6×10^{-3} proton/g sec. If we assume the neutron intensity to decrease by a factor 2 per meter water, the neutron production at 6 meters water would be about 10^{-3}/g sec. The agreement is sufficient in view of the uncertain data.

Our considerations show that the total number of neutrons is certainly considerable, and of the same order of magnitude as the total number of electrons or quanta in cosmic radiation. Thus if the neutrons are produced by quanta, each quantum must produce on the average about one neutron. Of course, it is likely that an energetic quantum when it disintegrates a N or O nucleus, produces several neutrons at once so that not every quantum will be concerned in the production process. Moreover, it is as yet unknown whether quanta or other particles are responsible for the neutron production.

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Excitation of the 455-Kev Level of Li^7 by Proton Bombardment

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The yield of gamma-rays from a thin film of lithium bombarded by protons has been investigated up to 2.08 Mev, by recording both single and coincidence counts in G-M tubes. Above 0.85 Mev proton energy most of the radiation is shown to be due to excitation of the 0.455-Mev level of Li^7 without permanent capture of the proton. The yield of 17-Mev radiation does not drop to zero above 0.440 Mev. It falls to a low value and remains approximately constant up to 1.6 Mev. The absorption coefficient in lead for the soft gamma-radiation from lithium was compared to the absorption coefficient of annihilation radiation from N^{13}. A value of 0.459 Mev was obtained for the energy of the soft lithium radiation by assuming monochromatic radiation of 0.511 Mev from N^{13}. This close agreement with the expected energy indicates that not over 10 percent as many 0.28-Mev quanta as 0.511-Mev quanta are present in the radiation from N^{13}.

INTRODUCTION

THE excitation of gamma-rays from lithium by proton bombardment was studied three years ago at this laboratory using protons in the energy region 0.4 to 1.9 Mev.[1]

A gamma-ray resonance of lithium had previously been established for protons of 0.440 Mev energy by Hafstad, Heydenburg and Tuve.[2] These gamma-rays were found by Lauritsen and his colleagues to have an energy of approximately 17.5 Mev. The previous work here showed the presence of considerable radiation caused by protons above 0.85 Mev, but no measurements were made of the energy of this radiation.

The work reported upon in this paper shows that most of the radiation above 0.85 Mev proton energy is due to the excitation of an energy level of Li^7 which was found by Rumbaugh, Roberts and Hafstad[3] to be 0.455 ± 0.015 Mev above the ground state. Their paper will hereafter be referred to as RRH.

While this paper was being written, Fowler and Lauritsen[4] reported obtaining from lead absorption measurements similar to ours, a value of 0.495 ± 0.025 Mev for the energy of the radiation due to 1.08- and 1.29-Mev protons on lithium. They attribute this to excitation of the 0.455-Mev level, but have no explanation for the high value they obtained for the gamma-ray energy.

Our values for the absorption coefficient of the radiation agreed with those of Lauritsen, but when corrections were applied for a hard component, the energy obtained for the soft component agrees with the value expected from

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[1] Herb, Kerst and McKibben, Phys. Rev. **51**, 691 (1937).
[2] Hafstad, Heydenburg and Tuve, Phys. Rev. **50**, 504 (1936).
[3] Rumbaugh, Roberts and Hafstad, Phys. Rev. **54**, 657 (1938).
[4] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **56**, 841 (1938).

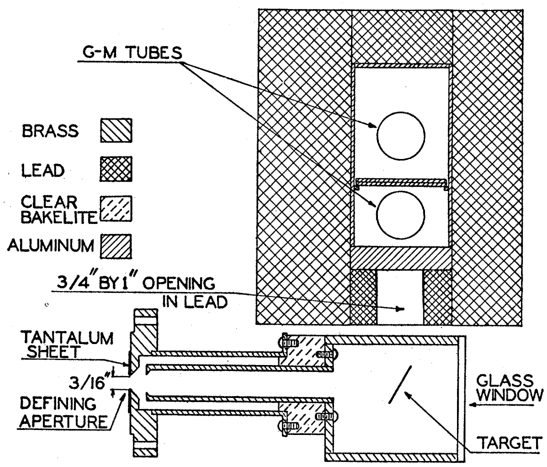

FIG. 1. Target chamber and counter arrangement.

RRH. Excitation curves for the total radiation and for its hard component are also extended up to 2.08 Mev.

Experimental Arrangement

Figure 1 shows the arrangement of target chamber and counters. Lithium targets were prepared by evaporation of lithium metal onto a sheet of tantalum mounted as shown in the figure. Diaphragms outside the chamber limited the proton beam to a small part of the target so that the film used was fairly uniform. Tantalum was used for these diaphragms and for the target backing since it was found to give no observable gamma-radiation.

