First Excited State of B^{11}: Possibility of Spin-Flip Stripping*

D. H. WILKINSON†
Brookhaven National Laboratory, Upton, New York
(Received October 2, 1956)

The first excited state of B^{11} at 2.14 Mev emits gamma rays which have an isotropic distribution when excited over a wide range of energy in the reaction $B^{11}(p,p')B^{11*}$ and an isotropic correlation in the reaction $B^{10}(d,p)B^{11*}$. The natural assumption is therefore that the state is of spin 1/2 as is suggested by the shell model. This assignment is supported by certain gamma-ray studies in the reaction $Li^7(\alpha,\gamma)B^{11}$. However, in both the reaction $B^{10}(d,p)B^{11}$ and the mirror reaction $B^{10}(d,n)C^{11}$ leading to this level or its mirror level in C^{11}, an $l=1$ stripping pattern is found, suggesting $3/2 \leqslant J \leqslant 9/2$. The observed isotropies could be given by emission from a state of 3/2− to the 3/2− ground state if the gamma ray were purely $E2$. In the present investigation it is shown by a Doppler shift method using $B^{11}(p,p')B^{11}$ that the lifetime of the first excited state is less than 4×10^{-14} sec. It is shown that this limit is inconsistent with $E2$ sum rules and therefore that the transition is chiefly $M1$ and that the spin of the level must be 1/2−. This is consistent with the stripping result only if it is possible for the departing nucleon in such a reaction to flip its intrinsic spin and so transmit a further unit of angular momentum to the nucleus.

INTRODUCTION

THE low-lying levels of the lighter nuclei are all of considerable importance in that they are the ones of which any valid nuclear model will be asked to give its first account or which are, alternatively, used to fix the parameters of putative models. The ground-state spins and parities of all stable and "one-off-stable" nuclei are now known in the $1p$-shell at least. The same is true of all first excited states of the stable nuclei with the exception of $A=11$, $T_z=\pm1/2$, namely the 2.14-Mev state of B^{11} (the 1.90-Mev state of C^{11}). The shell model in intermediate coupling[1] is firm in requiring that this state should be 1/2−. There exists, however, sharply conflicting evidence on this point.

Firstly there is the evidence that suggests that the character is indeed 1/2−. Study of the reaction $Li^7(\alpha,\gamma)B^{11}$ shows no gamma-ray transitions to this level from the 5/2+ level at 9.28 Mev.[2] If the character were $3/2- \leqslant J \leqslant 7/2-$, the missing $E1$ transition would have $|M|^2<2\times10^{-4}$ which is much less than one usually cares to envisage in light nuclei[3] if there is no inhibition by the isotopic spin selection rule.[4] If the state were indeed 1/2−, all would be well. Then there are studies of the angular properties of the transition. The angular correlation between the protons leading to this level and gamma rays leading from it in the reaction $B^{10}(d,p)B^{11}$ has been measured[5] to be isotropic to within 5%. The angular distribution of the gamma rays following inelastic scattering of protons into this level is isotropic to within 3% over the whole range of incident proton energy from threshold up to 5.2 Mev.[6] Within this energy range, the cross section for this inelastic scattering passes through a number of well-marked resonances and it is inconceivable that such isotropy should result because the intermediate C^{12} state always has $J=0$ or that only $l=0$ protons are involved in its formation. This isotropy must certainly be due to the properties of the B^{11} state. The simplest assumption is again that the state is of $J=1/2$. However, since the ground state of B^{11} is 3/2−, exact isotropy could still be obtained if the first excited state were also 3/2− and the radiation joining them pure or almost-pure $E2$ since $W(\frac{3}{2}\,\frac{3}{2}\,22;\,2\frac{3}{2})$ is "accidentally" identically zero. This possibility has already been remarked upon.[6] The same possibility would also of course explain the isotropic correlation in the stripping reaction; the evidence from the (α,γ) reaction may just reflect an unusually weak $E1$ transition. However, the simplest explanation of the facts is always that the state is 1/2− as is also very much favored by the shell model.[1]

