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Inelastic Scattering of 500-Mev Electrons from Li^6 and Li^7†

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500-Mev electrons have been scattered from enriched Li^6 and ordinary Li (92.5% Li^7) between scattering angles of 60° and 135° in the laboratory system. The cross section integrated over the inelastic continuum at these large momentum transfers has been compared with the free-proton cross section at the corresponding angles. The results when compared with those obtained for other light nuclei may be used to yield some insight as to the extent to which the scattering from the individual nucleons can be considered as incoherent.

I. INTRODUCTION

In the course of a program to study the scattering of electrons from individual nucleons bound inside of light nuclei, we have investigated the inelastic continuum of scattered electrons associated with the disintegration of Li^6 and Li^7. So far, measurements of this kind have been performed for the deuteron[1] and for beryllium and carbon.[2] Results obtained for Li^6 and Li^7 have already been briefly reported[3] and will be discussed in more detail in this paper.

Yearian and Hofstadter[1] thoroughly studied the inelastic electron continuum associated with the disintegration of the deuteron by scattered electrons. The width of the continuum reflects the momentum distribution of the proton and neutron within the deuteron. At the high momentum transfers at which these experiments were performed, the elastic scattering of electrons from the deuteron as a whole is small compared to the scattering from the individual nucleons. Furthermore magnetic scattering prevails as compared to charge scattering. Both statements apply also to the present experiment on the two stable lithium isotopes. In reference 1 the total cross section $(d\sigma/d\Omega)_d$ for quasi-elastic scattering from the proton and neutron bound in the deuteron was derived either from the total area under the inelastic scattering continuum or from the measured height of the continuum at its peak value[4] combined with Jankus's theory[5] of the total cross section. By comparing this cross section with the free-proton cross section under identical conditions, the authors extracted the neutron's contribution σ_n. Using the known form factor for the proton, Yearian and Hofstadter arrived at the conclusion that the size of the magnetic cloud associated with the neutron is $(0.8\pm0.15)\times10^{-13}$ cm.

For a light nucleus $_ZA^N$ with Z protons and N neutrons, the differential cross section $d^2\sigma/d\Omega dE$ integrated over the inelastic continuum can be expressed as the sum of the free-proton and free-neutron cross sections,

$$\left(\frac{d\sigma}{d\Omega}\right)_{_ZA^N}=Z\left(\frac{d\sigma}{d\Omega}\right)_p+N\left(\frac{d\sigma}{d\Omega}\right)_n, \qquad (1)$$

provided the individual nucleons scatter incoherently at these large momentum transfers, i.e., as if they were free and independent from each other. For reasons which will be discussed below, Eq. (1) cannot be expected to be more than a crude approximation which may need considerable refinement. Even for nuclei as light as Li^6 or Li^7, a non-negligible multiplicative correction factor $(1+\Delta)$ may have to be introduced on the right-hand side of Eq. (1). For lithium, with its wider momentum distribution of the nucleons within the nucleus, a larger kinematic correction factor is to be expected than that computed by Blankenbecler[6] for the deuteron. The assumption of incoherence is a good approximation even at large momentum transfers only as long as meson exchange effects and final-state interactions are negligible. In the deuteron the distance between proton and neutron is most of the time appreciably larger than the pion Compton wavelength $\hbar/m_\pi c$, and it seems therefore not unreasonable to assume that meson exchange effects are small for the deuteron. For any other light nucleus like Li^6 or Li^7 in which the nucleons are much more densely packed, meson exchange effects may show up much more strongly. It seems, however, to be extremely difficult to estimate from presently available meson theories the contribution to the observed cross section due to these effects which are known to be of such importance in the photodisintegration of the deuteron even far below the pion production threshold. Meson exchange effects will affect predominantly the low-energy part of the inelastic continuum where the energy transferred from the incident electron to the nucleon rest-

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[1] M. R. Yearian and R. Hofstadter, Phys. Rev. **110**, 552 (1958); see also Hofstadter, Bumiller, and Yearian, Revs. Modern Phys. **30**, 482 (1958).

[2] H. F. Ehrenberg and R. Hofstadter, Phys. Rev. **110**, 544 (1958).

[3] U. Meyer-Berkhout and R. Hofstadter, Bull. Am. Phys. Soc. Ser. II, **2**, 390 (1957); see also *Proceedings of the Seventh Annual Rochester Conference on High-Energy Nuclear Physics, 1957* (Interscience Publishers, New York, 1957).