Gamma-ray yields were measured by two thin-walled glass G-M tubes enclosed in a lead box as shown in Fig. 1. An aluminum plate on the floor of the shielding box served as a source of secondary electrons. An investigation of the absorption of secondary electrons by taking coincidence yields as a function of the thickness of aluminum between the counters can determine the energy of hard radiation.

The tubes were connected in a circuit such that the single counts in the lower G-M tube were recorded through a scale-of-ten circuit and at the same time coincident discharges of the two Geiger-Mueller tubes were recorded in another scaling circuit.[5] The bombardment current was measured by the current integrator previously described.[1] With this system the counting rate for singles and the counting rate for coincidences could each be expressed in counts per microcoulomb of bombarding protons.

[5] The arrangement is described in more detail in the paper by Plain, Herb, Hudson and Warren, Phys. Rev. **57**, 187 (1940).

Excitation Curves

The presence of soft radiation emitted by protons on lithium was first noticed in this work when the ratio of coincidence to single counts was found to be very low for radiation due to protons of 1.6 Mev energy striking a thick target. Preliminary measurements of the absorption in lead indicated that most of the radiation was due to excitation of the 0.455-Mev level of lithium.

From a thin film (film I) which was then prepared, singles and coincidence yields were investigated simultaneously over the energy region 0.4 to 1.9 Mev. These data are shown in Fig. 2, with the ordinates for coincidences multiplied by six to make the two curves coincide over the 0.440-Mev region, where only hard radiation is present. Because the two curves remain identical up to almost 0.8 Mev, all radiation in this region is believed to be hard.

The yield curves show that the hard gamma-ray intensity does not drop to zero above the 0.440-Mev resonance, but decreases to a low, constant value ($\sim$6 times the counting rate due to background). Above 0.8 Mev the singles yield rises sharply, but the coincidence yield remains practically constant at its low value. The rise in singles yield must therefore be due to radiation so soft that practically none of its secondary electrons can penetrate both counter tubes. These measurements were made with no aluminum between the counters so that in order to cause coincidences, secondary electrons had to traverse two counter walls which gave an equivalent of approximately 0.3 mm of aluminum.

A broad resonance for soft radiation at proton energies around 1.05 Mev has been well traced, both in the earlier publication[1] and in this work. A slight hump near 1.31 Mev reproduced itself in all three curves of Fig. 2, and in the two curves previously published. Between 1.4 and 1.8 Mev, excitation curves for both film I and film II appear to show resonance structure, but since the two do not agree very well the resonances cannot

