we have interpreted as being due to the transformation of $_3Li^7$ into $_4Be^8$ and a neutron, as postulated in reaction (4). The area under the hump is approximately 5 percent of the area under the entire curve; this indicates that $_4Be^8$ is formed in 5 percent of the disintegrations.

As the neutrons were observed at right angles to the incident deuterons, the energy of disintegration, Q, is given by

$$Q=9/8E_N-3/4E_H,$$

where E_N is the neutron energy and E_H is the energy of the incident deuteron. The extrapolated maximum neutron energy is 13.4 ± 0.5 MEV. Because Mano's range-velocity curve is for mean and not extrapolated range, we have subtracted 0.1 MEV from our extrapolated energy. Using a neutron energy of 13.3 MEV and a bombarding energy of 0.85 MEV, we find that $Q=14.3\pm0.5$ MEV. From the value of 14.6 ± 0.25 MEV found by Oliphant, Kempton and Rutherford for the energy of disintegration into two alpha-particles and a neutron, we calculate the mass of $_4Be^8$ to be 0.3 ± 0.75 MEV greater than that of two alpha-particles. A recalculation of Kirchner's mass of $_4Be^8$ with Bethe's new isotopic scale[19] gives a mass just equal to that of two alpha-particles. Recently, Oliphant, Kempton and Rutherford[20] have shown that $_4Be^8$ is formed according to the reactions $_4Be^9+{}_1H^1\rightarrow{}_4Be^8+{}_1H^2$; $_4Be^9+{}_1H^2\rightarrow{}_4Be^8+{}_1H^3$ and find a mass of $_4Be^8$ which is 0.2 MEV greater than that of two alpha-particles. The present evidence seems strongly to indicate the existence of a $_4Be^8$ nucleus with a mass slightly greater than that of two alpha-particles, although a mass equal to or less than that of two alpha-particles cannot be excluded at the present time.

We wish to thank Professor C. C. Lauritsen for valuable suggestions made during the progress of this work, and the Seeley W. Mudd Fund for its financial support.

[19] H. A. Bethe, Phys. Rev. **47**, 633 (1935).
[20] Oliphant, Kempton and Rutherford, Proc. Roy. Soc. **A150**, 241 (1935).

NOVEMBER 1, 1935 PHYSICAL REVIEW VOLUME 48

On the Nuclear Moments of Lithium, Potassium, and Sodium[1]

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(Received August 7, 1935)

The atomic beam method of "zero moments" was applied to the measurement of the nuclear spin and hfs separation of the normal $^2S_{\frac{1}{2}}$ state of Li^7. The experimental arrangement was such that the precision obtained was about 1 percent. It was verified that the nuclear spin was 3/2, and the hfs separation was measured to be 0.0268 ± 0.0003 cm^{-1}. By using the modified Goudsmit formula the nuclear magnetic moment was calculated to be 3.20 nuclear magnetons compared with the value of 3.28 calculated from hyperfine structure measurements on the $^3P_0-{}^3S_1$ group ($\lambda5485$) of $(Li^7)^+$ by Breit and Doerman using wave functions. The same method applied to potassium and sodium yielded hfs separations of 0.0154 ± 0.0002 and 0.0596 ± 0.0006 cm^{-1}, respectively, which lead to nuclear magnetic moments of 0.397 and 2.08 nuclear magnetons. With another arrangement of the apparatus yielding higher resolution than was previously obtained it was possible to set the value of 5/2 as an upper limit for the spin of the K^{41} nucleus. With the same arrangement applied to lithium it was found that the nuclear spin of Li^6 is 2/2 or greater and that the magnetic moment of the nucleus is of the order of magnitude of that of the deuteron.