We now consider the evidence that the character is not 1/2−. This comes from the stripping reactions $B^{10}(d,p)B^{11}$ and $B^{10}(d,n)C^{11}$. In the first[7] the transitions to the first excited state were few compared with those to neighboring levels. The pattern to the 2.14-Mev state was not at all clean and varied somewhat with deuteron energy in the neighborhood of $E_d=8$ Mev but seemed to indicate an angular momentum transfer by the ingoing neutron of $l=1$. This then says that the level is of odd parity but that $3/2 \leqslant J \leqslant 9/2$ since the ground state of B^{10} is 3+. The second reaction,[8] also performed in the neighborhood of $E_d=8$–9 Mev, also shows only relatively weak transitions to the first excited state but

* Work performed under the auspices of U. S. Atomic Energy Commission.

† Permanent address: Cavendish Laboratory, Cambridge, England. This work was performed while the author was Visiting Physicist at Brookhaven National Laboratory during the summer of 1956.

[1] D. R. Inglis, Revs. Modern Phys. **25**, 390 (1953); D. Kurath, Phys. Rev. **101**, 216 (1956).

[2] G. A. Jones and D. H. Wilkinson, Phys. Rev. **88**, 423 (1952); see F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955) for amended assignments.

[3] D. H. Wilkinson, Phil. Mag. **1**, 127 (1956).

[4] We shall assume that the parity is surely odd—see later.

[5] J. Thirion, Ann. phys. **8**, 489 (1953).

[6] Blair, Kington, and Willard, Phys. Rev. **100**, 21 (1955) and private communication.

[7] N. T. S. Evans and W. C. Parkinson, Proc. Phys. Soc. (London) **A67**, 684 (1954).

[8] M. Cerineo (private communication); Maslin, Calvert, and Jaffe (private communication from J. R. Holt).

this time the pattern is much cleaner and is unambiguously of $l=1$. We therefore have a clear-cut conflict between the simplest explanation of the first set of experiments and also the indication of the shell model, all of which favor $J=1/2-$ and the answer given by the stripping measurements.

The work described in the present paper was carried out to clarify this situation. It is based on the earlier remark that the only reasonable explanations for the results on inelastic proton scattering[6] in B^{11} are either that $J=1/2-$ or that $J=3/2-$ and that the radiation to the ground state is wholly or almost wholly $E2$.

E2-M1 MIXTURE

It is first of all interesting to inquire how much $M1$ radiation could be mixed up with the predominant $E2$ transition required to give isotropy under the assumption $J=3/2-$ and yet not have been detected in producing a measurable anisotropy. Since we pass through so wide a proton energy range within which other reactions such as $B^{11}(p,\gamma)C^{12}$ give strongly anisotropic reaction products, we can explain the observed anisotropy neither by $J=0$ in the compound nucleus nor by $l=0$ nor by any curious accident appropriate only to a particular character for the compound nucleus state such as a particular mixing of orbital angular momenta or gamma-ray multipolarities.

For illustration only we shall assume that, owing to the large energy loss the outgoing protons will tend to be of zero orbital angular momentum. This then limits the compound nucleus spins to $J=1-$ and $J=2-$. Both could be formed by $l=0$ protons which would give isotropy, so we study their formation by $l=2$ protons which can easily pass into B^{11} at an energy of 3 Mev. If we now assume that channel spin which is the more disadvantageous to our present purposes, i.e., that which gives least anisotropy, we find that a 10% anisotropy would result from a 0.8% admixture of $M1$ by intensity with the predominant $E2$ for $J=1-$ and 4% for $J=2-$.

In connection with the expected anisotropy, the following remark is of interest. The penetrability of B^{11} for incident protons of 3.0 Mev and angular momenta $l=0, 1, 2$ stands in the ratio 4:3:1, respectively. This may suggest that formation by protons of zero orbital angular momentum is most likely and so we should expect in any case a large measure of isotropy. This argument is, however, largely false because when we use a thick target or a thin target over a wide range of bombarding energy, it is the integrated yield across the various individual resonances which is the interesting consideration and this will be determined entirely by the *smaller* of the two proton widths, incoming and outgoing, whichever that may be, since we know that inelastic scattering is the dominant inelastic process. Owing to the small energy available to it, this smaller width will be that of the inelastically scattered proton, at least in the energy range of interest here, even though it may have $l=0$ and the incident proton $l=2$. The yields will therefore be essentially the same for all incident l values, even though considerations of initial penetrability alone may seem to favor $l=0$ and hence isotropy of the gamma ray.