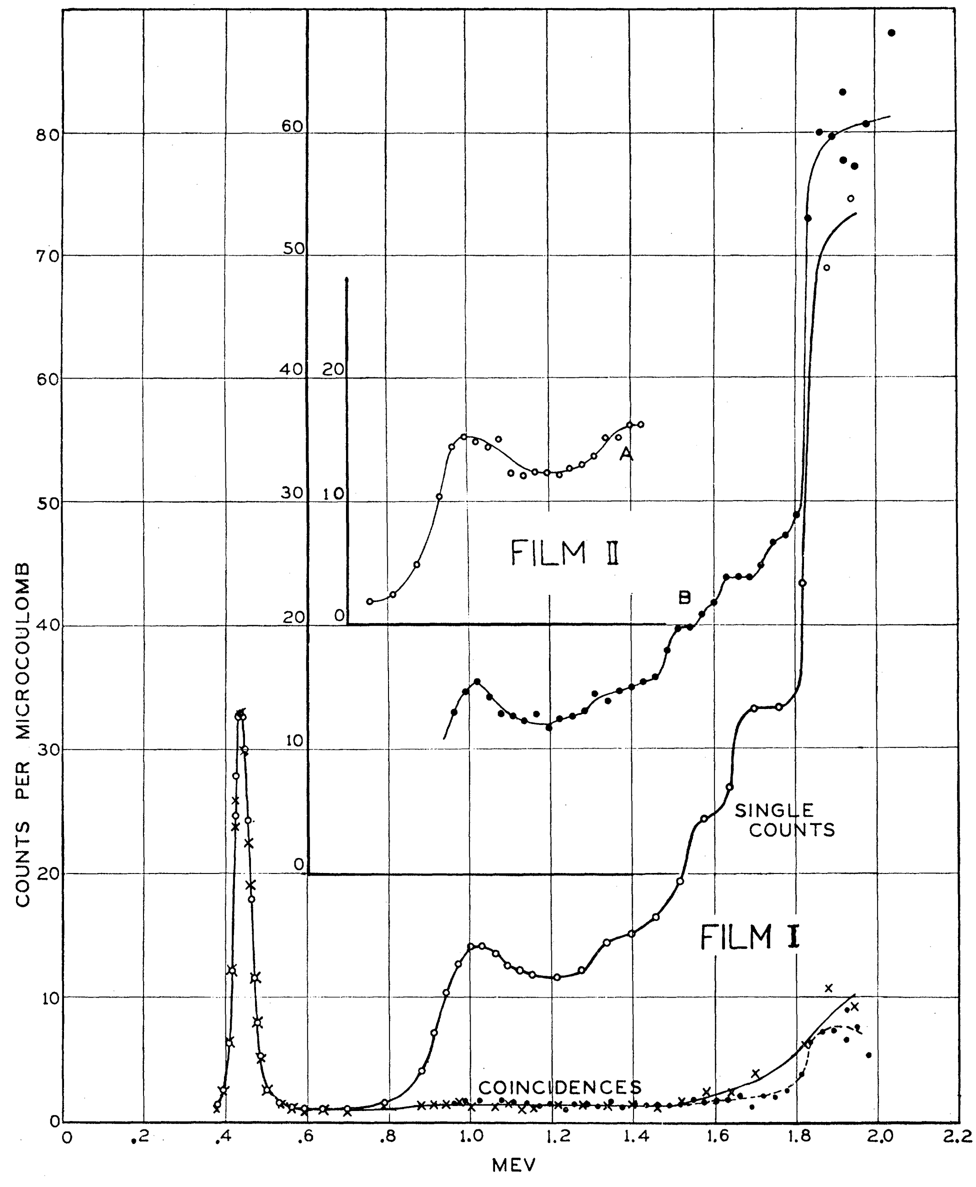

FIG. 2. Single and coincidence yields from thin lithium targets as a function of proton energy. The singles yield measures the total gamma-ray intensity, and the coincidence yield measures the intensity of the hard component.

be considered as definitely established. A large, sharp increase in intensity at 1.83 Mev is unmistakable.

Since the threshold for neutron emission was recently reported by the Westinghouse Research Laboratories group[6] to be at 1.86 Mev, it is thought possible that part of the increase at 1.83 Mev in Fig. 2 may be due to neutrons. In the present work, insufficient precautions were taken to exclude the possibility of an error in the voltage as large as the observed difference. Observations on the nature of the reactions above 1.8 Mev and extension of the excitation curves were cut short to begin revision work on the electrostatic generator.

The form of the singles yield curve does indi-

[6] Haxby, Shoupp, Stephens and Wells, Annual meeting American Physical Society, December 28, 1939.

cate that the observed rise at 1.83 Mev is due principally to gamma-rays, since the curves appear to flatten out above 1.9 Mev. It is thought likely that a neutron yield curve would continue to increase over a considerable voltage region above the threshold. The observed rise in coincidence yield may be due to neutrons, to an increase in the intensity of ~17-Mev gamma-rays, or to resonance excitation of a new component of gamma-radiation of sufficient energy to cause coincidences.

From a consideration of the preceding curves it is seen that the coincidence yield measures the intensity of the hard component. Apparently independently of any changes in the singles yield, the coincidence yield from 0.6 to 1.6 Mev retains its low but measurable value, approximately six times the correction for generator and cosmic-ray background. Accidentals could not be responsible for the observed intensity, according to the measured resolving time of the circuit (6.8×10^{-5} sec.); and besides, the accidentals should increase as the square of the single counting rate, but the observed coincidences do not increase. This leads to the conclusion that the coincidence yield even above 0.8 Mev is a measure of the hard component of the radiation.

The energy of the hard component was measured for radiation from a lithium target which had an absorption thickness of ~0.25 Mev for 0.7-Mev protons. When protons of 0.97

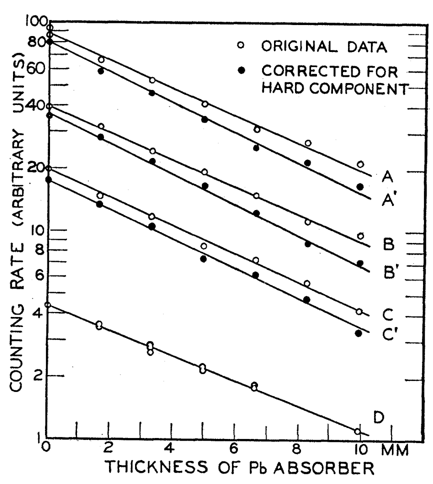

FIG. 3. Lead absorption curves for lithium gamma-radiation (*A*, *B*, and *C*) and for positron annihilation radiation (*D*).