INTRODUCTION

THE hyperfine structure of the $(Li^7)^+$ spectrum and the band spectra of the Li_2^7 molecule have been studied by a number of investigators.[2] The band spectra results have yielded a value of $3/2\ h/2\pi$ for the nuclear spin of Li^7, which is consistent with the results

[1] A preliminary report on the spin and magnetic moment of Li^7 was given at the Washington meeting of the Am. Phys. Soc. Fox, Millman and Rabi, Phys. Rev. **47**, 801 (1935).

[2] Schüler, Zeits. f. Physik **66**, 431 (1930); Harvey and Jenkins, Phys. Rev. **35**, 789 (1930); Güttinger and Pauli, Zeits. f. Physik **67**, 743 (1931); Goudsmit and Inglis, Phys. Rev. **37**, 328 (1931); Granath, Phys. Rev. **42**, 44 (1932); Ladenburg and Levy, Zeits. f. Physik **88**, 449 (1934).

obtained from the hyperfine structure studies.* The hyperfine structure measurements were made on the $^3P_0-{}^3S_1$ group (λ5485) of Li^+. The separations were large enough to yield very precise values, from which the magnetic moment of the Li^7 nucleus has been calculated with the theory of Breit and Doerman,[3] to be 3.28 nuclear magnetons. The hyperfine structure of the levels of neutral Li^7 is not suitable for spectroscopic study. In view of the probable importance of an accurate knowledge of nuclear moments, particularly those of the lighter elements, in connection with a theory of nuclear structure, these experiments were undertaken with the object of measuring accurately the hfs separation of the normal $^2S_{1/2}$ state of the Li^7 atom. For experiments of this type the method of "zero moments" by using atomic beams[4] is most suitable. The results of the experiments to be described will allow a comparison of the theory of Breit and Doerman, which depends on the calculation of wave functions, with the semi-empirical theory of Goudsmit[5] and Fermi and Segrè.[6] Since in experiments of this type the precision is equally good for large and small hfs separations, it was considered desirable to measure also the hfs separations of the normal states of K^{39} and Na^{23} with a view toward obtaining greater precision than was obtained in previous experiments. In addition it was hoped that some information about the nuclear spins and hfs separations of the normal states of Li^6 and K^{41} would be obtained.

The experimental method involved is fully described in recently published papers.[4]

Apparatus

The apparatus, shown schematically in Fig. 1, which had been previously used to investigate the nuclear moments of the principal isotopes of potassium,[4] was modified to attain greater precision. A new duralumin field block supporting two wires of twice the diameter of those in the field block used in the potassium work was constructed. This resulted in a decrease of the ratio of the gradient to the field by one-half. If Δy is the error in measuring the distance between the atomic beam and the field wires, then

$$\frac{\partial H/\partial y}{H}\Delta y=\frac{\Delta H}{H}$$

and consequently there is a gain in precision in reducing the ratio of the gradient to the field. There is, of course, a corresponding reduction in resolution which was partly compensated for by using narrower beams. There is an additional gain in precision due to the fact that the field and the gradient become more uniform over the height of the beam with an increase in the size of the wires. The height of the beam was limited to 1.5 mm and the beam passed along the field wires at a distance of a few hundredths of a mm from the surface. The collimating slit was 0.012 mm and the oven slit was 0.010 mm.

Procedure

The procedure is similar to that followed in the work on potassium.[4] The temperature of the oven was raised to about 600°C over a period of three hours and then stabilized. Before any magnetic field was impressed a plot was made of the intensity of the beam with respect to the position of the detector. We shall refer to this plot as the shape of the original beam. The end of the field block toward the detector was then moved a measurable distance until a one-mil filament mounted at a measured distance from the surface of the wires at this end of the block was exactly in the center of the original beam. With this "stopping filament" so situated, the beam pattern at the position of the detector shows a minimum of intensity at the center of the original beam and maxima on either side of this shadow cast by the stopping filament. The collimating slit having been set by means of a telescope at a measured distance from the surface of the wires at the end of the field block toward the oven, the position of the beam with respect to the wires was then known. The collimating slit was then moved a measured distance either toward or away from the field block so that the stopping filament no longer intercepted the beam, and this new

* Some slight doubt has been cast upon this result by the studies of Ladenburg and Levy whose results indicate a nuclear spin of 5/2.