The argument is still partially true because $l=0$ outgoing protons will be most probable, in which case $l=0$ as well as $l=2$ is always possible for the ingoing proton. But with the penetration amplitudes differing by only a factor of 2 between $l=0$ and $l=2$ ingoing protons, the much wider fluctuations to be expected in the reduced proton widths completely swamp this slight general preference towards isotropy.

Also $J=0$ for the compound nucleus states, another way of securing a trivial isotropy, will be *ceteris paribus* disfavored by the small associated statistical weight.

These considerations make it reasonable to require that the $M1$ admixture be less than 50% in intensity compared with the $E2$ strength if the first excited state of B^{11} is to be $3/2-$.

In view of these illustrations and remarks, it is clear that even allowing for the tendency towards isotropy produced by those resonances of $J=0$ and those induced predominantly by ingoing protons of zero orbital angular momentum, we cannot allow anything like 50% as much $M1$ radiation in intensity as compared with the $E2$ component if effective isotropy is to be maintained.

POSSIBLE SPEED OF THE *E2-M1* MIXTURE

A limit on the maximum speed of an $E2$ transition may be placed with the aid of various sum rules. That most appropriate to the present problem is that relating to $E2$ transitions without change of isotopic spin in $T_z=0$ nuclei.[9] Although B^{11} is not of $T_z=0$, we can split it into "B^{10}" plus a neutron for the purposes of describing this transition, and since we are dealing with an $E2$ transition the contribution of the odd neutron is very small. The "B^{10}" then makes a collective transition such as is responsible for gathering as much of the summed strength as possible into a single gamma ray; such transitions do not change the isotopic spin, so the isotopic spin of the B^{11} remains $T=\frac{1}{2}$. This sum rule then tells us that

$$\frac{\Gamma_\gamma}{E^4}\leqslant\frac{1}{60}\frac{e^2}{hc}\frac{A}{\hbar^2c^2}\frac{\langle r^2\rangle_{00}}{Mc^2},$$

where $\langle r^2\rangle_{00}$ is the mean square proton displacement in the ground state. For this quantity we use the value 3.2×10^{-26} cm^2, which comes from an expression derived from elastic electron scattering which holds down to the very lightest nuclei.[10] For the case of the B^{11} transition,

[9] M. Gell-Mann and V. L. Telegdi, Phys. Rev. **91**, 169 (1953).
[10] R. Hofstadter, *Proceedings of the 1956 Amsterdam Conference on Nuclear Reactions* (to be published).

this tells us that the lifetime of the level against $E2$ emission must be longer than 2.6×10^{-13} sec. It would, however, be very difficult and artificial to construct a model in which all the $E2$ sum rule were concentrated in a transition between two states of $J=3/2$. The strongest transition one could reasonably envisage would be one in which a collectively excited core (in a 2+ state) was coupled to a $p_{3/2}$ nucleon, thus giving excited states of $J=1/2-$, $3/2-$, $5/2-$, and $7/2-$ falling to the $3/2-$ ground state. The above sum rule strength would then be shared among the four transitions and the transition between the states of $J=3/2-$ would receive only a small portion of the whole. Even neglecting this final argument, however, and allowing the maximum 50% relative contribution from the $M1$ admixture as discussed above, we see that for the explanation of the isotropy in terms of a state of $J=3/2-$ to hold, the lifetime of the first excited state must be greater than 1.7×10^{-13} sec. A shorter lifetime would imply a much greater admixture of $M1$ radiation than is consistent with the observed isotropy, even under the unlikely assumption that the $E2$ component contains the entire sum rule.

