Electron Shake Off following the β^- Decay of He^6

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The charge spectrum of the Li^6 ions formed following the β^- decay of He^6 has been measured as a function of their recoil energy by means of a specially designed mass spectrometer. The analysis is as follows: charge 1 $(89.6\pm0.2)\%$; charge 2 $(10.4\pm0.2)\%$ of which $(0.31\pm0.05)\%$ is dependent on recoil energy; charge 3 $(0.042\pm0.007)\%$ of which $(0.024\pm0.009)\%$ is dependent on recoil energy. Comparison with theory shows that electron shake off results primarily from excitation by the sudden nonadiabatic change in nuclear charge. An expression is given for describing the simultaneous excitations from the sudden changes in nuclear charge and velocity.

I. INTRODUCTION

FOLLOWING β^- decay, an atom is left with a single positive charge as the result of the change in nuclear charge. It may also be sufficiently excited to lose one or more of its orbital electrons. This excitation arises principally from the sudden change in nuclear charge since the β^- particle leaves the atom too rapidly for the electrons to adjust adiabatically to their new environment. If, because of this "Coulombic shaking," a hole is created in one of the inner orbitals, or, if two electrons are excited into virtual states, further ionization may take place by Auger processes.

Extensive experimental[1–4] and theoretical[5–9] work has been done on the problem of shake off following beta decay, but the study of He^6 holds a position of particular importance. Because of the simplicity of dealing with only two electrons, and because of the availability of accurate wave functions for He and Li^+, Winther[10] was able to make calculations on the charge spectrum arising from the decay of He^6 which can be compared with experimental results with a minimum of ambiguity. A preliminary communication[11] on the relative intensity of charge-2 ions formed from the β^- decay of He^6 gave confirmation to Winther's calculations. Since that time, the accuracy of the data has been greatly improved, and the investigation has been extended to the measurement of charge-3 Li ions.

Two other groups have made measurements on the percentage of He^6 decays resulting in doubly charged ions. Ridley[12] found the relative abundance of charge 2 to be $(13\pm4)\%$ which is in agreement with our result of $(10.4\pm0.2)\%$. Allen *et al.*,[13] as an adjunct to their work on the recoil spectrum of He^6, have given $(29\pm15)\%$; however, their equipment was not designed for this measurement and the authors expressed some doubt on its validity.

Helium-6 also offers an ideal medium for observing a second-order shake off associated with the sudden change in nuclear velocity. Each nucleus recoils from the ejection of its β^- particle and neutrino so that there is a continuous spectrum of recoil velocities from zero to the maximum permitted by the conservation of momentum and energy. The extent of the shake off associated with recoil energy should likewise vary from zero to a maximum. For most nuclei undergoing β^- decay the recoil causes a negligible perturbation. For the 3.508-MeV decay[14] of low-mass He^6, however, the high energy of the recoil ions ($E_{max}=1418$ eV) produces a large enough effect to be visible in our experiment.

The measurements to be presented in this paper are the relative abundances of the three differently charged Li^6 ions formed from the decay of He^6.

II. RECOIL AND CHARGE SPECTROMETER

The spectrometer shown in Fig. 1 is essentially the same as that reported by Snell and Pleasonton[15] in their study on Ar^{37}. It allows one to observe ions emanating from a field-free volume filled with the radioactive gas. The energy spectra reveal not only differences in the dependence of the different charge states on recoil energy, but also, when summed over the charge states, can be interpreted in terms of the angular correlation between the β^- particle and neutrino. In fact, this interest in the $\beta^- - \nu$ correlation was the initial reason for introducing He^6 into the spectrometer and for studying the operation in detail. Some of the experimental details, which are abbreviated in the following discussion, may

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be found in our later report[16] on the correlation measurements.

