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An Independent Determination of Fixed Points on the High Voltage Scale

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Since present methods allow the comparison of high voltages with an accuracy of 0.1 percent, it was felt that a more accurate determination of certain fixed points would be desirable. This work is an attempt to establish more precisely the voltages of several well-known nuclear reactions which have been used as convenient voltage calibration points. The absolute values of the proton energies obtained for the various calibration points are: 1.883 Mev for the Li(p, n) threshold, 2.058 Mev for the Be(p, n) threshold, 0.877 Mev for the first strong F(p, γ) resonance, and 0.4465 for the Li(p, γ) resonance. The absolute values are thought to be accurate to within 0.3 percent and the relative values to about 0.1 percent.

THE high voltage scale used up to the present time is based on a determination of the voltage at the Li(p, γ) resonance by Hafstad *et al.*, using a calibrated resistance voltmeter.[1] This measurement, which was also checked by Parkinson *et al.*,[2] gave a value of 0.440 Mev for this resonance. The consistency of their measurements indicated a probable error of around two percent but additional checks on the high voltage scale obtained from the scattering of protons in argon[3] and the C(p, n) threshold[4] seemed to indicate that the scale was correct to within one percent. The values found in this work, however, are approximately 1.5 percent higher than previously accepted values.

EXPERIMENTAL METHOD

The method used in this work consisted of measuring the energy of the proton beam at the Li(p,n) threshold with a calibrated electrostatic analyzer. The calibration of the analyzer was made by using electron beams of accurately measured energies and was checked by calculating the deflection constant of the analyzer from its geometry. The proton energies corresponding to the Be(p, n) threshold and to the Li(p, γ) and F(p, γ) resonances were found by comparing these energies with that at the Li(p, n) threshold.

ANALYZER DESIGN AND CALIBRATION

An electrostatic analyzer with curved plates and a single fixed detector had been used for some time in connection with the concentric electrode electrostatic generator for measuring the energy of the ion beam. This analyzer and the auxiliary apparatus are described elsewhere.[5] In the present work, since the analyzer was to be calibrated with electrons of moderate energy, it seemed desirable to be able to reverse the deflector voltage as a check on the effect of stray magnetic fields and of possible surface charges. The analyzer was, therefore, made to be of the parallel plate type with three fixed detectors as shown in Fig. 1. One detector was placed on the axis of the analyzer in order to establish the position of the undeflected beam, and the other two were equally spaced above and below it. The position of the lower detector was made slightly adjustable by means of an eccentric cam. This position was adjusted during preliminary runs with the electron beam so that reversal of the deflector voltage caused the beam to shift from the center of the upper detector to the center of the lower detector. A leveling screw on the detector end of the analyzer provided the

[1] L. R. Hafstad, N. P. Heydenburg, and M. A. Tuve, Phys. Rev. **50**, 504 (1936).
[2] D. B. Parkinson, R. G. Herb, E. J. Bernet, and J. L. McKibben, Phys. Rev. **53**, 642 (1938).
[3] N. P. Heydenburg, L. R. Hafstad, and M. A. Tuve, Phys. Rev. **56**, 1078 (1939).
[4] R. O. Haxby, W. E. Shoupp, W. E. Stephens, and W. H. Wells, Phys. Rev. **58**, 1035 (1940).
[5] A. O. Hanson, "Voltage-measuring and -control equipment for electrostatic generators," recently submitted to *The Review of Scientific Instruments*. This paper will be referred to elsewhere in the text as (I).