Another cruder estimate of the maximum admissible $E2$ speed can be made in the following way: Take the Weisskopf unit for an $E2$ transition and multiply it by Z^2; then apportion this speed between transitions that do not and transitions that do change the isotopic spin proportionally to the square of the Clebsch-Gordan coefficients in the isotopic spin. In this way we find the limit:

$$\Gamma_\gamma<2.2\times10^{-3}[C_{\frac{1}{2}0^{\frac{1}{2}}}^{1\frac{1}{2}}]^2/\{[C_{\frac{1}{2}0^{\frac{1}{2}}}^{1\frac{1}{2}}]^2+[C_{\frac{1}{2}1^{\frac{3}{2}}}^{1\frac{1}{2}}]^2\}\text{ ev.}$$

[For R^2 we set $(5/3)\langle r^2\rangle_{00}$ of the previous expression.] This yields the limiting speed of 5×10^{-13} sec which is close to but longer than the earlier estimate.

DOPPLER SHIFT EXPERIMENT

To deal with lifetimes of the order we have just discussed, the only presently feasible methods are by resonant scattering, by Coulomb excitation (including inelastic electron scattering), and by studies of the Doppler shift on slowing down a moving radiator in solid matter. The latter method is suitable for investigating the interesting lifetime limit in the present case and we have used it.

The gamma ray in question was produced in the reaction $B^{11}(p,p')B^{11*}$ using a thick target and protons of initial energy 3.0 Mev. The excited state is very prolifically excited as had already been found.[6] The gamma rays were observed in a 2-in. right cylinder of NaI(Tl) mounted on a DuMont type 6292 photomultiplier. A typical pulse spectrum is shown in Fig. 1 where both the 2.14-Mev gamma ray from B^{11} and the 720-kev line from the similarly excited first excited state of B^{10} are seen. Correct identification of the gamma ray was checked by a rough energy measurement in terms of the accurately known Co^{60} lines. The energy measured in this way was 2.11 ± 0.05 Mev.

Since it was desired to place as sharp a limit as possible on the lifetime of the state, we wanted to stop the recoiling B^{11} as quickly as possible and so wanted as dense a form of boron as possible for the target. The densest form available was boron carbide, B_4C, whose specific gravity is 2.52. The target with which the spectrum shown in Fig. 1 was taken and with which all the work in this report was performed was made of compacted Norbide Abrasive of 320 grain size. It was infinitely thick to the protons and was bonded with a very little hydrocarbon cement. It is clear from Fig. 1 that, as expected, gamma rays from the carbon and from other reactions in B^{10} and B^{11} are very few compared with those that form the object of our investigation.

In order to measure the Doppler shift, the gain was increased until the full-energy-loss peak fell at about 116 channels. Only the immediate region of this peak was investigated in this stage of the experiment and a typical spectrum is shown in Fig. 2. From each such spectrum it was felt that the peak may be located with an accuracy of the order of two- or three-tenths of a channel. However, the estimate of the accuracy of the experiment comes entirely from the internal consistency of the results.

The crystal was irradiated broadside on with its center $5\frac{1}{4}$ in. from the target, at 0° to the proton beam and at a mean backward angle of 161°. Spectra were taken alternately in the two positions in two consecutive sequences containing 6 alternating pairs of spectra each. Since for work of the attempted accuracy

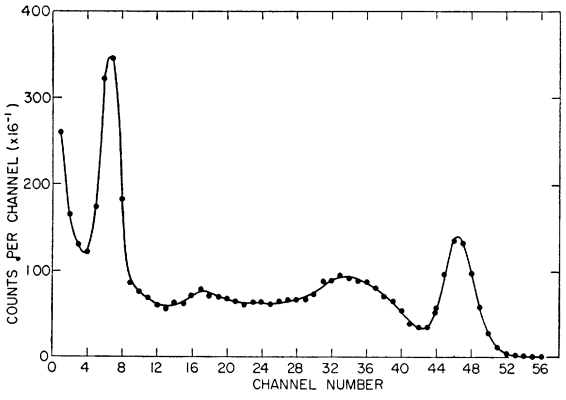

FIG. 1. Composite spectrum of the gamma rays resulting from the bombardment of a thick target of B_4C with protons of 3.0 Mev and detected in a 2-in. right cylinder of NaI(Tl). The peak at channel $46\frac{1}{2}$ is the full-energy peak of the 2.14-Mev gamma ray from the first excited state of B^{11}; the peak at channel 17 is due to pair production by the same gamma ray with escape of both annihilation photons from the crystal. The large bump around channel 34 is the combined Compton edge and one-quantum escape peak from the same gamma ray. The peak at channel 7 is due to the 720-kev gamma ray from the first excited state of B^{10}. This spectrum was taken with a bias of 14 channels.