Helium-6, which decays with a 0.797-sec[17] half-life, is produced by the $Be^9(n,\alpha)He^6$ reaction in about 150 g of BeO powder at the Oak Ridge Research Reactor in a position where the fast flux is about 10^{14} n/cm^2 sec. The He^6 is swept continuously by water vapor into our laboratory, where the water vapor is removed by condensation and the gas is purified by passing over hot Cu and CuO and through cold traps. The gas is supplied continuously to the conical source volume, and a small fraction of the Li^6 ions created in this volume recoils through the aperture at the small end of the cone. The resulting ion beam is then analyzed by magnetic and electrostatic analyzers in tandem. Double analysis establishes both the energy and charge of the ions, if they are assumed to be Li^6. This assumption is well founded; although it is conceivable that spurious ions might emanate from the cone with the proper ratio of charge to mass, it is difficult to imagine a mechanism to give them energies comparable to those of the Li^6 recoils. The analyzed ions are detected by an electron multiplier whose counts are normalized to those of a beta proportional counter near the source volume. The source and detector are in vacuum communication, but strong differential pumping across constrictions in the image planes of the analyzers reduces the background from decays at the entrance of the detector to a level which is gratifyingly small for the abundant charge-1 species, although almost overwhelming for the charge-3 component. Possible instabilities in the detector and monitor systems were studied by repeated measurements of the spectra. Although good stability was achieved, there remained some fluctuations in the intensity of radioactive contaminants in the source volume. Their activity had to be kept, by the proper maintenance of cold traps, at a stable fraction of the He^6 activity because the monitor responds to the activity of the contaminants as well as to the He^6.

Precision voltage supplies operate the ten-stage multiplier and the proportional counter. Precision supplies also furnish voltage for the electrostatic deflector, for an accelerating field at the entrance to the detector, and for a source potential if desired. The source volume can be biased either positively to accelerate the emerging ion beam before analysis, or negatively to prevent the beam from entering the spectrometer at all. Background measurements are normally taken under the latter condition. All voltages applied for acceleration and deflection are measured with calibrated resistance dividers and an L&N type-K potentiometer.

The magnetic field is monitored by a proton magnetic resonance fluxmeter. Errors from hysteresis effects in the magnet are avoided by making frequent recalibrations of the fluxmeter relative to the electrostatic analyzer. The absolute energy calibration is reported separately.[14]

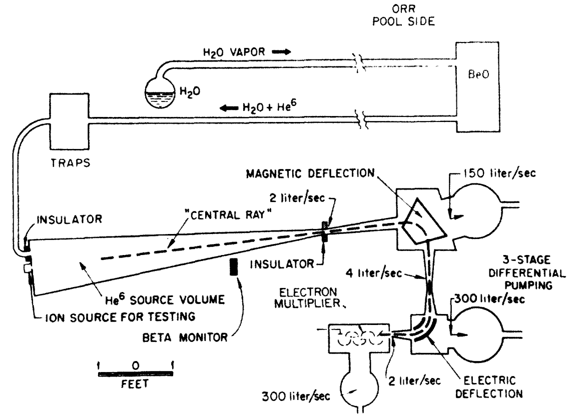

FIG. 1. He^6 recoil spectrometer.

Suitable precautions were taken to avoid spurious effects on the ion beam from reflection of ions into the beam from the chamber walls, from scattering of ions into or out of the beam by the residual gas, and from stray fields. Thin baffies line the walls to prevent ion reflections into the beam. The beam misses the electrostatic deflector plates, when their field is set properly, so that they do not require baffles. Scattering in the residual gas should be negligible at the low operating pressure of 1×10^{-6} Torr. Experimental confirmation of this statement was given by observations[16] at higher pressures. In addition, the relative intensities of the charge components were observed at 1200 eV (the peak of the counting rate), when the source volume was filled with N_2 to more than five times its normal pressures. These results are summarized in Table I. No substantial change in the data at elevated pressures is noted, so that any error in the charge spectrum that might be caused by pressure is small under operating conditions. Spurious electrostatic fields are avoided by shielding all insulators from the beam. Shielding against possible stray magnetic fields is provided by high permeability iron surrounding the chambers everywhere outside the magnet except for about two-thirds of the source volume. This region, which was left unshielded by default rather than by reason, had only a small magnetic field whose estimated effect on the measurements is less than the error quoted from other sources.