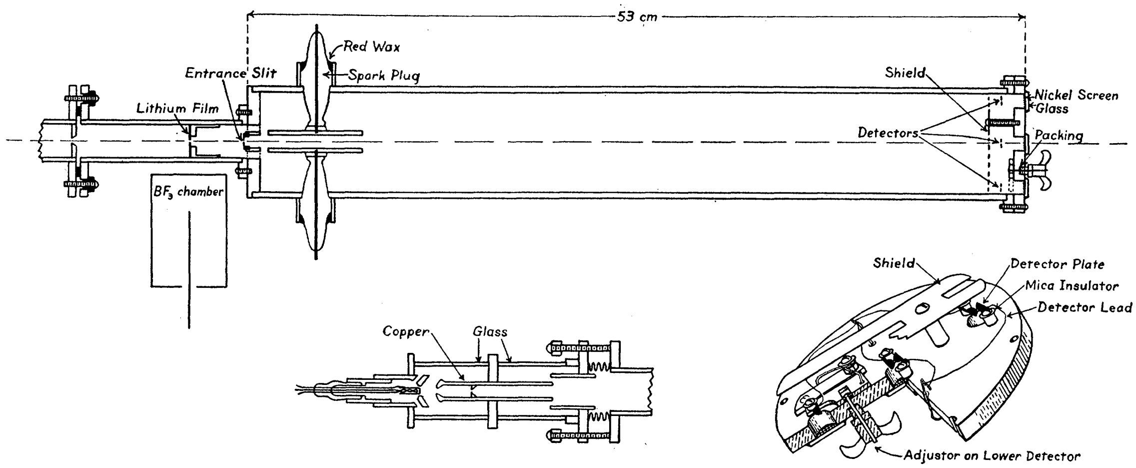

FIG. 1. Electrostatic deflector.

adjustment for centering the undeflected beam on the center detector.

For the calibration experiment the analyzer was mounted with its axis parallel to the earth's magnetic field. The exterior of the tube containing the deflector was wound with wire and a current was maintained in the solenoid thus formed so as to reduce the magnetic field in the interior to a low value.

The electron gun used to produce the beam of electrons is also shown in Fig. 1. An additional lens for focusing the beam was provided. This lens was shorted out, however, allowing the full voltage to be applied across the first gap since concentrating the beam by use of the additional lens made the density of the beam less uniform.

The gun was mounted about 30 cm ahead of the slit which defined the flat beam through the analyzer. The slit width was about 0.2 mm and the beam as seen on the glass behind the detectors appeared to be a uniform line about 0.5 mm wide. At first it was found that the beam hit the mica washers, which insulated the detector plates, causing them to charge up and distort the beam. This difficulty was overcome by inserting a metal shield which allowed the beam to strike only the central semicircular parts of the detector plates.

The schematic diagram of the electrical circuit for the electron calibration experiment is shown in Fig. 2. The voltage used to accelerate the electrons was obtained from the negative side of the high voltage deflector supply described in (I). A bank of B batteries was used to furnish the deflector voltage. The accelerating voltage and the deflector voltage were measured by means of good voltage dividers used with the same potentiometer.

The data shown in Table I give the numbers upon which the calibration is based. The procedure in taking these data was as follows: (1) To align the analyzer so that the beam was centered on the central detector with no voltage across the plates. The correct centering of the beam on the detectors was indicated by a zero reading on the galvanometer. (2) To set the deflector voltage at a given value and adjust the accelerating voltage until the beam was centered on the upper detector and to measure this voltage with the potentiometer. (3) To reverse the deflector voltage, readjust and measure the accelerating voltage when the beam was centered on the lower detector. (4) To check the deflector voltage. All the potentiometer readings were taken to four significant figures and were multiplied by the proper constants to get the values in the table which are recorded in volts. The values of V_a/V_d represent the average accelerating voltage divided by the average deflector voltage for each run.

As shown in Table I the deflector constant varies with the energy of the electrons because of the relativistic effect. In order to correct for this effect it is necessary to examine the equation for the deflection of a charged particle by a condenser.

The deflection at the far edge of an ideal con-

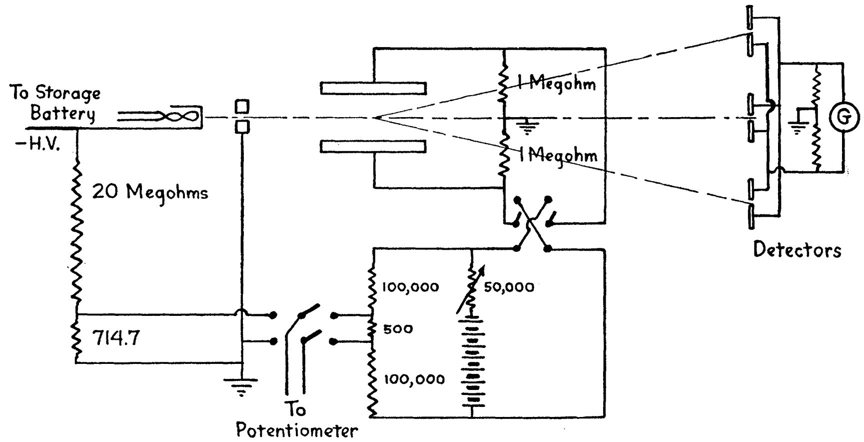

FIG. 2. Wiring diagram for electron calibration experiment.

denser is given by

$$d = \mathcal{E}et^2/2m = V_d el^2/2Smv^2, \quad (1)$$

where $\mathcal{E}$ is the electric intensity, V_d the voltage across the plates, t the time for the particle to travel the length of the plates, l and S the length and separation of the plates, and e, m, and v the charge, mass, and velocity of the particle. If the detector is placed at a distance L from the center of the deflector plates, the deflection D at the distance L is

$$D = Ld/(l/2) = V_d eLl/Smv^2. \quad (2)$$

TABLE I. Data on deflection measurements.