a very small drift in the gain of the system would be disastrous, a continuous check was kept. Before and after each boron run at each angle, a spectrum was taken using the 661-kev gamma ray following the decay of Cs^{137}. In order that the pulse heights should be comparable for analysis, a precision attenuator was used during the boron runs and removed for the Cs^{137} calibration; its exact value was of course immaterial and only constancy was asked of it. This then made a total of 72 spectra in the two sequences each of which contained 12 boron runs and 24 Cs^{137} calibrations.

Since the DuMont 6292 photomultiplier is known to have a rate-dependent gain,[11] a very close check was kept on the total counting rates. The Cs^{137} source was exposed in a standard location, so there was no worry on that score. However, the boron counting rate fluctuated as the proton current and was always brought back to the same value to within a few percent before each spectrum was taken and was monitored throughout the taking of each spectrum to make sure that it kept adequately steady. The particular photomultiplier used was chosen for its small dependence of gain on counting rate. This was measured both before and immediately after the Doppler shift measurements and it was found that the gain increased by 0.17% for each increase in counting rate by a factor of two over a wide range. The counting rates were held so constant that the greatest correction called for was completely negligible. (Note that since we are not attempting an absolute measurement of the energy of the boron gamma ray but only the accurate measurement of a percentage shift, there was no need to correlate the boron and Cs^{137} rates; it was necessary only that they be held individually steady.)

To evaluate the Doppler shift, the following procedure was used: The peak position for each of the 72 spectra was determined by drawing out each spectrum logarithmically on large-scale graph paper and was recorded to a tenth of a channel. For each boron run, the mean of the peak positions of its two flanking Cs^{137} runs was evaluated and then the boron peak position was corrected to a standard Cs^{137} peak value which was chosen as the average of all the Cs^{137} runs at both angles for that sequence. These corrections were very small. The 12 boron runs in each sequence, thus corrected, were then listed and each was compared with the mean value of the two flanking boron runs at the other angle, the one immediately before it in the sequence and the other immediately after it. In this way each sequence yields 10 estimates of the Doppler shift. This final stage in the reduction of the results is displayed in Table I. The peak positions were read from the graph to a tenth of a channel only; the entries in the table are given to a hundredth of a channel simply on account of the small corrections described above. The two values of $(1.25\pm0.03)\%$ and $(1.32\pm0.06)\%$ for the Doppler shift given by the two sequences are consistent with one another and we adopt as the figure for discussion $(1.28\pm0.05)\%$.

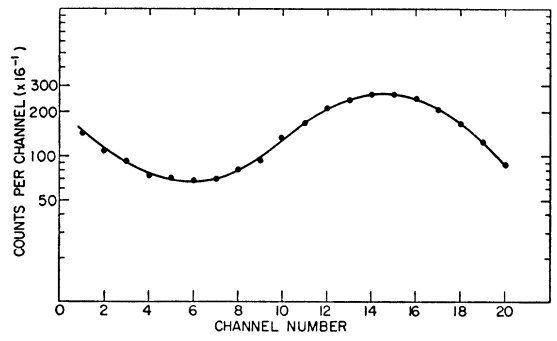

FIG. 2. Typical spectrum as used in the Doppler shift determination. It is plotted logarithmically and the peak at channel 14½ is the full-energy-loss peak of the gamma ray studied. This spectrum was taken with a bias of 102 channels.

[11] Bell, Davis, and Bernstein, Rev. Sci. Instr. **26**, 726 (1955).

TABLE I. Details of the two sequences of measurements used for determining the Doppler shift.