TABLE I. Effect of pressure on charge spectrum of Li^6 ions of 1200-eV recoil energy.

Charge	Pressure Low (10^{-6} Torr)	Pressure High (10^{-6} Torr)	Intensity at low pressure / Intensity at high pressure
1	1.0	5.4	1.004±0.004
2	1.0	5.4	1.024±0.018
3	1.0	6.9	0.92 ±0.21

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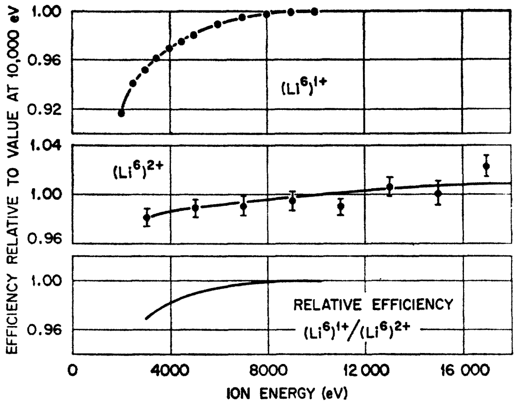

FIG. 2. Detection efficiency of the multiplier for singly and doubly charged Li^6 ions as a function of their energy when striking the cathode. For charge-1 ions the statistical uncertainties are less than the size of the data points.

III. MEASUREMENTS AND RESULTS

Before reporting the measurements we shall scan the general method of analysis. The energy spectrum for the sum of all recoil ions depends on the process of β^- decay, and the shake off phenomena simply divide this sum into its three charge components. If the shake off were energy independent, measurements could be limited to any convenient energy interval; however, since the shake off has a dependence on recoil energy, the *relative* charge abundance must be observed as a function of energy. The word "relative" is accented to indicate that the results on the charge spectrum can tolerate a rather poor measurement of the true energy spectrum. Perhaps this comment is academic, since we have made a careful measurement of the spectrum,[16] but it does clarify our procedure.

As an ion travels through the spectrometer from its origin in the source volume to its incidence on the multiplier's cathode, it experiences deflecting fields in the analyzers and also accelerating fields at the detector and, in some cases, at the exit from the source. By varying all of these field strengths inversely with the charge, one can subject the various charge components, at a given recoil energy, to the same focusing effects and accelerate them to the same final energy. The charge spectrum was obtained, under these conditions of identical focusing and equal final energy, by measuring the relative counting rates of the three lithium ions when the analyzers were properly tuned for maximum transmission of the ions. These rates varied from 80 000 counts/min, of which 10% were from background, for the prolific 1200-eV charge-1 ions down to 500 counts/min, of which 95% were from background, for 600-eV charge-3 ions.

Two sets of data were taken. The first set is composed of a series of careful measurements of the charge spectrum at one recoil energy, 1200 eV. The second set consists of measurements of the relative intensities of the ions as a function of recoil energy. For both sets of measurements the data were obtained in two stages; the abundance of the charge-2 ions was measured first relative to charge 1 and then relative to charge 3. This procedure provided flexibility in choosing operating conditions suitable to the relative intensities of the ions. During all runs, errors caused by long term drifts in the background were avoided by measuring the signal and background in alternate intervals of a few minutes each. Corrections for amplifier dead time were determined by the two-source method. The line shape of the transmitted ion beam was a function of the degree of acceleration applied to the ions before analysis; however, the procedure of taking data under identical focusing conditions permitted the comparison of counting rates at the peaks of the lines without corrections for their shapes.

A. Relative Abundances of 1200-eV Recoil Ions

Table II presents the operating conditions used in the various runs to determine the relative intensities of charge-2/charge-1 and charge-3/charge-2 Li^6 recoil ions at 1200 eV. The results of the measurements are given as percent abundances with standard errors based only on counting statistics.

