10$ Mev/amu) are passed through aluminum absorbers of known thickness, and the emergent ions are analyzed by means of a magnetic spectrograph to determine their charge and energy distributions. Accurate measurements of the mean emergent ion energy as a function of absorber thickness are reported for beams of He^4, B^{10}, B^{11}, C^{12}, N^{14}, O^{16}, F^{19}, and Ne^{20} ions with emergent energies in the range $10 > E/m > 1$ Mev/amu. The results can be interpreted as measurements of the range-energy relation for heavy ions. While the absolute accuracy of the range measurements is approximately ±1 mg/cm², the range difference $R(E^0)-R(E)$ is measured (as a function of E) with a typical accuracy of ±0.1 mg/cm². In the analysis the shape of the heavy-ion range-energy curve is compared with the accurately known shape of the proton range-energy curve (using the conversion factor $\Delta R = mZ_p^2(m_pZ^2)^{-1}\Delta R_p$) and the differences in shape are attributed to deviations of the effective charge of the ion from its nuclear charge. No detectable difference is found between the shape of the range-energy curve for He^4 ions and for protons. For heavier ions, deviations in the curve shape do occur. A simple empirical formula is found for the effective charge of an ion as a function of its velocity which is consistent with the deviations of the observed range-energy curves and presumably can be used to predict the range-energy curves for ions not investigated experimentally. By an independent analysis of the spectrograph data the equilibrium distribution of charge states in the O^{16} beam is determined as a function of emergent beam energy. The effective charge implied by the charge state distribution is found to be consistent with the effective charge as given by the empirical formula.

I. INTRODUCTION

A. Background

ALTHOUGH the penetration of energetic charged particles through a material medium has been the subject of widespread theoretical and experimental investigation for more than forty years,[1] the phenomenon is of such complexity that it generally has not been possible to predict the behavior of a particular type of particle in a given absorbing medium with precision on the basis of theory alone, or even from the behavior of other ions in other media. Experimental measurements have been necessary, not only for each combination of incident ion species and absorbing material, but for different regions of incident ion energy as well. The case of aluminum is of particular importance as well as being illustrative, since it often is regarded as the standard absorbing material. The range-energy relation for α particles in aluminum was investigated with high precision in the energy region up to 10 Mev, the highest energy available with natural α sources.[2] Yet there is a difference of 5% between the predictions for the range of a 40-Mev α particle given in two different collections of range-energy relations[3,4]

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[1] Extensive bibliographies and discussions of the available information from various viewpoints are given in references 3, 4, and 23, and by S. K. Allison and S. D. Warshaw, Revs. Modern Phys. 25, 779 (1953).

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[4] W. A. Aron, B. G. Hoffman, and F. C. Williams, Atomic Energy Commission Report AECU-663, May, 1951 (unpublished).