Sequence I			Sequence II		
Corrected B peak height	Mean of flanking B peaks	Shift %	Corrected B peak height	Mean of flanking B peaks	Shift %
115.91			116.47		
114.18	115.81	1.43	117.78	116.25	1.32
115.71	114.31	1.22	116.02	117.92	1.64
114.44	115.81	1.20	118.06	116.12	1.67
115.91	114.50	1.23	116.23	118.00	1.52
114.57	115.83	1.10	117.93	116.31	1.39
115.75	114.42	1.16	116.39	117.86	1.26
114.28	115.82	1.35	117.80	116.50	1.12
115.90	114.45	1.27	116.61	117.87	1.08
114.61	116.03	1.24	117.94	116.64	1.11
116.17	114.70	1.28	116.67	118.00	1.14
114.80			118.05		
Mean shift = $1.25\pm0.03\%$			Mean shift = $1.32\pm0.06\%$		

DOPPLER SHIFT CALCULATION

We must now consider the Doppler shift that would be displayed if the lifetime of the state were very short compared with the slowing-down time of the recoiling B^{11}.

The cross section for the excitation of this level is known.[6] It is very small below a proton bombarding energy of 2.6 Mev, then rises sharply to a resonance at 2.66 Mev, above which it falls to about 0.4 of its peak value, then rises again, and at 3.0 Mev has increased to about 0.8 of its value at the resonance. Since our target was infinitely thick, we integrated the cross section along the proton path and obtained an effective proton momentum corresponding to an energy of 2.85 Mev for the Doppler shift calculation.

An uncertainty is now introduced because the angular distribution of the outgoing inelastically-scattered proton is not known. However, because its energy is

rather small its width will be the determining factor in the total yield, and so outgoing protons of $l=0$ will be the most important, in which case the effect on the mean Doppler shift is zero because of the isotropic emission in the center-of-mass frame. In any case the only effect of the outgoing proton on the Doppler shift comes through the asymmetry in its emission associated with the interference term between compound nucleus states of opposite parity. This asymmetry will vary with the proton energy and, since the maximum energy of the outgoing proton in the center-of-mass system is only 0.56 Mev we can probably ignore this uncertainty. We have therefore computed the Doppler shift in terms of the momentum of a proton of 2.85 Mev.

The final correction to be considered is that due to the finite size of the detector. This correction was made by numerically integrating the Doppler shift over the detector area in the two positions. This gave a reduction of the full 0° to 180° Doppler shift by 3% of its value.

The final theoretical shift so evaluated for our conditions and geometry and for a short-lived B^{11} state is 1.26%.

LIMIT ON THE LIFETIME

Our experimental shift of $(1.28\pm0.05)\%$ is to be compared with the shift of 1.26% calculated for a very short lifetime. It therefore seems very unlikely that the recoiling B^{11} can have lost as much as 15% of its initial velocity of 2.0×10^8 cm/sec before emitting its gamma ray.

We must now convert this limit into a time. To do this we have used data on the slowing down of carbon atoms.[12] Comparison of these data with data on the slowing down of nitrogen and oxygen atoms[13] suggests that the difference between the slowing of boron and carbon atoms will be very slight at these low speeds. We have also assumed that the slowing will depend only on the mass traversed. Since the data are presented for air, this means that our limit will tend to be conservative because, mass for mass, the stopping power is slightly greater for lighter substances. From these data we find that the loss of 15% of the initial speed takes place in about 4×10^{-14} sec in our B_4C target and so we believe that the lifetime is less than this value.

This figure is considerably shorter than the minimum lifetimes derived above for reconciling the observed isotropies with a predominantly $E2$ transition from a $3/2-$ state, and we therefore believe that the first excited state of B^{11} is now firmly established as $1/2-$. On the other hand, for an $M1$ transition our limit merely implies that $|M|^2>0.08$ in Weisskopf units which is unexceptionable. The intermediate-coupling shell model calculations of Kurath predict a lifetime of a few times 10^{-15} sec for this transition (private communication).

[12] G. A. Wrenshall, Phys. Rev. **57**, 1095 (1940).
[13] P. M. S. Blackett and D. S. Lees, Proc. Roy. Soc. (London) **A134**, 658 (1932).

