in which $\mathbf{E}$ is the static field intensity will give a measure of the transition probabilities for the half-frequency transitions ($\mathbf{E}=0$) and for the normal transitions ($\mathbf{E}\neq 0$, $\omega=(E_m-E_n)/\hbar$) respectively. It was found for the case of interest to us ($J=1$ in the initial and final states) that these sums are comparable provided $\mathbf{E}'$ and $\mathbf{E}$ are of the same magnitude. Hence, if a normal transition is observed when $\mathbf{E}'$ and $\mathbf{E}$ are equal, it is expected that a half-frequency transition will be observed with this same value of $\mathbf{E}'$ when $\mathbf{E}=0$.

The theory of half-frequency transitions in the presence of a static field is easily worked out. The representation $\phi(J, I_1, F_1, I_2, F, M)$ is applicable provided the static field is sufficiently weak. The expression $a_m^{(2)}$ for the case of zero field is modified to read:

$$a_m^{(2)} = -\frac{1}{\hbar^2}\sum_n a_n^{(0)} \sum_l (m|\boldsymbol{\mu}\cdot\mathbf{E}'|l)(l|\boldsymbol{\mu}\cdot\mathbf{E}'|n)\{\ \}$$

in which

$$\{\ \} = \frac{\exp\left[-i2\omega t + \frac{i}{\hbar}(E_m^{(0)}-E_n^{(0)})t\right]-1}{\left[-i2\omega + \frac{i}{\hbar}(E_m^{(0)}-E_n^{(0)})\right]\left[-i\omega + i\frac{E_l^{(0)}-E_n^{(0)}}{\hbar}\right]} - \frac{\exp\left[-i\omega t + \frac{i}{\hbar}(E_m^{(0)}-E_l^{(0)})t\right]-1}{\left[-i\omega + \frac{i}{\hbar}(E_m^{(0)}-E_l^{(0)})\right]\left[-i\omega + i\frac{E_l^{(0)}-E_n^{(0)}}{\hbar}\right]}.$$

There is now a sum over a number of states n because our initial state is no longer a pure state $\phi(J, I_1, F_1, I_2, F, M)$, but involves a mixture of such states due to the perturbing effect of the static electric field. If the initial state were $\phi(J, I_1, F_1, I_2, F, M)$ in the absence of a static field, it will involve the states $\phi(J', I_1, F_1', I_2, F', M)$ in which $J'=J\pm 1$, $F_1'=F_1$, $F_1\pm 1$; $F'=F$, $F\pm 1$. Resonance occurs when $\omega=(E_m^{(0)}-E_n^{(0)})/2\hbar$ caused by the first factor within the brackets exactly as for the case of zero static field; at this resonance the second factor in the brackets is negligibly small. There is, of course, a first-order $a_m^{(1)}$ in this case which leads to the normal transitions between two states which at zero field have the same J value.

If the static field is sufficiently large so that the interaction of the field with the dipole moment is larger than the internal molecular interactions involving $\mathbf{I}_2$, then a weak field representation should be used. The resonance at the half-frequencies is predicted exactly as above. The transition probability is reduced somewhat, however, because the amplitude of that part of the initial state which is involved in the half-frequency transition $[\phi(J, I_1, F_1, I_2, F, M)]$ is reduced by the perturbation due to the static field.

If the static field is sufficiently large so that a strong field condition applies $[\mu^2E^2/(\hbar^2/2A)\gg eq_1Q_1]$ and if the radiofrequency field is perpendicular to the static field, then the M selection rule becomes $\Delta m_2=0$, $\Delta m_1=0$, $\Delta m_J=0, \pm 2$. Such a transition would not be observed for a $J=1$ state molecule because the deflection of a molecule in the A and B fields depends only upon $|m_J|$.

Professor I. I. Rabi first pointed out to us the possibility of half-frequency transitions. Also we wish to thank him for many stimulating discussions.