Any uncertainty related to the detection efficiency must be included in the final assignment of errors. In Fig. 2 are plotted arbitrarily normalized efficiency curves for singly and doubly charged Li^6 ions as a function of the energy of the ion when it strikes the cathode of the electron multiplier. Because the efficiencies for both charges show negligible energy dependence above 8000 eV, we assume that they have reached nearly 100%. For this reason we made our measurements at high final energies. An uncertainty of $\pm 1\%$ arises from this assumption. Our final value is $(10.6\pm 0.1)\%$ for the relative abundance of the charge-2 ions at 1200-eV recoil energy.

The central problem in the measurement of the charge-3 ions is the low intensity relative to background. Two devices were employed to help alleviate this situa-

TABLE II. Relative abundances of charge-2 and charge-3 Li^6 ions of 1200-eV recoil energy.

Charge state e	Energy of ion emerging from source volume (eV)	Energy of ion striking multiplier (eV)	Activation of multiplier	Relative abundance A_e (1200) (%)
2	1200	8200	1st	$10.5\ \pm 0.2$
	2948	10 000	1st	$10.8\ \pm 0.2$
	2948	8900	2nd	10.62 ± 0.05
	2000	10 000	2nd	10.61 ± 0.07
	2000	10 000	2nd	10.59 ± 0.08
	2000	10 000	2nd	10.43 ± 0.09
			Wt. average	10.59 ± 0.04
3	5000	8000	1st	0.065 ± 0.005
	4982	7000	2nd	0.063 ± 0.010
	2906	5000	2nd	0.060 ± 0.007
	4982	7000	2nd	0.052 ± 0.004
			Wt. average	0.058 ± 0.003

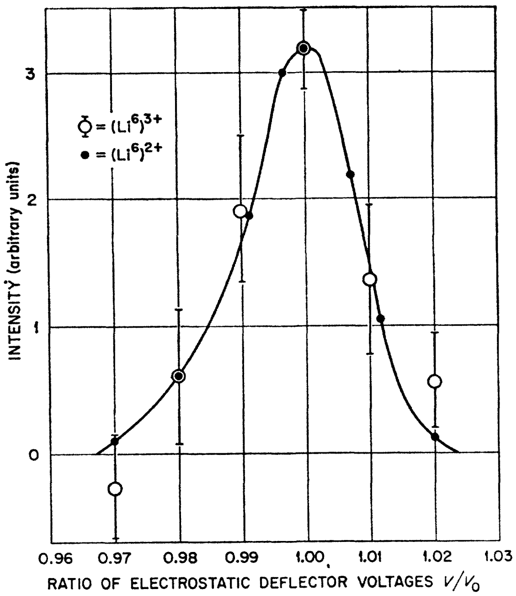

FIG. 3. Comparison of the peak profiles of charge-2 and charge-3 Li^6 ions. The curve is drawn through the data points for charge 2; the statistical uncertainties in these data are less than the size of the points as plotted.

tion. Firstly, discrimination of the signal over the less efficiently detected general background was improved by reducing the gain of the detector's amplifier by a factor of 16. Secondly, less acceleration was applied to the ions at the entrance to the multiplier in order to reduce the energy acquired by ions that are created by He^6 atoms decaying in this region. The latter device was particularly useful in discriminating against low energy charge-1 background ions.

Although the net improvement in the ratio of signal to background was a factor of about 10, the background was still very large. In order to obtain confidence in the measurements we determined whether or not the net signal for charge-3 vanished when the analyzers were improperly tuned. Figure 3 shows the line shape for charge-2 ions obtained by varying the electrostatic deflector voltage at a fixed magnetic field. The voltage is given relative to the amount required for maximum transmission of the beam. The open circles with error flags give corresponding data for charge-3 ions; clearly they are present.

The changes in operating conditions introduced only a negligible loss in detection efficiency for the analyzed ions; for the second activation of the multiplier it was only 2% for 6000-eV singly charged ions, and presumably less for ions of multiple charge. An efficiency curve for charge-2 ions at the lower gain setting showed, at most, an increase of 3% over the range of 3000 to 8000 eV. Equal efficiencies were assumed for charge-2 and charge-3 ions at the energies used in making the measurements. We estimate an additional uncertainty of about $\pm 2\%$ from this assumption, and give $(0.058 \pm 0.004)\%$ as the relative abundance of the charge-3 ions at 1200-eV recoil energy.