SPIN-FLIP STRIPPING

The conflict with the stripping results is now extreme. We believe that the state is $1/2-$, and yet an $l=1$ stripping pattern is obtained where that spin assignment would demand $l=3$. A possible resolution of the difficulty as discussed in the Introduction was suggested to the author by W. C. Parkinson in a conversation at the Amsterdam Conference in July, 1956. He pointed out that we could go from the B^{10} target nucleus of $3+$ to a final $1/2-$ state in B^{11} or C^{11} in a stripping reaction with only an $l=1$ transfer by the ingoing nucleon if at the same time the intrinsic spin of the departing nucleon was flipped, the change of spin of one unit being transferred to the residual nucleus. It was this conversation that stimulated the performance of the present investigation which the author had had in mind for some time.

It seems probable that some such spin-flip stripping is involved in the present case. This possibility is, of course, ignored in standard stripping theory and in all published estimates of spins or limits of spins derived from stripping reactions. It appears likely, however, that it is always present. Usually, however, the ordinary stripping, without spin-flip, predominates and the ignoring of the possibility of spin-flip is not serious. But if the ordinary stripping is for some reason inhibited, then the spin-flip variety may predominate as here and may then give a wrong answer for the nuclear spin if it is taken for ordinary stripping. The reason why ordinary stripping is inhibited in this case is that $l=3$ transfer is required and so it will proceed only through the presence in the first excited state of B^{11} or C^{11} of the $1f$ configuration and this is very remote. The relative weakness of the spin-flip stripping is seen in the fact that we have noted in the Introduction, namely that the stripping to the first excited state tends to be feeble compared with the transitions to neighboring states for which ordinary stripping is allowed.

The possible mechanism for the spin-flip is not clear. If it were accompanied by a flipping of the intrinsic spin of a nucleon in the residual nucleus, then we should probably look upon the process as the "backward stripping" of that nucleon out of the target nucleus[14] and expect the outgoing nucleus to be peaked in the backward hemisphere. On the other hand, the spin-flip may be due to a spin—other-orbit interaction and be accompanied by a tilting of one of the orbits in the residual nucleus, in which case the peak could remain in the forward hemisphere.

In either event it may be expected that the effect will be strongest when the whole deuteron has to come close to the target nucleus before stripping takes place. This will be so when the deuteron wave function is itself being called upon to supply a lot of momentum for the outgoing nucleon, *viz.*, when the energy release

[14] L. Madansky and G. E. Owen, Phys. Rev. **99**, 1608 (1955).

is high and the deuteron energy rather low. We might therefore expect to find spin-flip stripping showing up most strongly for the lower lying states in reactions of large Q value.

ACKNOWLEDGMENTS

I am grateful to Professor W. C. Parkinson for reviving my interest in the first excited state of B^{11} and for pointing out the interesting implications for stripping theory. I should also like to thank Mr. A. G. Rubin for his help in taking the measurements.

Note added in proof.—Professor Parkinson has kindly informed me that the idea of spin flip by the departing nucleus in a stripping reaction is due not to him but to Professor A. P. French of the Cavendish Laboratory, Cambridge, and now of the University of South Carolina who conceived of it in about 1952 in terms of an exchange process of intrinsic spins. Professor Parkinson also informs me that the possibility of spin flip in the particular case of interest here is discussed by Dr. N. T. S. Evans in his Ph.D. thesis (1956) at the Cavendish Laboratory.

PHYSICAL REVIEW VOLUME 105, NUMBER 2 JANUARY 15, 1957

Quadrupole Moments of Os^{189}, Ta^{181}, Lu^{175}, and La^{139}

KIYOSHI MURAKAWA AND TOHRU KAMEI*
Institute of Science and Technology, Komaba-machi, Meguro-ku, Tokyo, Japan
(Received October 5, 1956)

The quadrupole moment of Os^{189} was determined from the hyperfine structure of the level $5d^6 6s^2\ ^5D_4$ of Os I and was found to be $Q(Os^{189}) = (+0.8 \pm 0.2) \times 10^{-24}$ cm^2 without shielding correction. The quadrupole moments (without shielding correction) of Ta^{181}, Lu^{175}, and La^{139} that were determined previously from the configurations $5d^3 6s^2$, $5d6s^2$, and $5d^2 6s$ respectively are, in units of 10^{-24} cm^2, $+3.9 \pm 0.4$, $+5.1 \pm 0.3$, and $+0.5 \pm 0.2$ respectively. If one assumes a shielding correction of -0.3 for the $5d$ electron, these values become $Q(Os^{189}) = +0.6 \pm 0.14$, $Q(Ta^{181}) = +2.7 \pm 0.3$, $Q(Lu^{175}) = +3.6 \pm 0.2$, and $Q(La^{139}) = +0.3 \pm 0.1$ in units of 10^{-24} cm^2, where the probable error does not include the uncertainty of the shielding correction.