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Hyperfine Structure and Isotope Shift in Barium

O. H. Arroe
University of Wisconsin, Madison, Wisconsin*
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Spectroscopic hyperfine structure studies with separated isotopes of barium have definitely confirmed a nuclear spin $\frac{3}{2}$ for the odd isotopes Ba^{135} and Ba^{137}. The lines of the even isotopes show no structure. The isotope shift is linear among masses of the same parity, but there is a relatively great odd-even shift: Note the order 138, 136, 134, 137, 135 in BaI, and 138, 136, 137, 134, 135 in BaII. The relative positions of the components (centroids, for odd masses) of the resonance lines, in $10^{-3}\pm 0.7.10^{-3}$ cm^{-1} are

	138	137	136	135	134
BaI $6s^2\ {}^1S_0-6s6p\ {}^1P_{\frac{1}{2}}$	0	+5.2	+2.2	+7.4	+4.4
BaII $6s\ {}^2S_{\frac{1}{2}}-6p\ {}^2P_{\frac{1}{2}}$	0	+6.0	+4.8	+11.1	+9.6
$6s\ {}^2S_{\frac{1}{2}}-6p\ {}^2P_{\frac{3}{2}}$	0	+6.4	+5.4	+12.6	+10.8

I. INTRODUCTION

SINCE hyperfine structure in the barium spectrum was reported by McLennan and Allen,[1] several investigators have tried to use the structure they found in several lines to determine the nuclear spin of the odd isotopes Ba^{135} and Ba^{137}. From the data of Ritschl and Sawyer,[2] Schuler and Jones[3] found the nuclear spin to

* Supported by Navy contract N7onr-285TO #1, NR 019 107.
[1] J. C. McLennan and E. J. Allen, Phil. Mag. **8**, 515 (1929).
[2] R. Ritschl and R. A. Sawyer, Zeits. f. Physik **72**, 36 (1931).
[3] H. Kallman and H. Schuler, Ergeb. d. exakt. Naturwiss. **11**, 134 (1932).

TABLE I. Ba isotope samples.

Conc. of in	130	132	134	135	136	137	138
"134"	0.032	0.079	51.39	20.94	7.06	4.42	16.08
"135"	0.019	0.032	1.475	67.32	12.35	5.63	13.17
"137"	0.02	0.02	0.07	0.29	1.67	38.98	58.97
"138"	0.101	0.097	2.42	6.59	7.81	11.32	71.66

"138" = natural barium

be $\frac{3}{2}$ for Ba^{137}, the more abundant of the odd isotopes. From intensity measurements Kruger, Gibbs, and Williams[4] found a most probable value of 5/2, while Murakawa[5] suggested $\frac{3}{2}$, after measurements of the same lines, which were mainly the BaII resonance lines $6s\,^2S_{\frac{1}{2}}-6p\,^2P_{\frac{1}{2},\frac{3}{2}}$. Benson and Sawyer[6] found the same result as did Murakawa from an investigation of more lines than had been considered before. Using a molecular beam resonance method and taking the value $\frac{3}{2}$ for the nuclear spin, Hay[7] found the magnetic dipole moments of Ba^{137} and Ba^{135} to be $+0.9354$ and $+0.8363$ nuclear magneton, respectively, with the ratio 1.1174 ± 0.0010. Kopfermann and Wessel[8] tried to resolve the very small isotope shift in the BaI resonance line $6s^2\,^1S_0-6s6p\,^1P_1$ by atomic beam absorption. They found a shift of the lighter isotopes to higher frequency, dependent only upon the mass difference, with a distance of $12\cdot10^{-3}$ cm^{-1} between isotopes two mass units apart.

A serious difficulty in all investigations has been the great abundance of the even barium isotopes. In the present investigation of nuclear spin and isotope shift enriched samples[9] of the isotopes Ba^{134}, Ba^{135}, and Ba^{137} have been used. The isotopic constitution of the samples used is shown in Table I.

II. EXPERIMENTAL

The light source used was the specially constructed liquid-air-cooled hollow cathode described elsewhere,[10] in connection with a Hilger constant deviation spectrometer with a 60-mm aperture lens and prism system and focal lengths, respectively, 55 and 125 cm for the collimator and the camera. A Fabry-Perot interferometer with separators up to 40 cm and a corresponding resolving power of $3.5\cdot10^6$ was placed in the parallel beam between the collimator and the prism. The total half-intensity line width was about 0.018 cm^{-1}, corresponding to a temperature in the discharge about 20° above that of liquid air.

During the investigation of the very small isotope shift, exposures with the different isotopes were taken successively on the same photographic plate, which was moved in its own plane, perpendicular to the lines, making it possible to detect a shift of the order $1\cdot10^{-3}$ cm^{-1}. The exposure times ranged from less than one minute for the resonance lines to about one hour for the weakest of the lines.