[3] Breit and Doerman, Phys. Rev. **36**, 1262 (1930).

[4] Cohen, Phys. Rev. **46**, 713 (1934); Millman, Phys. Rev. **47**, 739 (1935).

[5] Goudsmit, Phys. Rev. **43**, 636 (1933).

[6] Fermi and Segrè, Zeits. f. Physik **82**. 729 (1933).

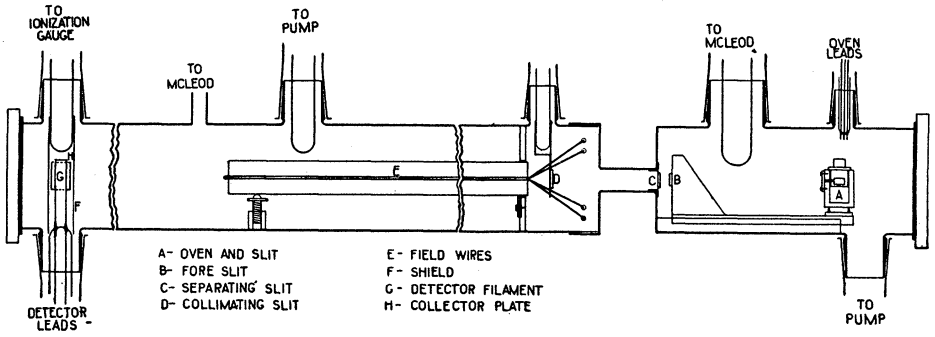

FIG. 1.

position of the beam with respect to the field wires was known precisely. This procedure (unlike that followed in the potassium work where the stopping filament was burned out after being set in the position where it intercepted the beam) was followed so that the stopping filament was always available for resetting the position of the beam with respect to the field wires. Measurements were made with the beam passing between the stopping filament and the wires and also with it passing on the side of the filament away from the wires. The apparatus was taken apart several times and the stopping filament was set at different distances from the surface of the field wires and at different positions along the field block near the detector end. After reassembling the apparatus, the collimating slit was set by means of a calibrated telescope at a measured distance from the surface of the field wires independently for each run. In this way the possibility of a systematic error in the position of the beam was greatly reduced.

Runs were made with lithium, potassium, and sodium in the oven separately and also with mixtures of potassium and lithium present. In the cases where a mixture was in the oven, the temperature of the oven was first raised to the working temperature for potassium and measurements were made. When the potassium was finally boiled off completely (after a few hours), the temperature was raised to the lithium working temperature and measurements again were made. The results of such measurements gave not only very precise values for the hfs separations of potassium and lithium, in agreement with values obtained from runs taken on each element separately, but also precise ratios of their hfs separations.

DISCUSSION OF PRECISION

The precision of our measurements does not depend on a knowledge of the temperature of the oven, on the distribution of velocities of the atoms in the beam, or on an accurate knowledge of the original beam shape. There are four factors which affect the precision:

(1) The determination of the ammeter reading of the current in the field wires at which the intensity of the "zero moment" peak is a maximum. In making this determination the current was varied in small steps and the resulting intensities were recorded. It was found that the ammeter readings corresponding to the determinations of the maximum intensities did not differ amongst themselves by more than 1/3 percent for a particular setting of the beam position. As numerous readings were taken the errors arising from this source could hardly exceed 1/5 percent.

(2) The conversion of the ammeter readings to current. This depended on the calibration of the shunt used and on the reading of a potentiometer measuring the potential difference across the shunt. The shunt resistance was measured with a Kelvin double bridge and was found to agree with the factory calibration to about 1/5 percent. The standard cell used with the potentiometer was checked against a factory calibrated standard. The currents carried by the shunt were always considerably below the rated capacity.