[4] S. D. Drell, *1958 Annual International Conference on High-Energy Physics at CERN*, edited by B. Ferretti (CERN, Geneva, 1958), p. 20.

[5] V. Z. Jankus, Phys. Rev. **102**, 1586 (1956); also Ph.D. thesis, Stanford University, 1956 (unpublished).

[6] R. Blankenbecler, Bull. Am. Phys. Soc. Ser. II, **2**, 389 (1957); Phys. Rev. **111**, 1684 (1958).

nucleus system is largest. On the other hand, the influence of final-state interactions estimated by Jankus[5] and Blankenbecler[6] for the deuteron will be strongest on the high-energy side of the continuum. Unfortunately no theory is available for other nuclei than the deuteron, which would allow one to use the value of the differential cross section $d^2\sigma/d\Omega dE$ at the peak ordinate of the inelastic continuum, where corrections are known to be smallest, as a starting point to find the neutron's contribution.[4] Therefore, as long as the magnitude of Δ is not known, an experiment on a nucleus like lithium can hardly yield any information about the neutron. But the extent to which the results derived from the experimental data for lithium, simply on the basis of Eq. (1) with $\Delta=0$, are consistent with those obtained from the much better understood deuteron may provide some insight into the nature and magnitude of the additional effects contributing to the observed cross section and correspondingly into the Δ-correction.

II. APPARATUS AND PROCEDURE

The experimental setup and the procedure of taking data were exactly the same as has been described in references 1 and 2. Targets of ordinary lithium (natural abundance of Li^7 92.6%) and enriched Li^6 (95.6%) of different thicknesses between 0.3 in. and 0.5 in. were bombarded with 500-Mev electrons from the Stanford Mark III linear accelerator. In the case of the Li^7 experiment the electrons were analyzed according to their momenta at five different scattering angles, namely $\Theta_{\text{lab}}=60$, 75, 95, 115, and 135°. Li^6 was investigated at 500 Mev and 135° only. The energy spread of the incident beam and the magnet resolution of the 36-in. spectrometer were both set at 1%. The differential cross section integrated over the inelastic continuum has been compared at each scattering angle with the free-proton electron scattering cross section. $(CH_2)_n$ targets comparable in thickness to the lithium samples were used to measure the yield of electrons scattered elastically from free protons. Care was taken that no negative pions were counted as electrons. This was accomplished by setting the discriminator at such a high level that no positive pions were counted with reversed magnet current at a spectrometer setting where ordinarily positive pions can be observed with the fluorocarbon Čerenkov counter.

Figure 1 shows the observed energy distribution of 500-Mev incident electrons after having been scattered from a Li^7 target by 60° or 135° with respect to the incident beam in the laboratory system. Also plotted in the figure is the free-proton peak observed with a $(CH_2)_n$ target but otherwise unchanged conditions. The areas are normalized in each case so as to correspond to equal numbers of incident electrons and scattering nuclei except that the free-proton peak is scaled down by a factor of five for reasons of convenience.

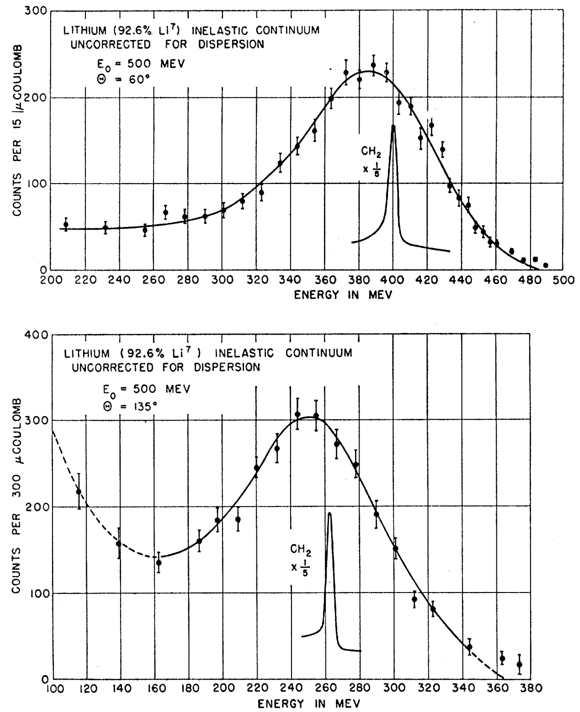

FIG. 1. The inelastic continuum for lithium (92.6% Li^7) at 500 Mev at a scattering angle of 60° and 135°. The free-proton peak scaled down by a factor of five is also shown.