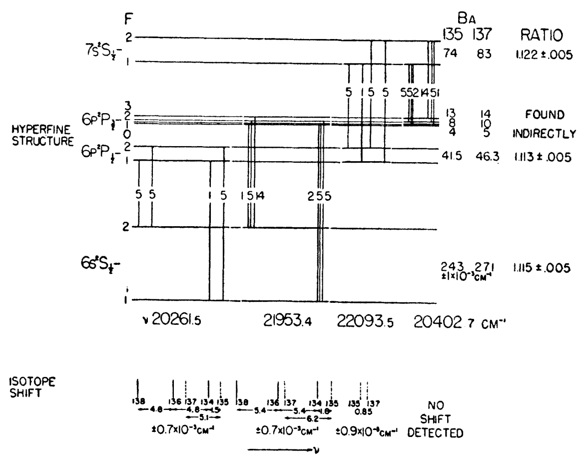

FIG. 1. Hyperfine structure in the lines $6s\,^2S_{\frac{1}{2}}-6p\,^2P_{\frac{1}{2},\frac{3}{2}}$ and $6p\,^2P_{\frac{1}{2},\frac{3}{2}}-7s\,^2S_{\frac{1}{2}}$ of Ba.

III. RESULTS

The hyperfine structure found in the lines $6s\,^2S_{\frac{1}{2}}-6p\,^2P_{\frac{1}{2},\frac{3}{2}}$ and $6p\,^2P_{\frac{1}{2},\frac{3}{2}}-7s\,^2S_{\frac{1}{2}}$ is shown in Fig. 1. This structure gives a verification of the nuclear spin $\frac{3}{2}$ for both odd isotopes, and the ratio found between corresponding intervals for the two isotopes agrees within the uncertainty with the ratio 1.1174 given by Hay.

The non-linear isotope shift found in the lines requires further explanation than a pure mass effect, such as possibly a difference between odd and even isotopes in nuclear polarizability[11] by electrons as well as a linear effect for mass numbers of the same parity. The same is the case qualitatively for the isotope shift in the BaI resonance line $6s^2\,^1S_0-6s6p\,^1P_1$, which is shown in

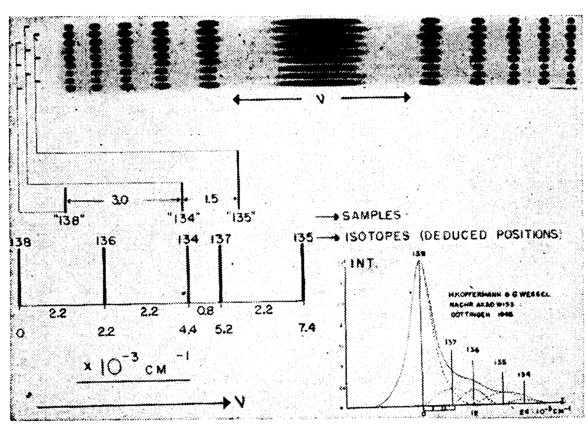

FIG. 2. Isotope shift in the BaI line $6s^2\,^1S_0-6s6p\,^1P_1$.

[4] Kruger, Gibbs, and Williams, Phys. Rev. **41**, 722 (1932).
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[9] Produced by the Y-12 plant, Carbide and Carbon Chemicals Division, and obtained by allocation from the AEC.
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Fig. 2. Not only the magnitude of the shift, but also the relative positions of odd and even isotopes, are incompatible with the results of Kopfermann and Wessel.

In the BaI line $6s^2\,{}^1S_0-6s6p\,{}^1P_1$ both the odd isotopes are to the high frequency side of the three even isotopes, but in the BaII lines $6s\,{}^2S_{\frac{1}{2}}-6p\,{}^2P_{\frac{1}{2},\frac{3}{2}}$ the odd-even shift is approximately only half as great relative to the two-mass-unit shift, and 137 is situated between 136 and 134. In finding the deduced positions of the isotopes in the BaI line, it was necessary to assume that the even isotopes were evenly spaced, as was found to be the case in the BaII lines.

The investigations are being continued in an attempt to determine the shift in the transitions $6s^2\,{}^1S_0-6s6p\,{}^3P_1{}^0$ and $6s6p\,{}^3P_1{}^0-6p^2\,{}^3P_{0,1,2}$.

This work was carried out under the direction of Professor J. E. Mack, to whom the author wishes to express his gratitude for his encouragement and many valuable suggestions.

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Li^8 Splinters from Nuclear Bombardments*

S. COURTENAY WRIGHT**
Radiation Laboratory, Department of Physics, University of California, Berkeley, California
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Li^8 has been produced by 340-Mev proton and 190-Mev deuteron bombardments of C, N, Ne, A, Kr, and Xe. The target element formed the gas of a proportional counter. The 0.88-second beta-decay of Li^8 produces Be^{8*} which disintegrates into two alpha-particles with a half-life of 10^{-21} seconds. Li^8 was detected by observation of these alpha-particles and identified by its half-life. Deuteron excitation functions for the production of Li^8 are given for C, N, Ne, and A. In the case of 190-Mev deuterons the cross section varies from about 13×10^{-28} cm² for C to 4×10^{-29} cm² for Xe. For 340-Mev protons the variation is from about 7×10^{-28} cm² for C to 3×10^{-29} cm² for Xe. A discussion of the process involved is given.