Since there are only three possible charge states for lithium, the relative intensity of the singly charged ions at 1200 eV is $(89.4 \pm 0.1)\%$.

B. Relative Abundances as a Function of Recoil Energy

Many measurements were made of the relative intensities of the ions as a function of recoil energy. For each set of data the curves of relative abundance vs energy were fitted by least squares to the linear function

$$A_e(E) = A_e(0) + k_e E, \tag{1}$$

where $A_e(E)$ represents the percent abundance of an ion of charge e and recoil energy E, and $A_e(0)$ is the intercept at zero recoil energy. Table III presents the results in terms of the slopes, k_2 and k_3, of the least-squares fits.

The first five entries in the table were found without using preacceleration of the ions. The other entries were obtained with the analyzers set to accept ions of a given energy, so that ions of different recoil energies were analyzed by varying the amount of preacceleration. It is encouraging to note that there is no perceptible difference in the results obtained for charge-2 ions with and without preacceleration.

After normalization to the accurately obtained values at 1200 eV, all data for a given charge were combined into a single set. These composite sets of data are plotted in Figs. 4 and 5. Using the slopes of the least-squares fits to these data and the values of the relative abundances at 1200 eV, we obtain, in the form of Eq. (1), the final result for the percent abundances of the Li^6 recoil ions

$$A_1(E) = (89.9 \pm 0.2) - (4.5 \pm 0.7) \times 10^{-4}\, E, \tag{2}$$

$$A_2(E) = (10.1 \pm 0.2) + (4.2 \pm 0.7) \times 10^{-4}\, E, \tag{3}$$

TABLE III. Relative abundances of charge-2 and charge-3 Li^6 ions as functions of recoil energy, in terms of the slopes, k_2 and k_3, of the least-squares linear fits to the data.

Charge state e	Recoil energies investigated (eV)	Energy of ion emerging from source volume (eV)	Slope of linear fit $10^{-4}\, k_e$ $(eV)^{-1}$
2	from 1300 to 369	Same as recoil energy	4 ± 2
	1200, 700	Same as recoil energy	4 ± 2
	1300, 700	Same as recoil energy	5 ± 3
	from 1300 to 369	Same as recoil energy	6 ± 3
	from 1300 to 369	Same as recoil energy	0 ± 2
	1200, 600	2938	5 ± 1
	1200, 600	2000	4 ± 1
	1200, 900	2000	4 ± 3
		Wt. average	4.1 ± 0.6
3	1200, 600	5000	0.47 ± 0.15
	1200, 700	2906	0.32 ± 0.24
	1200, 900	4982	0.19 ± 0.27
	1200, 600	4982	0.17 ± 0.22
		Wt. average	0.34 ± 0.10

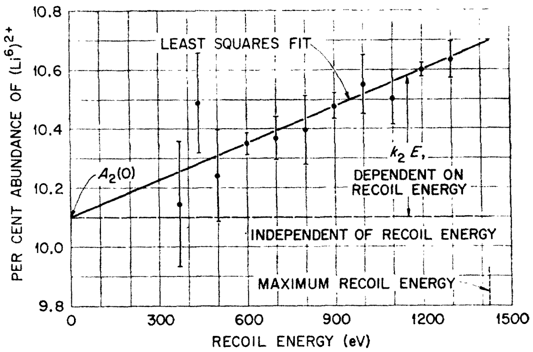

FIG. 4. Relative abundance of charge-2 Li^6 ions as a function of recoil energy.

and

$$A_3(E) = (0.018\pm0.015) + (0.33\pm0.13)\times10^{-4}\,E, \quad (4)$$

where the recoil energy is in electron volts. The standard errors assigned are based on the uncertainties associated both with the slopes of the least-squares fits to the data of Figs. 4 and 5 and with the measurements of the relative abundances of the ions at 1200 eV. They also include an estimate of the possible experimental errors discussed in Sec. II.

