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An Absolute Calibration of the $Li^7(p,n)$ Threshold Voltage*

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The $Li^7(p,n)$ threshold has been the most generally accepted secondary voltage standard for nuclear experiments done with an electrostatic generator. Recent measurements of this threshold by electrostatic analyzer methods have given a result about 2 percent higher than the older value made by an extrapolation of a resistor measurement of the $Li(p,\gamma)$ resonance at 440 kv. The $Li^7(p,n)$ threshold has now been measured by a third method, the radio frequency ion speed gauge. The calibration by this method is absolute in that the kinetic energy of the particle is determined in terms of its known mass to charge ratio and two easily measurable parameters: a length and a frequency. The results of this calibration place the threshold at (1.8812 ± 0.1 percent) Mev, in good agreement with values obtained from the electrostatic analyzer measurements.

Because of its sharpness and easy reproducibility the energy threshold of the $Li^7(p,n)$ reaction has become generally accepted as a secondary standard reference voltage for many nuclear experiments. The absolute calibration of this standard is consequently of considerable importance since its value, and other measurements made relative to it, enter in the determination of the masses of several atomic nuclei,[1] the neutron, the neutrino,[2] and the absolute value of many nuclear energy levels and resonances.

The most commonly used value of this secondary standard is based on the measurement of the $Li^7(p,n)$ threshold made by the Westinghouse group[3] in 1940, wherein they extrapolated the resistor measurement of the $Li^7(p,\gamma)$ resonance at 440 kv by Hafstad, Heydenburg and Tuve[4] to the $Li^7(p,n)$ threshold at 1.85 Mev using a compensated generating voltmeter of known linearity. This result was considered to be in error by as much as 1 percent or 2 percent because of the accuracy and corona characteristics of the resistor measurement and the long extrapolation involved. In 1944 Hanson and Benedict[5] measured the threshold by electrostatic deflection methods and obtained a value of 1.883 Mev for this threshold. The recent measurements of Herb, Snowdon and Sala[6] using a refined electrostatic analyzer yield a value of 1.882 Mev. The present measurement has been done by a method experimentally very different from either of the previous measurements and should serve as an independent calibration of this threshold.

EXPERIMENTAL

Method

The radio frequency ion speed gauge was used to make an absolute measurement of the velocity or voltage of the ion beam from the Westinghouse electrostatic generator at a point about 0.5 percent above the expected $Li^7(p,n)$ threshold. This voltage calibration point was interpolated to the threshold by a compensating generating voltmeter using a linear interpolation over this short voltage range. The generating voltmeter was also used as a source of error signal to stabilize the electrostatic generator voltage to better than 0.1 percent by the biased corona point method.

Absolute Voltage Calibration

The radio frequency speed gauge,[7] which is described in the accompanying article by W. Altar and M. Garbuny, permits one to establish a number of calibration points on the nuclear voltage scale. The calibration is absolute in the sense that the kinetic energy of a particle is determined in terms of its known mass plus directly and accurately measurable parameters: length and frequency. The ion beam of the electrostatic generator (Fig. 1) is intensity modulated by a defocusing electrode placed below the ion source probe and supplied from a 50V, 70 mc crystal controlled oscillator, mounted within the high voltage electrode of the electrostatic generator. After acceleration by the high voltage field of the generator, the modulated beam was analyzed into its various mass components by a deflection magnet and the desired beam sent through the two gaps in the resonant cavity. The cavity (Fig. 2) is of the coaxial type with the inside of the center conductor used as a field free beam drift tube. The two tuning condensers are adjusted simultaneously to bring the resonant frequency of the cavity to 70 mc, while keeping the *RF* voltages across the two gaps equal. The ion beam, as it passes through the first gap in the *RF* cavity, induces a 70 mc voltage in the cavity because of its density modulation. As it passes through the second gap, the voltage induced in this gap will either add or subtract from that of the first gap depending on the phase difference of the 70 mc modulation cycle between the two gaps. If the transit angle $\Delta\theta$ is equal $n\pi$, where n is an

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[1] W. E. Stephens, Rev. Mod. Phys. **19**, 19 (1947).

[2] Shoupp, Jennings, and Sun, Phys. Rev. **75**, 1 (1949).

[3] Haxby, Shoupp, Stephens, and Wells, Phys. Rev. **58**, 1035 (1940).

[4] Hafstad, Heydenburg, and Tuve, Phys. Rev. **50**, 504 (1936).

[5] A. O. Hanson and D. L. Benedict, Phys. Rev. **65**, 33 (1940).

[6] Herb, Snowdon, and Sala, Phys. Rev. **75**, 246 (1949).