Detector	V_a Accelerating voltage	V_d Deflecting voltage	$\frac{V_a}{V_d}$	$\frac{V_a}{V_d}\left(1-\frac{V_{a_{kv}}}{2(511+V_{a_{kv}})}\right)$
Upper	11,749	218.20		
Upper	11,747			
Upper	11,744			
Lower	11,746			
Upper	11,740		53.838	53.236
Lower	11,749			
Upper	11,744			
Lower	11,746	218.14		
Upper	19,520	360.20		
Lower	19,534		54.315	53.217
Upper	19,534			
Lower	19,534	360.04		
Upper	8,263	153.96		
Lower	8,263		53.669	53.223
Upper	8,263			
Lower	8,263	153.96		
Neutralizing magnetic field raised 50%				
Upper	8,263	153.96	53.682	53.238
Lower	8,268	153.96		
No neutralizing magnetic field				
Upper	8,277	154.00	53.747	53.301
Lower	8,277	154.00		

If we use the non-relativistic relation $mv^2 = 2V_a e$, where V_a is the accelerating voltage applied to the particle, we find that the deflector constant for a given deflection is simply

$$V_a/V_d = Ll/2SD. \quad (3)$$

Where the velocity of the particle approaches the same order of magnitude as that of light we must use the transverse mass and the actual velocity of the particle in the kinetic energy relation. If E is the total energy of the particle and E_0 the rest energy, the kinetic energy is

$$V_a e = E - E_0,$$

where

$$E = \frac{m_0 c^2}{(1-v^2/c^2)^{\frac{1}{2}}} = mc^2 \quad \text{and} \quad E_0 = m_0 c^2$$

and m and m_0 represent the transverse mass and the rest mass, respectively. From these relations we find

$$\frac{v^2}{c^2} = \frac{mv^2}{mc^2} = \frac{E^2 - E_0^2}{E^2}$$

and

$$mv^2 = \frac{E^2 - E_0^2}{E} = 2V_a e\left(1 - \frac{V_a e}{2(E_0 + V_a e)}\right). \quad (4)$$

Equation (3) then becomes

$$\frac{V_a}{V_d}\left(1 - \frac{V_a e}{2(E_0 + V_a e)}\right) = \frac{Ll}{2SD}. \quad (5)$$

The left-hand side of this equation was determined experimentally and represents the deflection constant of the analyzer for particles having non-relativistic velocities. The data in Table I show that the value obtained for this constant is independent of the energy of the electrons. Magnetic effects are almost negligible and effects due to surface charges are also unimportant since the results agree consistently when the deflector voltage is reversed. The value of the constant is seen to be 53.22 ± 0.10. The estimated uncertainty of 0.2 percent is based on the fact that the resistors used in the voltage dividers were determined with a precision of 0.1 percent.

CALCULATION OF THE DEFLECTOR CONSTANT

After the analyzer was used to determine the proton energy at the Li(p, n) threshold, as described later in this paper, it was dismantled and the important dimensions were accurately measured. These dimensions were: The length of the deflector plates, $l = 6.17$ cm. The distance from the center of the deflector plates to the center detector, $L = 47.59$ cm. The average separation of the plates, $S = 0.994$ cm. The variation in the separation of these plates was 0.005 cm. The distance between the center detector and either of the other detectors, $D = 3.132$ cm.

The deflector constant can be calculated approximately from Eq. (3) but in order to get any accuracy it is necessary to consider the effect of the fields at the ends of the deflector plates. The conditions at the end near the entrance slit are sufficiently like those considered by Herzog to allow reading the correction from the graph (Fig. 3) given in his paper.[6] The conditions at this end correspond to a thick aperture having a width $0.80\,S$ (S being the plate separation) placed at a distance of $0.87\,S$ from the edge of the plates. This correction (C_1) amounts to 0.31 cm. The conditions at the other end of the plates correspond to a very large exit slit and the correction cannot be read directly from Herzog's graph. An independent estimate of this correction was made by determining the equipotential lines of a model of the analyzer placed in an electrolytic tray and calculating the effect of the field at this exit end of the plates. The value for the end correction at this end of the plates (C_2) obtained in this way was 0.50 cm. This is in agreement with the value extrapolated from the graph given by Herzog.