The ratio of the two cross sections σ_{Li}/σ_p can be obtained directly from the areas under the corresponding peaks of Fig. 1 after the $1/E$ dispersive correction allowing for the constant relative momentum acceptance of the analyzing spectrometer has been applied. Since it is difficult, when using a $(CH_2)_n$ target, to measure the fraction of electrons contained in the bremsstrahlung tail of the free-proton peak, this fraction was computed using the well-known equations for bremsstrahlung emission and the Schwinger-Suura radiative correction. They amounted to about 25 to 30% of the measured yield, depending on the energy at which the free-proton peak was cut off. No such radiative corrections, however, have been applied to the inelastic lithium continua since the bremsstrahlung tails themselves contribute to the measured area of the continuum, causing a typical asymmetry in the distribution similar to the one actually observed. Omission of this correction is unlikely to affect the results by more than a few percent. More serious, especially at the larger scattering angles, since difficult to correct for, is the observed partial overlap of the inelastic continuum with another peak occurring at low momenta. This peak is due to electrons having produced real pions while being scattered. This partial overlap, which becomes more serious the heavier the nucleus, makes it somewhat difficult to find the total area under the curve one is interested in, and therefore reduces to some extent the reliability of such yield comparisons. An attempt was made to estimate the total area by reasonable extrapolation (method I) and it is thought that the error introduced through

TABLE I. Summary of results for Li^6 and Li^7.

	Li^7					Li^6
Θ_{lab}	60°	75°	95°	115°	135°	135°
$(\sigma_{\mathrm{Li}}/\sigma_p)_{\mathrm{I}}$	5.2 ± 0.8	5.4 ± 0.8	5.6 ± 1.1	6.9 ± 1.7	7.0 ± 1.7	6.3 ± 1.3
σ_p, cm^2/sterad[a]	1.11×10^{-31}	3.80×10^{-32}	1.34×10^{-32}	6.5×10^{-33}	4.16×10^{-33}	4.16×10^{-33}
R_{I}	$0.5_5 \pm 0.2$	$0.6_0 \pm 0.2$	$0.6_5 \pm 0.3$	$0.9_8 \pm 0.4$	1.0 ± 0.4	1.1 ± 0.4
$(\sigma_{\mathrm{Li}}/\sigma_p)_{\mathrm{II}}$	4.4 ± 0.7	4.6 ± 0.8	5.2 ± 1.0	6.0 ± 1.2	6.3 ± 1.6	5.5 ± 1.2
R_{II}	$0.3_5 \pm 0.2$	$0.4_0 \pm 0.2$	$0.5_5 \pm 0.25$	$0.7_5 \pm 0.3$	$0.8_3 \pm 0.4$	$0.8_3 \pm 0.4$
$(\sigma_n/\sigma_p)_{\Delta=0}$[b]	...	0.22 ± 0.12	$0.4_5 \pm 0.3$[c]	$0.6_5 \pm 0.35$[c]	0.83 ± 0.3	

[a] Computed from the Rosenbluth equation for an exponential proton with rms-radius of 0.8×10^{-13} cm.
[b] Values derived from the deuteron with $\Delta=0$ taken from reference 1.
[c] Interpolated values since in reference 1 values for σ_n/σ_p are reported for $\Theta=75°$, 90°, 105°, 120°, and 135° only.

the uncertainty of the extrapolation does not exceed 20 or 25%. Another approach (method II) consists in drawing a center line through the maximum of the continuum after application of the dispersive correction and taking only the high-energy part (right section in Fig. 1) of the continuum. The area of this section multiplied by two is then taken as the total area. But it is doubtful whether such a procedure makes more sense since the maximum of the continuum may be shifted either by final-state interaction, or by binding effects, or for some other reason. Furthermore, radiative and/or other effects can cause an asymmetry of the continuum. Lacking better methods, both procedures were used to find a value for $\sigma_{\mathrm{Li}}/\sigma_p$. The results of method II, since part of the radiative losses are neglected, should be considered only as a lower limit for $\sigma_{\mathrm{Li}}/\sigma_p$.