[7] Altar, Garbuny, and Coltman, Phys. Rev. **72**, 528A (1947).

odd integer, the excitation from the second gap will cancel that of the first and a minimum in the *RF* signal from the cavity will result. Whence,

$$\Delta\theta = n\pi = 2\pi f \Delta t, \tag{1}$$

where Δt is the time of transit of any group of ions of velocity v through the length L between the gaps, and f is the frequency so that:

$$\Delta t = n/2f = L/v. \tag{2}$$

The velocity of the ions will therefore be:

$$v = 2fL/n, \tag{3}$$

and the equivalent voltage, V, of a beam of particles of velocity v and mass to charge ratio M_0/e considering the relativistic correction is:

$$V = \frac{M_0c^2}{e}\left[\frac{1}{(1-\beta^2)^{\frac{1}{2}}} - 1\right], \quad \beta = \frac{v}{c}, \tag{4}$$

where c is the velocity of light. To an approximation sufficiently accurate for this experiment, the voltage at which a minimum occurs is:

$$V = \frac{2M}{e}\frac{f^2L^2}{n^2}\left(1 + \frac{3f^2L^2}{n^2c^2}\right). \tag{5}$$

The voltage of the ion beam or of the electrostatic generator at the point where the *RF* signal is a minimum can therefore be calculated from the modulation frequency f and the length L between the gaps. The following atomic constants are used:[8]

Ratio charge/mass of electron $e/m = (5.2741 \pm 0.0005) \times 10^{17}$ e.s.u./g.
Ratio mass proton/electron $= M/m = 1836.57 \pm 0.20$.
Velocity of light $= c = (2.99776 \pm 0.00004) \times 10^{10}$ cm/sec.

The value L for the spacing between midpoints of the two gaps, measured with a special inside micrometer calibrated against the laboratory shop standard, was:

$$L = (1.2488 \pm 0.0002) \text{ meters.}$$

The error assigned to this measurement includes nonparallelism of the gap end plates and differences between the two gap widths.

The frequency f of the beam modulation oscillator was measured by using an intermediate crystal controlled secondary standard, the frequency of which was adjusted to within a few cycles of the 5 mc standard frequency signal from *WWV*. It was possible to beat a 70 mc harmonic of this oscillator against the modulation oscillator in the electrostatic generator electrode resulting in an audible beat note of less than 2 kc. The frequency f was therefore:

$$f = (70 \pm 0.0020) \times 10^6 \text{ cycles.}$$

A number of calibration points are available with the radio frequency ion speed gauge by using various values of the order number n and beam mass number M. Since the *RF* signal generated in the cavity is proportional to the square of the ion current, it is advantageous to use the hydrogen molecular ion beam ($M=2$) as it has about twice as much current as the proton beam. Also the voltage at which a minimum occurs with $M=2$ and $n=13$ is closer to the $\mathrm{Li}^7(p,n)$ threshold, thereby requiring a shorter interpolation by the generating voltmeter. The mass of the molecular ion, mass 2, beam is that of two protons plus an electron, so that the voltage of the minimum of mass $=2$ and order number $n=13$ is calculated to be 1.8915 ± 0.05 percent Mev from Eq. (5).

The 70 mc beam modulator was in turn amplitude modulated with a 1000 cycle signal to allow the use of audio amplifiers in the *RF* receiver whose function is to measure the induced voltage in the cavity. The signal induced by the modulated ion beam in the cavity was picked up by a voltage probe and fed to a preamplifier and impedance matching tube adjacent to the probe. The signal was further amplified and detected by a S-27 communication receiver with a 1000 cycle narrow-band filter in the output. This filter reduced the receiver bandwidth to about 100 cycles and thus considerably increased the signal to noise ratio. The *RF* signal from the cavity could be read on a meter or oscilloscope.