TABLE I. *Lead absorption of gamma-rays.*

	Gamma-rays from Protons on thin Li			Positron Annihilation Radiation
Curve	*A–A′*	*B–B′*	*C–C′*	*D*
Proton energy (Mev)	1.214	1.639	1.032	
Original absorption coefficient (Curves *A*, *B*, & *C*)	1.523	1.490	1.551	1.414
Correction for hard radiation	10.9%	9.0%	7.9%	
Absorption coefficient of soft component (Curves *A′*, *B′*, & *C′*)	1.690	1.690	1.662	
Average value		1.681		
Energy of radiation (Mev)		0.459		0.511

Mev were used for bombardment, a thickness of 6.1 mm of aluminum was required to reduce the coincidences by one-half. For gamma-rays due to 1.64-Mev protons, a half-value thickness of 7.4 mm of aluminum was obtained. The probable error in these values is large because of the high singles counting rate due to the intensity of soft radiation. With a singles counting rate low enough to avoid many accidental coincidences, the true coincidence rate was low, and only 240 counts were taken at each of three points to determine the half-value thickness. Within the probable error these values agree with the half-value thickness obtained for 17.5-Mev radiation from the 0.440-Mev resonance, and indicate that the coincidence yield over the entire voltage region investigated is due to 17.5-Mev radiation.

Energy of the Soft Component

The absorption coefficient in lead for radiation emitted from film I at each of several proton energies (see Table I) was obtained by taking the singles yield as a function of the thickness of lead sheets placed just below the window of Fig. 2. These data when plotted on the semi-logarithmic scale of Fig. 3 as curves *A*, *B* and *C* gave the "original absorption coefficients" listed in Table I.

The proportion of hard radiation for each voltage investigated was taken as the ratio at that voltage of the ordinate for coincidences to the ordinate for singles yield from film I (Fig. 2). A lead absorption curve was taken separately for 17.5-Mev radiation to determine how the single counts due to the hard component decreased with thickness of lead. From these data on the proportion and absorption of hard radiation, corrections for the number of counts due to the hard component were subtracted from the yields shown at each point of curves A, B, and C. The yields resulting from this correction are shown as the points determining curves A', B', and C', for the soft component. The absorption coefficients obtained from these curves are nearly equal, with an average value of 1.681 cm^{-1}.

Determination of the energy of radiation with this absorption coefficient had to be made by comparison with the absorption coefficient of a known radiation under identical conditions. Annihilation radiation, due to positrons from N^{13}, was used for this purpose as follows:

Radioactive nitrogen was prepared by deuteron bombardment of a carbon target, which was placed in the same position as the lithium target. After bombardment the chamber was flushed with air and was open at atmospheric pressure during the measurements. The measurements over 39 min. gave a value of 11.1 min. for the half-life. This agrees[7] with Ellis and Henderson's value of 11.0 min., which Livingston and Bethe adopted, but recent results of careful work by Ward give a value for the half-life of 9.93 ± 0.03 min. The source of error in our work is not understood. If it is caused by contaminants it is possible that the use of this radiation for calibration may have caused error in the value obtained for the energy of the soft radiation from lithium.

A brass plate was laid on the surface of the target so that positron annihilation radiation was produced very nearly in the same position as the lithium target.

Measurement of the absorption coefficient of positron recombination radiation in lead gave a value of 1.414 cm^{-1}. By use of this absorption coefficient and Heitler's theoretical curves[8] for the variation of absorption coefficient with energy, an energy of 0.459 Mev is obtained for the soft component of lithium radiation.

Since no transmutation seems capable of explaining these gamma-rays, and since RRH have observed an energy level 0.455 Mev above the ground state in Li^7, it appears certain that the observed rays must be due to excitation of this energy level without permanent capture of the proton.

In these computations it was assumed that radiation from N^{13} consisted only of annihilation radiation, with an energy of 0.511 Mev. This procedure may be questioned since several observers have reported some 0.28-Mev radiation in addition to a negligible amount of radiation harder than 0.511 Mev. From his latest work with a cloud chamber Richardson[9] reported that 21 percent as many quanta of 0.28 Mev as of 0.511 Mev were emitted, with an uncertainty factor of two. Lyman[10] obtained 10 ± 7.5 percent, using gamma-gamma coincidences, and 12 percent from β-ray spectrum analysis. Watase and Itoh[11] find similar results. In contradiction to these results, Valley,[12] working with a magnetic spectrograph with x-ray film as a detector, reported nothing in the region 0.28 ± 0.03 Mev, with 2.5 percent as an upper limit (i.e., <0.05 quanta of 0.28 Mev per disintegration). Since our value for the Li^7 energy level agrees closely with that of RRH, it was thought worth while to compute the possible effect of soft radiation and from estimates of the probable errors to set some upper limit to the amount of such radiation present.

