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Threshold for the Proton-Neutron Reaction in Copper*

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The direct determination of the (p, n) threshold for Cu^{65} has been found. The energy of the $Li^7(p, n)$ threshold had been previously checked against the $F(p, \gamma)$ resonances, and the value, 1.85 ± 0.01 Mev of this threshold of Li^7 was used as the voltage standard in this experiment. The value for the Cu^{65} (p, n) threshold was found to be 2.164 ± 0.01 Mev. If the mass of Cu^{65} is taken as 64.955, the mass for Zn^{65} is computed to be 64.9565 ± 0.001. If after positron emission the resultant nucleus is in the ground state, the maximum energy of the positron spectrum may be computed to be 0.355 ± 0.001.

INTRODUCTION

THE first observation of (p, n) reactions was made by Du Bridge, Barnes, and Buck[1] by measurement of the activities induced by the neutrons in silver foils. Since then the values of the proton energy threshold, for the (p, n) reactions in Li^7, Be^9, B^{11}, and C^{13} have been observed and accurately measured[2–5] yielding accurate mass data for Be^7, B^9, C^{11}, and N^{13} as well as furnishing accurate and easily reproducible voltage calibration points for the nuclear energy scale. The (p, n) threshold for Cu^{65} has now been determined using the $Li^7(p, n)$ threshold for voltage reference. This enables us to make a computation of the mass of Zn^{65}, and establishes accurately the maximum energy of the positrons emitted from Zn^{65} when it decays into Cu^{65}.

EXPERIMENT

The Westinghouse pressure electrostatic generator[6, 7] was used as a source of high energy protons. The voltage stability was approximately 0.1 percent for short times and was not controlled by automatic means. The magnetically deflected spot of mass one (H^+) was used to avoid any possible deuterium contamination. The target arrangement is shown in Fig. 1, in which the tantalum aperature of the Faraday cage was small enough to insure that all protons entering the cage would strike the target. The beam alignment was checked by means of a quartz plate which could be let down over the target. The proton beam current was integrated with a device similar to one described by B. E. Watt[8] except that a 300-v battery was installed in series with the input so as to suppress secondary electrons formed at the entrance to Faraday cage and 313C tube was used instead of the neon glow

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[1] L. A. Du Bridge, S. Barnes, J. H. Buck, Phys. Rev. **51**, 995 (1937).

[2] L. A. Du Bridge, S. Barnes, J. H. Buck, Phys. Rev. **53**, 447 (1938).

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[4] J. E. Hill, Phys. Rev. **57**, 567A (1940).

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[6] R. O. Haxby, W. E. Shoupp, W. E. Stephens, W. H. Wells, Phys. Rev. **57**, 348, 567 (1940).

[7] R. O. Haxby, W. E. Shoupp, W. E. Stephens, W. H. Wells, Phys. Rev. **58**, 162 (1940).

[8] B. E. Watt, Rev. Sci. Inst. **17**, 334 (1946).

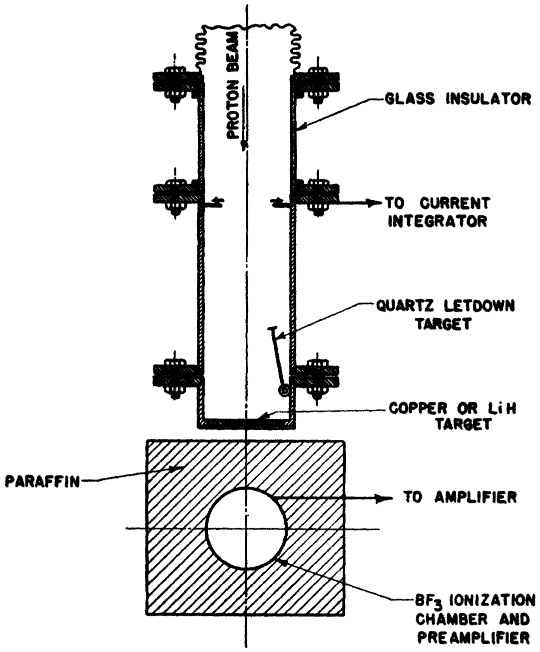

FIG. 1. Arrangement of target, paraffin, and BF_3 ionization chamber.

lamp. Neutrons emitted by the target were slowed down by paraffin, detected by means of a BF_3 chamber, a preamplifier, and a linear amplifier, and recorded through a scale of 16 and an integral recorder. The design of the BF_3 chamber was patterned after Segrè and Wiegand.[9] Commercial unenriched BF_3 was used and the ionization chamber was operated slightly above atmospheric pressure. A Geiger counter γ-ray monitor was operated simultaneously with the neutron detector. The compensating generating voltmeter used was the same as that previously employed[7] and had been checked for linearity against the 0.862-Mev fluorine gamma-ray resonance using the H^+, HH^+, and HHH^+ beams. The voltage was varied by means of a single corona point mounted on the end of a remotely controlled rod that was moved towards or away from the high voltage electrode. The energy of the $Li^7(p, n)$ threshold had been previously checked against the $F(p, \gamma)$ resonances and the value, 1.85 ± 0.01 Mev, of this (p, n) threshold of Li^7 was used as the voltage standard in these experiments. These measurements are established for the same voltage scale[7] previously used for Li^7, Be^9, B^{11}, and C^{13}. This scale may be in error in absolute value by as much as 1 or 2 percent, however, the relative scale should be accurate to about 0.1 percent.