I. INTRODUCTION

SINCE the discovery of Li^8 by Crane *et al.*,[1] in 1935, its characteristics have been studied extensively. The ground state of Li^8 is probably ${}^3P_2$ according to Feenberg and Wigner.[2] It beta-decays with a 0.88 second half-life[3] to several excited states of Be^8. The maximum energy of the beta-particle is about 13 Mev. According to Wheeler[4] the principal Be^8 level involved is a ${}^1D_2$ state situated 3.3 Mev above the ground state and with a width of 1.8 Mev. The Be^8 nucleus breaks up promptly (10^{-21} seconds) into two alpha-particles. The total energy spectrum of the two alpha-particles gives a picture of the parent Be^8 level, apart from a small recoil energy from the original beta-decay. Recent experiments by Bonner *et al.*,[5] and Christy *et al.*,[6] tend to confirm Wheeler's views although some of the finer details are still in doubt. An extensive review of these questions can be found in the paper on energy levels in light nuclei by Hornyak and Lauritsen.[7]

Segrè and Wiegand[8] in an unsuccessful search for delayed proton emitters corresponding to the delayed neutron emitter N^{17} observed an alpha-particle activity of approximately 1 sec. half-life in 190-Mev deuteron bombardments of several elements. They ascribed this activity to Be^8 formed from Li^8. Their identification of this activity was based on the absence, apart from samarium, of other alpha-emitters in elements below lead and the similarity between the observed half-life and that of Li^8.

The purpose of this experiment was to study the systematics of Li^8 production in high energy bombardments of various elements. Li^8 has a convenient half-life and the alphas from its disintegration[8a] may be easily detected in the presence of other beta-activities. These factors make this isotope an amenable fragment to study in high energy nuclear disintegrations.

The average range of the alphas from Li^8 is about 1.3 mg/cm² of Al. This combined with the low cross section made the use of solid targets impractical. By the use of gaseous targets the yield in the counter was increased by a factor of 50 as will be described below. These gaseous targets also formed the counter gas. The absolute cross sections for Li^8 production in 340-Mev proton and 190-Mev deuteron bombardments of C, N, Ne, A, Kr, and Xe were determined. The deuteron excitation functions were obtained for all gases men-

* Submitted in partial requirement for the degree of Doctor of Philosophy in Physics at the University of California at Berkeley, California.

** Now at the Institute for Nuclear Studies, University of Chicago, Chicago, Illinois.

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[2] E. Feenberg and E. Wigner, Phys. Rev. **51**, 95 (1937).

[3] Lewis, Burcham, and Chang, Nature **139**, 24 (1937).

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[5] Bonner, Evans, Malich, and Risser, Phys. Rev. **73**, 884 (1948).

[6] Christy, Cohen, Fowler, Lauritsen, and Lauritsen, Phys. Rev. **72**, 698 (1947).

[7] W. F. Hornyak and T. Lauritsen, Rev. Mod. Phys. **20**, 191 (1948).

[8] E. Segrè and C. Wiegand, private communication.

[8a] In the future for brevity the intermediate Be^8 state will be omitted in references to the decay of Li^8; i.e. Li^8 beta-decays to two alpha-particles.

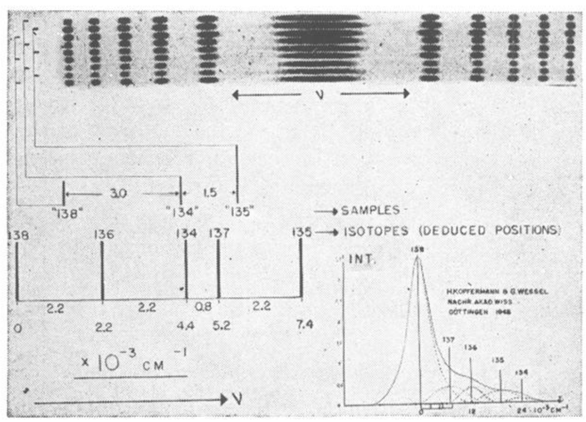

FIG. 2. Isotope shift in the BaI line $6s^2\,{}^1S_0-6s6p\,{}^1P_1$.