(3) The effect of stray magnetic fields. This was eliminated by making a determination of the current at which the intensity of the "zero moment" peak is a maximum with the magnetic field in one direction and repeating with the magnetic field reversed.

(4) The determination of the position of the beam with respect to the field wires, from which the effective magnetic field traversed by the beam can be calculated. This involves the measurement of a number of geometric

quantities and constitutes the largest source of error in the experiment. The beam was located with respect to two points along the length of the wires, i.e., the collimating slit and the stopping filament, in the manner described above. The field wires were examined for uniformity of cross section and were found to be circular and uniform to within 0.003 mm, the average diameter being 4.767 mm. The duralumin block which supports the wires was examined for straightness by stretching a No. 40 copper wire along its surface so as to be taut, and measuring the distance between this wire and the surface of the block with a microscope. The microscope axis was vertical so that any sag in the wire had no effect on the measurements. This examination showed the block to be straight to 0.004 mm. In addition, a point to point plot of the straightness of the wires after being mounted in the block was made by using a "last word" indicator calibrated to 1/10,000 in., and this plot showed that the wires were straight to within 0.005 mm. A further correction to the effective magnetic field corresponding to the maximum intensity of the "zero moment" peak involves the effects of the ends of the wires where the field and the gradient vary considerably from their values in the central portions of the field. Because of the great length of the field (61.1 cm) compared with the distance between the wire centers 0.4895 cm), this correction is easily made, and serves to lower the effective magnetic field by about 1/2 percent. The total error involved in the determination of the geometry mentioned above we estimate to be about 1 percent.

Results

Li^7

As typical of the agreement between results obtained from different runs, the following is a list of values obtained for the effective magnetic field at which the Li^7 atoms with total magnetic quantum number $m=-1$ have a zero moment: 143.0, 143.1, 143.1, 143.4, 143.2, 143.4, 143.2, 143.2, 143.3 gauss. The precision of our results as indicated by the agreement between these values is not real, however, because of the systematic errors in the measurement of the position of the beam relative to the field wires.

It was verified that the nuclear spin of the Li^7 atom is $3/2\ h/2\pi$ as is readily seen from Fig. 2(A). The hfs separation of the normal $^2S_{1/2}$ state is calculated to be 0.0267 ± 0.0003 cm^{-1}. With the formulae of Goudsmit[5] as modified by Fermi and Segrè,[6] the magnetic moment of the Li^7 nucleus is calculated to be 3.20 nuclear magnetons. In view of the nature of the theory involved in this result, it is in very satisfactory agreement with the value of 3.28 calculated by Breit and Doerman.[3]