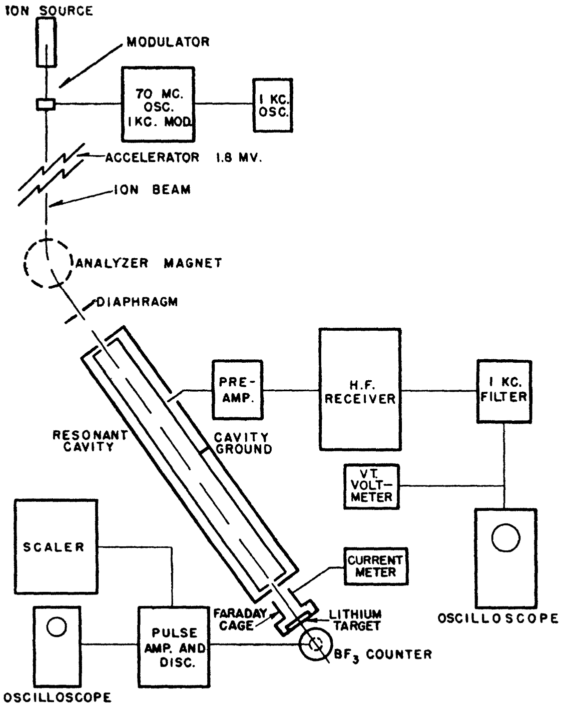

FIG. 1. *RF* ion speed gauge assembly. The magnetic analyzer permits rapid switching from the proton beam used for threshold measurement to the mass 2 beam used for the speed measurement, the mechanical geometry remaining fixed.

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[8] J. W. DuMond and E. R. Cohen, Rev. Mod. Phys. **20**, 82 (1948).

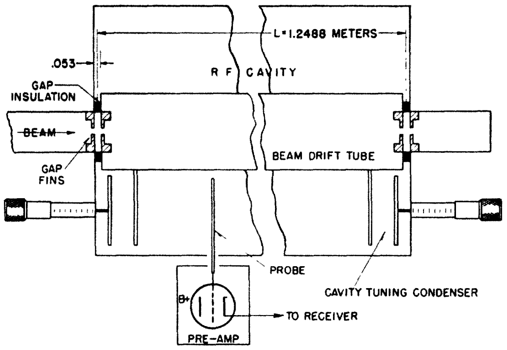

FIG. 2. Schematic section of the speed gauge cavity, giving essential dimensions.

Voltage Comparison and Stability

A compensated generating voltmeter[3] has previously been successfully used as means of voltage comparison on the Westinghouse electrostatic generator and its use was extended to stabilizing the generator operating voltage. In this voltmeter a rotating pick-up plate produces a 120 cycle error signal, the magnitude and phase of which is a measure of the inhomogeneities in the field behind a reference voltage plate. Voltage is applied to this plate until it coincides with an equipotential surface of the field of the high potential electrode. This condition is indicated by a minimum in the 120 cycle signal and a phase shift in the neighborhood of the minimum.

By demodulating this a.c. signal in a phase demodulator against a standard phase, a d.c. voltage can be derived whose sign depends on whether field due to electrode voltage is above or below the reference voltage and is, of course, zero at balance. This d.c. is amplified and is used to bias the grid of a transmitting tube in series with the corona point in the usual manner. In the Westinghouse electrostatic generator this biased corona point is on the end of a movable rod whose position can be mechanically changed. When the corona point is biased off completely by the voltage control system, some of the corona is transferred to the sharp edges of the grounded support rod with reduction of the over-all discharge current. This fortunately allows for a dual type of control, one by rod position and the other by bias voltage, so that the system can give continuous regulation. Thus the voltage is stabilized to about 0.1 percent or less at voltage levels of 2 Mev.

The d.c. null voltage from the demodulator is used also to indicate balance of the generating voltmeter at which point the reference plate voltage is proportional to the generator electrode voltage. The reference plate voltage, about 1 kv, is divided by an uncalibrated but very stable resistor divider by a factor of 0.001 and measured to an accuracy of one part in 10^5 by a type K potentiometer. When the electrostatic generator voltage is standardized by some other process such as the radio frequency speed gauge, or $\mathrm{Li}^7(p,n)$ threshold, the voltage reading of the type K potentiometer becomes a measure of the electrode voltage, and all intermediate measurements in the generating voltmeter system are eliminated. Departure from linearity of the generating voltmeter is known to be small over ranges of at least 1 Mev, and errors over a range of about 100 kv are negligible compared to errors in determining the minimum from the cavity, or the $\mathrm{Li}^7(p,n)$ threshold.

Threshold Measurement

The $\mathrm{Li}^7(p,n)$ threshold was measured in a target chamber (Fig. 3) with a thick metallic lithium target which was heated at all times to prevent deposition of oil from the diffusion pumps. A large spiral dry ice trap in the vacuum line to the diffusion pumps also helped to prevent oil deposits on the target. No sign of carbon discoloration of the target was found after hours of operation. The neutrons produced by the reaction were measured by a large enriched $\mathrm{B}^{10}\mathrm{F}_3$ proportional counter with appropriate amplifier and scaling circuits, and oscilloscopes. Enough neutrons were produced in the reaction to permit determination of the threshold by the "spot check method," correlating the appearance on the oscilloscope of pulses due to the neutrons during voltage fluctuations of the generator. This method, although requiring some personal judgment on the part of the experimenter, allows the threshold to be more exactly matched with the generating voltmeter reference plate reading.