Upper limits for the proportion of 0.28-Mev radiation are indicated in two ways by the present work. First, the lead absorption curve labeled D in Fig. 2 is straight. The absorption coefficient for 0.28-Mev radiation in lead is 3.4 times the coefficient for 0.511 Mev, according to Heitler's curves. From a graph drawn to include various proportions of 0.28-Mev radiation it seems probable that some curvature would have been observed if there had been more than 30 percent as many 0.28-Mev quanta as 0.511-Mev quanta. The radiation from annihilations producing only one quantum (1 Mev) is known to be negligible, and computations show that radiation harder than 0.511 Mev, from positrons annihilated while in motion is also neglig-

[7] C. D. Ellis and W. J. Henderson, Nature **135**, 429 (1935); M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 359 (1937); A. G. Ward, Proc. Camb. Phil. Soc. **35**, 523 (1939).

[8] W. Heitler, *Quantum Theory of Radiation* (Oxford, 1936), pp. 124, 160 and 216.

[9] J. R. Richardson, Phys. Rev. **55**, 609 (1939).

[10] E. M. Lyman, Phys. Rev. **55**, 1123(A) (1939).

[11] Watase and Itoh, Proc. Phys. Math. Soc., Japan **21**, 389 (1939).

[12] G. E. Valley, Phys. Rev. **56**, 838 (1939).

ible. The straightness of the lead absorption curve is therefore an indication of the maximum possible proportion of radiation with energy appreciably different from 0.511 Mev.

A second indication is the fact that the energy of the Li^7 gamma-radiation (0.459 Mev) measured here agrees with the value 0.455 ± 0.015 Mev obtained by RRH in an entirely different way. The probable error in the whole determination was figured from estimates of: first, the errors in measuring the absorption coefficients of the positron radiation and of the soft component of the lithium radiation; second, the errors in reading slopes and absorption coefficients from Heitler's curves; and third, the error given by RRH for the energy of the excited level. The over-all probable error is taken as the square root of the sum of the squares of the individual probable errors. It is about the same as the error that would have been made in determining the energy of the lithium level if there had been 10 percent as many 0.28-Mev quanta as 0.511-Mev quanta in the radiation from N^{13} and its positrons.

This upper limit of 10 percent is on the low side of Lyman's 10 ± 7.5 percent but since it was obtained in such a devious way, it must be considered only as supplementary evidence that very little 0.28-Mev radiation is emitted.

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Positive Excess and Electron Component in the Cosmic-Ray Spectrum

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The sea-level cosmic-ray energy spectrum has been determined, using a 30-cm counter controlled cloud chamber in a 12,400-oersted magnetic field. The spectrum of mesotrons alone is obtained by inserting a 10-cm lead filter in the counter train, the total spectrum is obtained with no filtering, and the spectrum of the soft (electron) component is then the difference between these two spectra. An excess of positive particles exists both with and without the lead, the ratio of positives to negatives being 1.21 ± 0.08 (standard error) in the former, and 1.18 ± 0.08 in the latter case. Comparison of the spectra with and without lead shows the presence of an absorbable component (electrons) in the energy region 2 to 8×10^8 ev but no absorbable particles of higher energy. The spectra have been corrected for the distortion at low energies caused by the magnetic field. The corrected mesotron spectrum possesses a maximum and a rapid decrease below the maximum while the total spectrum shows no maximum but a continuous increase in number with decreasing energy.

IN June, 1939, at the Chicago cosmic-ray symposium H. Jones[1] reported on the energy distribution of mesotrons. The energy spectrum was obtained with the large cosmic-ray magnet at the University of Chicago, using a 10-cm lead filter to remove electrons. The results showed a greater number of positive than negative particles, the excess, amounting to 29 percent, being spread rather uniformly throughout the spectrum. Such an excess might mean either a greater absorption of negatives in the lead or a real positive excess in the energy spectrum incident on the magnet. Blackett's[2] work on the unshielded energy spectrum showed a small positive excess which was interpreted by him as being probably of no significance. Ringuet,[3] using a lead absorber, found a large positive excess at high energies but no excess without the lead. Pair production of mesotrons would of course result in an equality in regard to sign, and such an equality

[1] H. Jones, Rev. Mod. Phys. **11**, 235 (1939).

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