C. Total Charge Spectrum

It is also of interest to average the relative abundances over the energy spectrum. This average is the result that would be obtained if measurements were made with an apparatus that observes ions of different charge states independently of their energies. Denoting this average for ions of charge e by $\bar{A}_e$, we have

$$\bar{A}_e = \int_0^{E_{\max}} A_e(E)N(E)dE, \quad (5)$$

where $N(E)dE$ is the fraction of recoils with energy E to $E+dE$. Substituting Eq. (1) for $A_e(E)$ gives

$$\bar{A}_e = A_e(0) + k_e \int_0^{E_{\max}} EN(E)dE \quad (6)$$

$$= A_e(0) + 730k_e, \quad (7)$$

where the integral has been evaluated by graphical integration, using the function[16] $N(E)$ that corresponds to the axial vector interaction for the Gamow-Teller transition of He^6. It may be noted that the average $\bar{A}_e$ is the equivalent to the charge spectrum for ions of 730 eV; this evaluation at 730 eV instead of at half-maximum ion energy reflects the slight asymmetry in the function $N(E)$.

Substitution in Eq. (7) of the values of $A_e(0)$ and k_e from Eqs. (2), (3), and (4) yields the following charge

TABLE IV. Charge spectrum of Li^6 ions formed from the beta decay of He^6 (percent abundance).

	Theory[a]	Experiment		
Charge	Energy independent	Energy independent	Recoil energy contribution	Total
1	89.5±1.5	89.9 ±0.2	−(0.33 ±0.05)	89.6 ±0.2
2	10.5±1.5	10.1 ±0.2	0.31 ±0.05	10.4 ±0.2
3	<0.1	0.018±0.015	0.024±0.009	0.042±0.007

[a] See reference 10.

spectrum:

Charge 1, $\bar{A}_1 = (89.9\pm0.2)\% - (0.32\pm0.05)\% = (89.6\pm0.2)\%$;

Charge 2, $\bar{A}_2 = (10.1\pm0.2)\% + (0.30\pm0.05)\% = (10.4\pm0.2)\%$;

Charge 3, $\bar{A}_3 = (0.018\pm0.015)\% + (0.024\pm0.009)\% = (0.042\pm0.007)\%$.

The results are also tabulated in Table IV. It should be noted that the error in A_e is derived from the independent errors associated with k_e and $A_e(1200)$ rather than from the interrelated errors in k_e and $A_e(0)$. This is particularly evident for $\bar{A}_3$.

IV. DISCUSSION

A. The Sudden Approximation

The charge spectrum with its recoil energy dependence can be discussed in terms of the electron excitations resulting from the sudden transformation of the He^6 nucleus into a moving Li^6 nucleus: One may visualize the excitation as a "shaking" process in which "Coulombic shaking" by the sudden change in nuclear charge plays a dominant role and "recoil shaking" by the sudden appearance of a recoil velocity plays a minor role. The final charge of the Li^6 ion depends on the

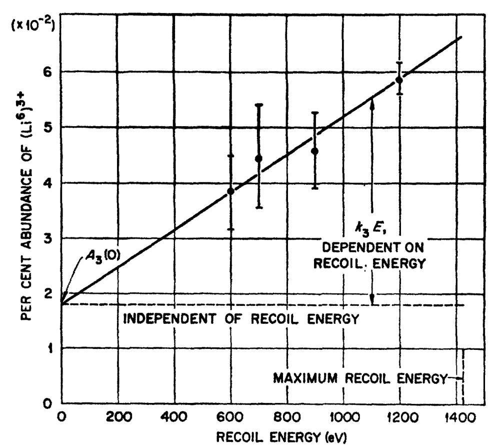

FIG. 5. Relative abundance of charge-3 Li^6 ions as a function of recoil energy.

degree of excitation. Winther[10] was able to make quantitative predictions, neglecting recoil shaking, for the charge-1 and charge-2 components. Levinger,[7] on the other hand, has considered the effect of recoil energy on a system that does not change its charge. The following discussion is a more general treatment that includes the effects of both recoil and Coulombic shaking.