I. INTRODUCTION

ACCORDING to the calculations of Sternheimer,[1] the atomic core shields or antishields the nuclear quadrupole coupling, so that the quadrupole moment (Q) deduced from the hyperfine structure (hfs) of atomic spectra must be multiplied by the factor $1+\Delta$, in order to get the true quadrupole moment. Δ is the shielding correction, which we called the "polarization correction" in previous work. Sternheimer has recently published a more accurate calculation concerning the shielding correction.[2]

In our previous work[3,4] on $Q(La^{139})$, $Q(Lu^{175})$, and $Q(Ta^{181})$, the values of Δ for the $5d$ electron were taken from the tabulation in reference 1. The more accurate calculation[2] shows that these values must be revised. Sternheimer[2] calculated the values of Δ for the configurations Cu I $3d^9 4s^2$ and W I $5d^4$; the other values are concerned with p electrons only. According to Sternheimer,[5] concerning the shielding correction for the states Ta I $5d^3 6s^2$ and Os I $5d^6 s^2$, it is likely from his calculations for W I $5d^4$ that for these states the antishielding will predominate, leading to $\Delta < 0$; however, such a conclusion cannot be drawn with certainty, but could be verified only by specific calculations for these elements with the appropriate wave functions. In the present work, therefore, we shall leave the accurate calculation of the shielding correction of the $5d$ electron of La, Os, Lu, and Ta for future work and tentatively assume that it is the same as in the case of W I $5d^4$, namely $\Delta = -0.3$, and examine whether it leads to reasonable values of Q.

II. QUADRUPOLE MOMENT OF Os^{189}

In previous work,[3,6] the hfs of Os I $\lambda 4260 (5d^6 6s^2\ ^5D_4 - 5d^6 6s 6p\ ^7D_5)$[7] was studied, but the splitting of the final level for the isotope $Os^{189}(I = \frac{3}{2})$ could not be deduced from the observed hfs by a purely empirical method, and this introduced uncertainty in deducing the value of $Q(Os^{189})$ (footnote 22 of reference 3). In the present work the hfs of Os I $\lambda 4420 (5d^6 6s^2\ ^5D_4 - 5d^6 6s 6p\ ^7D_4)$ was studied, and the result of the measurement is shown schematically in Fig. 1. From Fig. 1 of the present work and Fig. 3 of reference 3, we get the interval factor $A = 0.008$ cm^{-1}, and the quadrupole coupling constant $B = 0.10_4 \times 10^{-3}$ cm^{-1} for the common final level $5d^6 6s^2\ ^5D_4$ for the isotope Os^{189}.

---

* Present address: Institute of Nuclear Study, University of Tokyo, Tanashi, Tokyo, Japan.

[1] R. M. Sternheimer, Phys. Rev. **80**, 102 (1950); **84**, 244 (1951); **86**, 316 (1952).

[2] R. M. Sternheimer, Phys. Rev. **95**, 736 (1954). Sternheimer's $1/(1-R)$ is our $1+\Delta$.

[3] K. Murakawa, Phys. Rev. **98**, 1285 (1955). Erratum: Eq. (5) should read $(d^4s\ ^6D_{\frac{1}{2}}^{\frac{1}{2}} | \omega | d^4s\ ^6D_{\frac{1}{2}}^{\frac{1}{2}}) = -(2/4375)(584R_2' - 91R_2'' + 132S_2)$.

[4] T. Kamei, Phys. Rev. **99**, 789 (1955).

[5] R. M. Sternheimer (private communication). We thank Professor Sternheimer for these suggestions and for communicating to us the result of his improved calculations prior to publication.

[6] K. Murakawa and S. Suwa, Phys. Rev. **87**, 1048 (1952).

[7] The classification and the term notation of the Os I spectrum are taken from W. Albertson, Phys. Rev. **45**, 304 (1934).