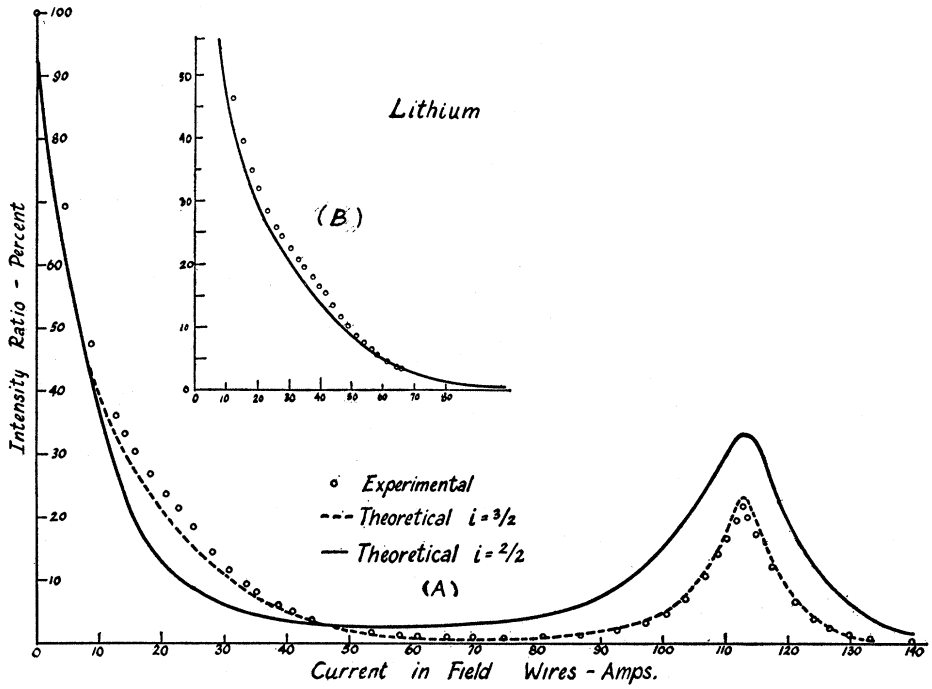

FIG. 2.

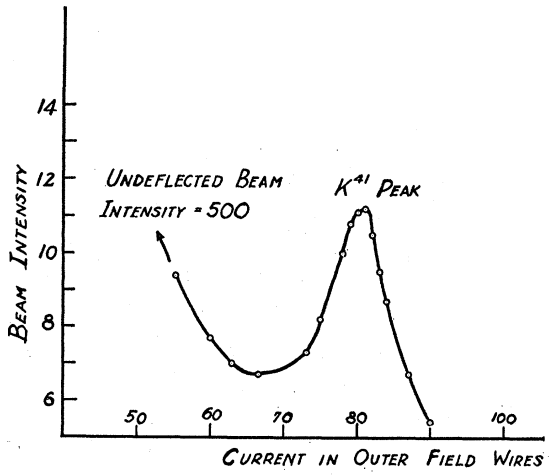

FIG. 3. Four-wire system current ratio 5 : 2.

K^{39}

The hfs separation of the normal $^2S_{1/2}$ state of K^{39} was measured to be 0.0154 ± 0.0002 cm^{-1}, from which the magnetic moment is calculated to be 0.397 nuclear magnetons.

Na^{23}

For Na^{23} the hfs separation of the normal $^2S_{1/2}$ state was measured to be 0.0596 ± 0.0006 cm^{-1}, which is somewhat higher than the value of 0.0583 cm^{-1} obtained by Granath and Van Atta,[7] but in excellent agreement with the result of 0.059 cm^{-1} of Jackson and Kuhn.[7a] Since our experimental result yields an independent measurement of the $^2S_{1/2}$ separation, it can be used in connection with the hyperfine structure measurements of the separations $\delta P_{1/2}-\delta S_{1/2}$ and $\delta P_{3/2}-\delta S_{1/2}$ independent of the cosine law of interaction between the nuclear spin and the total electronic angular momentum. When such calculations are made, the results for the hfs separations of the $^2P_{1/2}$ and the $^2P_{3/2}$ states do not agree with the results of Granath and Van Atta. However the precision of the spectroscopic measurements is not sufficiently good to attach great significance to this disagreement. The nuclear magnetic moment for Na^{23} is calculated to be 2.08 nuclear magnetons. This value may be compared to the value of 2.55 which would be obtained with the Fock wave functions as applied by Wills and Breit[8] and Shoupp, Bartlett and Dunn.[9]

K^{41}

In addition to the experiments described, further experiments on K^{41} and Li^6 were undertaken using the field block used by Millman in the potassium work. By increasing the ratio of the currents in the two sets of wires, the ratio of the gradient to the field was increased to about 15, thus resulting in higher resolution. This enabled us to resolve the "zero moment" peak due to K^{41} more clearly than was done in Millman's work as is shown in Fig. 3. Calculation shows that the background intensity due to the K^{39} atoms is about 1/4 percent of the intensity of the original beam, so that practically all of the intensity of the peak is due to K^{41}. Since the intensity of the peak is of the order of 2 percent of the original beam intensity, the nuclear spin of the K^{41} atom is not likely to be greater than 5/2.