The calculation of the shaking effects is based on the sudden approximation,[18] which assumes the β^- particle leaves the atom so quickly that there is no chance for adiabatic adjustment between it and the orbital electrons. This assumption requires[5,6] that the time spent by the β^- particle in traversing an electron shell is short compared to the electron orbital period. The assumption is valid for $\alpha Z_{\mathrm{eff}} \ll 1$, which holds true for the decay of He^6. (Here α is the fine structure constant and Z_{eff} is the effective nuclear charge.) The calculation also assumes that there is no direct interaction of the β^- particle with the orbital electrons; this direct effect is the order of $(\alpha Z_{\mathrm{eff}})^2$ relative to the dominant Coulombic shaking effect and, therefore, negligible for the decay of He^6.

In this sudden approximation the transition probabilities depend on the overlap integrals between the initial $(1s,1s)$ ground state of the He atom and the various final states of the Li ion with its nuclear recoil velocity V. The probability for transition to the (n_1l_1,n_2l_2) state of Li^+ is

$$P(1s,\, 1s \to n_1l_1,\, n_2l_2) = |\langle \mathrm{Li}^+ n_1l_1, n_2l_2 | e^{-iK(z_1+z_2)} | \mathrm{He}1s,1s\rangle|^2, \quad (8)$$

where

$$\langle \mathrm{Li}^+ n_1l_1, n_2l_2 | \mathcal{O} | \mathrm{He}1s,1s\rangle = \int d^3r_1 \int d^3r_2\, \Psi^*_{\mathrm{Li}^+ n_1l_1,n_2l_2}(\mathbf{r}_1,\mathbf{r}_2)\mathcal{O}\Psi_{\mathrm{He}1s,1s}(\mathbf{r}_1,\mathbf{r}_2),$$

and K is the wave number of the electron with velocity V relative to the nucleus. Final states can be either discrete levels or states with one or both electrons in the continuum.

It is convenient to expand the exponential in Eq. (8) in order to clarify the physical interpretation and to simplify the calculations. Expansion of the exponential gives the following transition probabilities:

$$P(1s,\, 1s \to n_1s,\, n_2s) = |\langle f|1|i\rangle|^2 - K^2\, \mathrm{Re}\langle f|1|i\rangle^* \langle f|(z_1)^2+(z_2)^2|i\rangle, \quad (9)$$

where $i=$ He $1s$, $1s$, $f=\mathrm{Li}^+ n_1s$, n_2s, and

$$P(1s,\, 1s \to n_1p,\, n_2s) = K^2 |\langle f|z_1+z_2|i\rangle|^2, \quad (10)$$

where $i=$ He $1s$, $1s$ and $f=\mathrm{Li}^+$ n_1p, n_2s. Because K is small, we have retained only terms through K^2. The first term in Eq. (9) contains the unit operator and yields the dominant monopole transition to final s states; these transition probabilities have no recoil dependence and are associated with Coulombic shaking. The second term in Eq. (9) represents interference with contributions from the unit operator. This interference term, which is proportional to recoil energy, causes a small reduction in the s-state transition probability. Equation (10) gives the dipole transition probabilities to states with one electron in a p state and the other in an s state. All terms containing the first power of K vanish; i.e., there is no interference getween the p- and s-state transitions.

The total transition probability summed over all final s and p states, including states with one or both electrons in the continuum, may then be written:

$$C+(a'-b')K^2=100\% \quad (11a)$$

or, alternatively, to facilitate comparison with the experiment,

$$C+(a-b)E=100\%, \quad (11b)$$

where C, a, and b (or C, a', and b') are constants. Here C is the total s-state transition probability resulting from Coulombic shaking, and $-bE$ and $+aE$ are, respectively, the s-state depletion and the p-state gain produced by recoil shaking. Clearly $a=b$; i.e., the depletion cancels the gain.