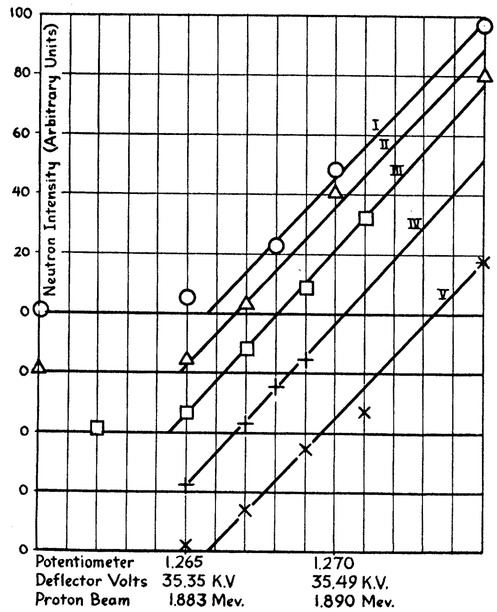

FIG. 3. Neutrons from the Li(p, n) reaction. Runs I, II, and III taken with the beam on the upper detector. Runs IV and V taken with the beam on the lower detector.

The length of the plates used in calculating the deflection constant is therefore $l' = l + C_1 + C_2 = 6.98$ cm. The distance L is also changed since the corrections at the two ends are not the same and becomes approximately

$$L' = L + \tfrac{3}{4}(C_1 - C_2) = 47.44 \text{ cm.}$$

The deflection constant as calculated from these values is

$$V_a / V_d = L'l'/2SD = 53.18 \pm 0.30.$$

The larger uncertainty given in this case is due to the larger probable error in determining the end corrections. The value for the deflector constant obtained in this way is, however, in good agreement with the experimental value.

THE DETERMINATION OF THE LITHIUM PROTON-NEUTRON THRESHOLD

For the determination of the threshold voltage for the Li(p, n) reaction, the analyzer was mounted on one of the outlets of the concentric electrode electrostatic generator. Metallic lithium was evaporated upon a slitted tantalum target and was placed in the tube in front of

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[6] R. Herzog, Physik. Zeits. **41**, 18 (1940).

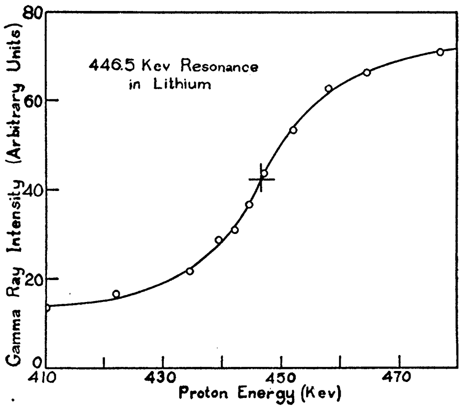

FIG. 4. Gamma-ray yield from a thick lithium target using the diatomic beam.

the defining slit to the analyzer as shown in Fig. 1. A $\frac{1}{4}$-inch circular aperture placed ahead of the target tube defined the beam before it struck the lithium target. A galvanometer was used to measure the total proton current entering the target tube but approximately one-half of this current passed through the slit in the lithium target and struck the smaller slit defining the beam passing through the analyzer. With this arrangement the part of the beam which passed through the analyzer should have the same distribution in energy as that which hit the lithium target.

A simple ionization chamber filled with boron trifluoride placed as shown in Fig. 1 was used to detect the neutrons. The data on the neutron yields as a function of proton energy were obtained by setting the deflector voltage at a definite value and adjusting the voltage of the generator so as to keep the beam centered on the upper (or lower) detector. A regulator operating from the detector plates served to keep the beam centered automatically. This regulator as well as the stabilized deflector voltage supply is described in (I). It was estimated that the fluctuations in the energy of the beam were at the most 0.3 percent and that the average energy of the beam was constant to about 0.1 percent. The deflector voltage remained constant to better than 0.02 percent. The neutron intensity as a function of proton energy is shown in Fig. 3. The runs were taken with different beam currents and various amounts of paraffin surrounding the target tube and the ionization chamber. The first three runs were taken with the beam centered on the upper detector and the remaining two with the deflector voltage reversed. The last run (No. 5) was taken with all paraffin removed. The ordinates for the various runs shown in Fig. 3 were adjusted and displaced for convenience in plotting. In all but the last run the intensity at the end of the run was as high as the detector system could record accurately (about 300 counts per second with a total proton current of one-half microampere). There was no background count below threshold except that due to voltage fluctuations.