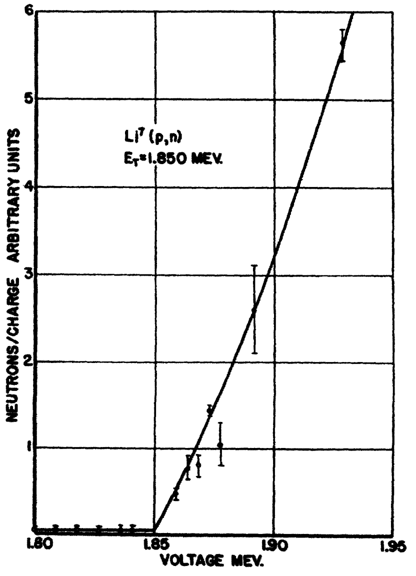

FIG. 2.

RESULTS

The number of neutrons counted by the BF_3 ionization chamber per current integrator count is plotted as a function of proton energy, read by the generating voltmeter, to give the curves shown in Figs. 2 and 3. A thick target of lithium

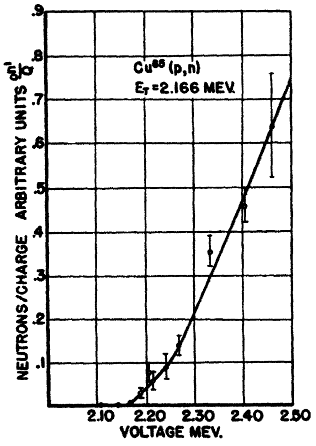

FIG. 3.

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[9] E. Segrè and C. Wiegand, Rev. Sci. Inst. 18, 86 (1947).

hydride was used for the $Li^7(p, n)$ voltage calibration data and a pure metallic copper target was used for the $Cu(p, n)$ data, otherwise the detection and measuring equipment was the same for lithium hydride and for copper targets. Beam currents of about 0.1 μa of resolved protons were used. The vertical lines indicated at the experimental points on Figs. 2 and 3 represent the expected statistical fluctuations in recorded neutrons.

In general, the (p, n) reaction may be written

$$_zX^A + {}_1H^1 \rightarrow {}_{z+1}Y^A + {}_0n^1 + Q_1, \qquad (1)$$

where Q_1 is a negative quantity since the reaction is endoenergetic. The value of Q_1 is determined from the energy threshold (E_t) by,

$$Q_1 = -E_tA/(A+1). \qquad (2)$$

The product nucleus Y may be radioactive and return to X by positron emission

$$_{z+1}Y^A \rightarrow {}_zX^A + 2M_e + \mu + E_+, \qquad (3)$$

or by K-electron capture

$$_{z+1}Y^A \rightarrow {}_zX^A + \mu + Q_2. \qquad (4)$$

In these equations X and Y are the atomic masses involved, M_e is the electronic mass, E_+ is the maximum energy of the positron spectrum, Q_2 is the energy balance, and μ is the rest mass of the neutrino. The threshold for Cu^{63} has been previously observed[10] to occur at 4.1±0.1 Mev and the maximum of the positron spectrum (half-life 38 min.) was given as 2.3±0.15 Mev. These data are in good agreement with the energy relations involved (Eqs. (1), (2), (3)). A long-life activity (235 days) was also observed in the $Cu(p, n)$ reaction and was assigned to Zn^{65}. The threshold energy (E_t) for the (p, n) reaction in copper observed here occurs at 2.164±.01 Mev. This threshold energy is considerably lower than that of Cu^{63} and must then be assigned to the remaining less abundant copper isotope Cu^{65} (29.87 percent). The reaction observed in this work is then

$$_{29}Cu^{65} + {}_1H^1 \rightarrow {}_{30}Zn^{65} + {}_0n^1 + Q_1. \qquad (5)$$

From the threshold $E_t = 2.164 \pm .01$ Mev,

$$Q_1 = -A/A+1, \quad E_t = -2.131 \pm .01 \text{ Mev}. \qquad (6)$$

If we use for the neutron-hydrogen mass difference $({}_0n^1 - {}_1H^1)^{11} = 0.755 \pm .016$ Mev, the $(Zn^{65} - Cu^{65})$ mass difference is,

$$(Zn^{65} - Cu^{65}) = 2.131 - 0.755 = 1.376$$
$$\pm 0.02 \text{ Mev} = 0.00147_7 \pm 0.00003 \text{ MU}.$$

Using the mass of Cu^{65} as 64.955 MU gives the mass for Zn^{65} the value 64.9565±0.001 MU. If after positron emission, the resultant nucleus is in the ground state, the maximum energy of the positron spectrum may be computed from Eq. (3) (assuming μ to be zero),

$$E_+ = 1.376 - 1.021 = 0.355 \pm .001 \text{ Mev}.$$

This value is in agreement with, but much more accurate than, the cloud-chamber value of 0.4 Mev obtained by the Rochester[10] group.

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[10] C. V. Strain, Phys. Rev. **54**, 12 (1021).

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