III. RESULTS AND DISCUSSION

Table I summarizes most of the results obtained in these experiments. First the measured cross-section ratios $\sigma_{\mathrm{Li}}/\sigma_p$ are listed as functions of scattering angle in the laboratory system for both Li^7 and Li^6 at 500 Mev. In the case of Li^6, data were taken only at 135°. Method II yields somewhat smaller cross-section ratios. The $\sigma_{\mathrm{Li}}/\sigma_p$ values at 135° represent the averaged results of three independent runs whereas at 60, 75, 95, and 115° data were taken only once. The quoted errors are based on rather conservative estimates and are mainly caused by the uncertainty in judging the area under the inelastic continuum. Reproducibility of the $\sigma_{\mathrm{Li}}/\sigma_p$ values was better than 10%. Next in the table are given the theoretical cross sections for elastic scattering of 500-Mev electrons from free protons computed from Rosenbluth's equation.[7] From these, σ_{Li} can be computed. The $\sigma_{\mathrm{Li}}/\sigma_p$ ratios determined at 500 Mev and 135°, where magnetic moment scattering from the proton accounts for about 93% of the total scattering, are about equal to the number of nucleons inside the isotope investigated. At smaller scattering angles, magnetic scattering from the proton is less dominant compared with charge scattering. Accordingly the ratio should drop with decreasing scattering angle, as was actually observed.

Next in Table I is given the quantity R, defined as

$$R=\frac{1}{N}\left\{\frac{\sigma_{\mathrm{Li}}}{\sigma_p}-3\right\}, \tag{2}$$

where $N=3$, 4 for Li^6, Li^7, respectively. If tentative validity of Eq. (1) as it stands is assumed for $\mathrm{Li}^{6,7}$, i.e., $\Delta=0$, then R would be equivalent to σ_n/σ_p. As was stressed in the introduction, theory does not provide a justification for such an assumption since nothing is known about the Δ-correction for lithium. A comparison of the R values derived from measurements on lithium with the σ_n/σ_p values determined by Yearian and Hofstadter[1] from deuterium with $\Delta=0$ leads, however, to the surprising result that these two quantities agree fairly well within the limits of error. The $(\sigma_n/\sigma_p)_{\Delta=0}$ values from the work of Yearian and Hofstadter are given in Table I for comparison. Data obtained by Ehrenberg and Hofstadter[2] for beryllium and carbon, although yielding slightly higher R values, are again consistent with the results obtained for the deuteron within the limits of error. There may be some trend for R to increase if more and more nucleons are added, but the limited precision of the results available at present does not allow establishing such a trend. Two explanations seem possible to explain the approximate agreement between these measurements. The various corrections to Eq. (1) may just cancel each other, i.e., $\Delta=0$, independent of A. Since some of the corrections are expected to depend on the mean distance between the nucleons within the nucleus which changes markedly as function of A between $A=2$ and $A=12$, such an accidental cancellation, although possible in principle for one particular nucleus, is not likely to occur for all A in this region. The alternative explanation that the individual corrections to Eq. (1) are each small by themselves seems equally surprising. Neither one of the two explanations can be discarded on the basis of these measurements. More precise measurements may possibly reveal discrepancies between these three experiments but none such can be detected as long as the limits of error are not substantially reduced.

A direct comparison between Li^6 and Li^7 at 500 Mev and 135° is also feasible. If one takes Eq. (1) literally,

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[7] M. N. Rosenbluth, Phys. Rev. **79**, 615 (1950).

such a comparison would yield directly the additional neutron's contribution to the scattering in Li^7. The method, however, suffers from the same limitations since theoretically Δ is unknown. For comparison, after having made the $1/E$ dispersive correction, the number of counts contained in the inelastic continuum down to the minimum where the meson production peak causes the continuum to rise again were added separately for both lithium isotopes. The fractional increase when going from Li^6 to Li^7 turns out to be not more than $(10.5\pm5)\%$, whereas a simple application of Eq. (1) with $\sigma_n/\sigma_p(500\text{ Mev}, 135°)=1$ and $\Delta=0$ would predict a fractional increase as large as 16.5%. One may again define a quantity R' which can be related to the observed fractional increase and which would be equal to σ_n/σ_p if Eq. (1) is taken literally, i.e., $\Delta=0$. A percentage increase of the area of only 10.5% leads to $R'=0.45$ which is markedly smaller than the value $R=1$ which is given in Table I. The discrepancy between the two results may reflect the limitations of the method, although, as will be noticed, they do not disagree by more than is compatible with the stated limits of error of the two measurements.

We have abstained from deriving neutron form factors from the measurements reported in this paper since the theoretical interpretation of these experiments, i.e., the magnitude of the Δ-correction, is still uncertain. It may be mentioned, however, that a σ_n/σ_p value of 0.45 would correspond to a magnetic cloud associated with the neutron roughly equal in size to that of the proton, whereas $\sigma_n/\sigma_p=1$ would correspond to a slightly smaller neutron size.

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