It is seen that the extrapolated threshold lies at a potentiometer reading of about 1.265. Most of the counts recorded at this potentiometer setting were observed to occur during voltage fluctuations. The counts at the potentiometer setting of 1.267, however, came in almost continuously indicating that the energy of the protons was definitely above the threshold energy. The extrapolated threshold is probably the most reliable value to take for the threshold since it should be independent of small voltage fluctuations. The potentiometer reading of 1.265 corresponds to a deflector voltage of 35.35 kilovolts and if the deflector constant is taken as 53.22 the energy of the protons at the threshold is 1.881 Mev. If we consider the small relativistic effect for protons at this energy we find that the above value should be raised by about 0.1 percent giving a final value of 1.883 Mev.

COMPARISON WITH OTHER STANDARDS

Although the relative values of other calibration points were considered to be quite reliable it was thought that it might be of interest to compare them directly by use of the analyzer which was at that time permanently on the electrostatic generator. (This was the first analyzer with the 40-cm collimator described in I.) The targets used in this work were thick targets of lithium and beryllium metal and potassium fluoride. These targets were mounted on a single target holder in such a way that any of the targets could be placed in the beam without breaking the vacuum. The threshold energies for the Li(p, n) and Be(p, n) reactions were determined from the intercepts of curves similar to those shown in Fig. 3. The gamma-ray yields

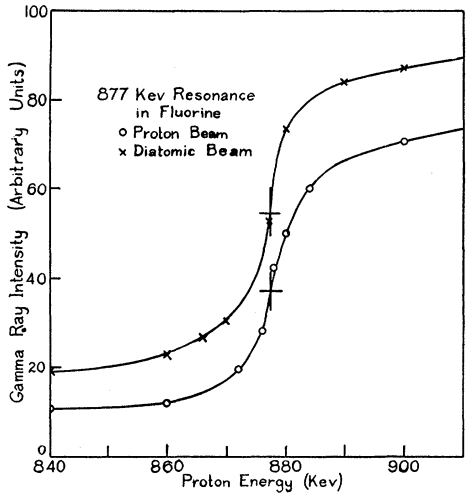

FIG. 5. Gamma-ray yield from a thick target of potassium fluoride.

from a thick target of lithium metal obtained with the diatomic beam and from a thick target of potassium fluoride with the proton and the diatomic beams are shown in Figs. 4 and 5. These yields were measured by means of a hydrogen filled Geiger-Mueller counter used with a Neher-Harper quenching circuit feeding a scale of 64 recording circuit. The resonance energies were taken as that corresponding to the position of the maximum slope in the yield curves. These energies and the previously accepted values are listed in Table II. The values obtained by using the diatomic beam are listed at one-half the energy indicated by the electrostatic analyzer. The values obtained for the fluorine resonance by using the proton and the diatomic beams indicate that the analyzer gives a linear measurement of energy to about 0.1 percent. It is seen that the relative values of the calibration points are in good agreement with the previous values.

It is disturbing to find that the value obtained for the Li(p, n) threshold is as much as 1.5 percent higher than that based on the 0.440-Mev Li(p, γ) calibration point. It is felt, however, that the values obtained in this work should be quite reliable since the sensitivity in both the calibration experiment and in the threshold work was such that the results were consistent to better than 0.1 percent. The wire wound resistors used to measure the voltage of the 40-kilovolt supply were rechecked shortly after this work and were found to be accurate to within 0.1 percent. The standard cell used with the potentiometer was checked before and after this work by the University of Wisconsin Standards Laboratory and was found to be reliable. It is still possible that there are some systematic errors in work of this nature, and it would be desirable to check at least one of these points by using a somewhat different method.

TABLE II. Resonance energies.

Reaction	Previous values based on the 0.440 Mev Li resonance	Values found in the present work	Per-cent in-crease	Reference to previous work
Li(p, n)	1.856 Mev	1.883 Mev	1.5	a
Be(p, n)	2.028	2.058	1.5	a
F(p, γ)	0.862	0.877	1.7	b
	0.867		1.2	c
Li(p, γ)	0.440	0.4465	1.5	c

[a] See reference 4 of text.
[b] E. J. Bernet, R. G. Herb, and D. B. Parkinson, Phys. Rev. **54**, 398 (1938).
[c] See reference 1 of text.

We wish to express our appreciation to Dr. R. G. Herb under whose guidance this work was done and to the Wisconsin Alumni Research Foundation for financial support.