Experimental Data

The electrostatic generator voltage was stabilized by the error signal from the generating voltmeter, and the

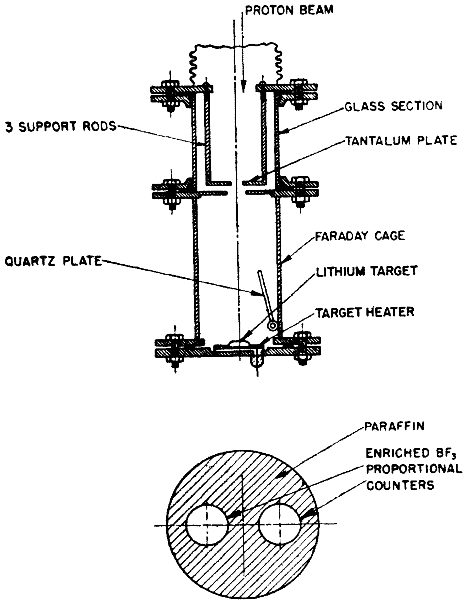

FIG. 3. Arrangement of target, paraffin, and BF_3 proportional counters.

RF signal from the speed gauge cavity was plotted against the generating voltmeter type K potentiometer reading over a region of about 100 kv above and below the expected minimum, as shown in Fig. 4, and a value for the minimum was selected from the resulting curve by inspection. Vertical lines are shown instead of points, representing the variation in *RF* cavity voltage due largely to residual fluctuation in the stabilized electrostatic generator voltage. A spot check of the $\mathrm{Li}^7(p,n)$ threshold was made before, after, and in the middle of such a run and the type K potentiometer readings averaged and used as the threshold. The threshold voltage in Mev was calculated from these results by simple proportion.

$\mathrm{Li}^7(p,n)$ threshold

$$=1.8915\frac{\text{threshold type } K \text{ reading}}{\text{cavity min. type } K \text{ reading}}\ \text{Mev.}$$

The results of 10 such curves selected only on the basis of known defects in the taking of the data have been averaged and the standard deviation calculated. Including the error in the calculation of the voltage equivalent to the cavity minimum the $\mathrm{Li}^7(p,n)$ threshold is (1.8812±0.0019) Mev in absolute volts.

DISCUSSION

Experimental Results

This method for measuring the absolute voltage of the ion beam in the megavolt range has the advantage that the physical parameters necessary to determine the voltage equivalent to a minimum in the *RF* cavity signal are easy to measure. The frequency can be measured to an accuracy much higher than needed in this experiment and the length of the drift space is a simple physical measurement. The values of the necessary atomic constants are known to be at least a factor of five better than the accuracy required by this experiment.

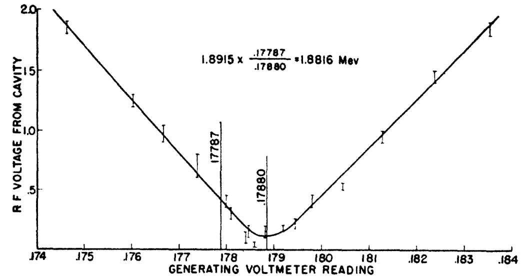

FIG. 4. Typical results of a single calibration run showing relation of $\mathrm{Li}^7(p,n)$ threshold to $M=2$, $n=13$ cavity minimum. Average of ten such runs yields a value of 1.8812±0.0019 Mev for the threshold.

Probably the largest source of error in this experiment is in the precise location of the minimum of cavity excitation due to the remaining fluctuations of the high voltage generator in spite of the control. However, it is hard to believe that this process can conceal any systematic error so that treatment of enough data by standard statistical methods should be valid.

An increase in the experimental accuracy by a factor of about five might be accomplished with the radio frequency ion velocity gauge by using an electrostatic generator equipped with an electrostatic analyzer to more closely define the voltage of the ion beam.

Previous experimental measurements of nuclear thresholds and resonances whose values are based on one of the older measurements of the $\mathrm{Li}^7(p,n)$ threshold should be corrected by the appropriate factor:

Old value of $\mathrm{Li}^7(p,n)$ threshold	Correction factor
1.85 Mev	1.0168
1.856 Mev	1.0136
1.883 Mev	0.999

We wish to express our appreciation to Mr. William Gueir, Mr. Kenneth Richmond, and Mr. Kenneth Fromm for their help in solving some of the experimental problems involved in use of the *RF* cavity with the electrostatic generator.