Li^6

It is seen in Fig. 2(A) that the experimental points lie very close to the theoretical curve everywhere except in the region where the current in the field wires is in the neighborhood of 20 amperes. This region of the intensity *versus* magnetic field curve was examined under higher resolution and the departure of the experimental

[7] Granath and Van Atta, Phys. Rev. **44**, 935 (1933).
[7a] Jackson and Kuhn, Proc. Roy. Soc. **A148**, 335 (1935).
[8] Wills and Breit, Phys. Rev. **47**, 704 (1935).
[9] Shoupp, Bartlett and Dunn, Phys. Rev. **47**, 705 (1935).

points from the theoretical curve was more pronounced as is seen in Fig. 2(B). The resolution was not good enough to actually resolve a peak due to Li^6 but it can be assumed, as was originally done with the unresolved peak due to K^{41}, that the discrepancy between the experimental and theoretical intensities is due to an unresolved "zero moment" peak of Li^6. It follows from this that the nuclear spin of Li^6 is 2/2 or greater, and that the ratio of the magnetic moments of the two isotopes of lithium, μ_6/μ_7, can be put between the limits of 0.15 and 0.25, the value depending on the spin of Li^6. If a spin of 2/2 is assumed the magnetic moment of the Li^6 nucleus is calculated to be of the order of magnitude of that of the deuteron.

We are much indebted to Dr. Sidney Millman and other workers in the molecular beam laboratory for their able assistance in the course of these experiments.

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Positive and Negative Thermionic Emission from Molybdenum

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(Received August 9, 1935)

The positive and negative thermionic emission for molybdenum has been investigated. The electron work function has been found to be 4.17 volts and that of the positive ion 8.35 volts. The positive ion emission has been shown to agree with the Saha theory of ion formation to within the experimental limits of error.

IT has been shown by Smith[1] and by Wahlin[2] that when molybdenum is heated to a sufficiently high temperature, positive ions of the metal itself are emitted. The temperature variation of this ionic current has been studied by Smith[1] and by Barnes[3] with differing results. Smith, following the analysis used by Bridgman[4] in his derivation of the Richardson equation, has derived a positive ion thermionic equation which for molybdenum takes the form:

$$\log_{10} i + 0.453 \log_{10} T + 2.7 \quad 10^{-4}T = -\varphi_{0+}e/2.303kT + C, \quad (1)$$

neglecting any effect of the surface heat of charging. From this equation he computed φ_{0+} to be 6.33 volts. Barnes using the same equation obtains a value of 8.17 volts.

Because of these discordant results it was thought worth while to repeat the experiment with better outgassing conditions than have been used hitherto.

The thermionic tube used was one with a single guard ring and a U type filament. The tube, the potentials used and the outgassing treatment were similar to those described in a study of the positive ion emission from columbium by Wahlin and Sordahl.[5]

Extreme care was exercised in the baking and heating process to eliminate alkaline impurities as far as possible. The baking of the tube was continued for at least 500 hours with the filament at a temperature of about 1700°K and the furnace at a temperature of 450°C. The heat treatment of the filament was then continued at a temperature of 1900°K with occasional flashing to 2100°K or higher until a value for the electron work function, as measured at intervals from a Richardson plot, did not vary with heat treatment for at least 200 hours. After the baking and heat treatment the pressure remained lower than 3×10^{-8} mm when the filaments were varied over the temperature ranges used.

Three disappearing filament optical pyrometers were used in measuring the temperatures. These were calibrated in the usual manner by sectoring up and down from the gold point and then checked against the palladium point. None

[1] L. P. Smith, Phys. Rev. **35**, 381 (1930).
[2] H. B. Wahlin, Phys. Rev. **34**, 164 (1929).
[3] L. L. Barnes, Phys. Rev. **42**, 491 (1932).
[4] P. W. Bridgman, Phys. Rev. **27**, 173 (1926).
[5] Wahlin and Sordahl, Phys. Rev. **45**, 886 (1934).