Our interest lies in the charge states resulting from these modes of excitation. Charge-1 ions are formed when one electron is left in the $1s$ ground state of Li^+ and the other electron is in a discrete bound state. Charge-2 ions are produced when one electron is ejected either by direct excitation into the continuum or by a two-step process through an intermediate virtual state. All states of Li^+ that have both electrons in excited levels are virtual states with sufficient energy for ionization, and it can be assumed that these states will decay by auto-ionization rather than by radiative transitions because the relative magnitude of the two processes is the order[19] of $10^6/Z^4$. Charge-3 ions can be formed by direct excitation of both electrons into the continuum. Each of the terms in Eq. (11a) or (11b) makes contributions to each charge species; thus, with subscripts denoting charge, Eq. (11a) becomes

$$P_1(E)+P_2(E)+P_3(E)=100\%, \quad (11c)$$

where

$$P_1(E)=C_1+(a_1-b_1)E,$$
$$P_2(E)=C_2+(a_2-b_2)E,$$
$$P_3(E)=C_3+(a_3-b_3)E.$$

The probabilities $P_1(E)$, $P_2(E)$, and $P_3(E)$ are analogous to the observed $A_1(E)$, $A_2(E)$, and $A_3(E)$ of Sec. III and provide the theoretical basis for the straight-line least-squares analysis in Figs. 4 and 5.

[18] For a fuller discussion of the sudden approximation, see, e.g., Leonard I. Schiff, *Quantum Mechanics* (McGraw-Hill Book Company, Inc., New York, 1955), 2nd ed., p. 217.

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B. Coulombic Shaking

Winther[10] has calculated the transition probability C_1 for Coulombic shaking leading to Li^+ bound states. He used accurate $(1s,1s)$ wave functions for the He atom and various $(1s,ns)$ wave functions for Li^+ to give transition probabilities up to $n=4$. He then estimated the small contributions from the remaining $(1s,ns)$ states. The resulting sum over all n is $(89.5\pm1.5)\%$. Subtraction from 100% gives the probability C_2+C_3 for excitation into virtual levels and into the continuum. He estimated further that the probability C_3 for double ionization is negligible $(<0.1\%)$. Thus, Coulombic shaking without recoil corrections predicts $(89.5\pm1.5)\%$, $(10.5\pm1.5)\%$, and $(<0.1)\%$ for the three charge species. These predictions are compared in Table IV with our experimental values obtained at zero-recoil energy. The predictions for charge-1 and charge-2 ions are in excellent agreement with our values of $(89.9\pm0.2)\%$ and $(10.1\pm0.2)\%$; the prediction for charge 3 is consistent with our value of $(0.018\pm0.015)\%$.

C. Recoil Shaking

The contributions that recoil energy gives to the transition probabilities have been designated in Eq. (11c) by $(a-b)E$, where aE is the summation of p-state transitions and $-bE$ is the summation of s-state depletions. Sample calculations have been made for both types. The p-state transition probability, $P(1s, 1s\rightarrow 1s, 2p)$, was calculated to be $(2.5\times10^{-4}\,E)\%$, while the depletion of the transition probability, $P(1s, 1s\rightarrow 1s, 1s)$, was calculated to be $(2.2\times10^{-4}\,E)\%$. Wave functions used in the first calculation were obtained from Morse *et al.*[20] and those used in the second calculation were obtained from Green *et al.*[21] We observe that the transition probabilities are the same order of magnitude as the experimentally observed dependence on recoil energy for charge-1 and charge-2 ions. See Eqs. (2) and (3). It is a rather formidable task to complete the calculations for all the transition probabilities that depend on recoil energy. It can be noted here, however, that the experimental data require $(a_e-b_e)E$ to be negative for charge-1 ions and positive for charge-2 and charge-3 ions; in other words, recoil shaking increases the degree of ionization.

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V. CONCLUSION

We have investigated the charge spectrum as a function of recoil energy of the Li ions that result from the β^- decay of He^6. The excellent agreement of the observed relative abundance of the charge-2 and charge-1 ions with that computed by Winther[10] has given confidence that the principal processes in removing an electron following β^- decay are well understood. These processes arise from the nonadiabatic change in nuclear charge. In addition, the secondary effect of recoil energy has been measured. The simultaneous excitation from the sudden change in nuclear charge and from recoil has been described in terms of a sudden approximation calculation.

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