PHYSICAL REVIEW VOLUME 136, NUMBER 4B 23 NOVEMBER 1964

Parity of Be^{11}†

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(Received 9 July 1964)

Two measurements have been made which are relevant to the parity of Be^{11}. In one experiment the gamma-ray spectrum from a mixed source of 13.6-sec Be^{11} and 7.4-sec N^{16} activities was examined with a 3-mm-thick lithium-drifted germanium detector having an experimental linewidth of 13 keV for 6-MeV gamma rays. Based on a calibration from lines due to the 6.132- and 7.116-MeV gamma rays in the decay of N^{16}, the 6.8-MeV gamma ray in the decay of Be^{11} has an energy of 6.792 ± 0.006 MeV. This is in agreement with the excitation energy of the $\frac{1}{2}^+$ or $\frac{3}{2}^+$ upper member of the 6.752–6.804-MeV doublet in B^{11}. In the other experiment a magnetic pair spectrometer measurement was made on the ground-state and first-excited-state transitions from the B^{11} 7.99-MeV level as excited in the $Be^9(He^3,p)B^{11}$ reaction. It was shown that these transitions are $E1$, thereby requiring even parity for the 7.99-MeV state, and that the spin of the state is $\frac{3}{2}$. Since the beta-ray transitions of Be^{11} to the 6.804- and 7.99-MeV levels of B^{11} are both known to have allowed logft values, the parity of Be^{11} is even.

INTRODUCTION

IN a previous study[1] of the decay scheme of 13.6-sec Be^{11}, it was found that beta-ray transitions take place to the ground state of B^{11} and to the known excited states at 2.13, 6.75, and/or 6.80 and 7.99 MeV. For the last two branches, the logft values of 5.93 and 5.53, respectively, indicated allowed transitions. At that time the preferred shell-model prediction for the spin parity of Be^{11} was $\frac{1}{2}^-$. If this were true, however, the logft values of 6.77 for the Be^{11} beta-ray branch to the $\frac{3}{2}^-$ ground state of B^{11} and 6.63 for the branch to the $\frac{1}{2}^-$ level at 2.13 MeV seemed abnormally high for allowed transitions. The NaI detectors used in the earlier work[1] did not have sufficient gamma-ray energy resolution to determine which member of the 6.75–6.80-MeV doublet was fed in Be^{11} decay, and furthermore there were uncertainties as to the parities of the doublet levels. The parity of the 7.99-MeV level in B^{11} was not known prior to the present work.

In the meantime, Talmi and Unna[2] have carried out a more refined shell-model calculation which suggests that the $p_{1/2}$ and $s_{1/2}$ orbitals in Be^{11} are inverted such that the ground state may be $s_{1/2}$, and therefore have even parity. In addition, they interpreted the Be^{11} decay-scheme data[1] as being more consistent with a $\frac{1}{2}^+$ assignment to Be^{11}. Further experimental work bearing on the parity of Be^{11} was carried out by Donovan *et al.*[3] From studies of gamma-ray branching, they concluded that the 4.46- and 5.03-MeV levels in B^{11} are most probably $\frac{5}{2}^-$ and $\frac{3}{2}^-$, respectively. Since it had been shown[1] that the logft values of the Be^{11} beta decay to both of these states are $\geqslant 8.2$, an even-parity assignment for Be^{11} seemed highly probable. Donovan *et al.* also pointed out that the beta decay of Be^{11} probably leads to the upper member of the 6.8-MeV doublet in B^{11}, inasmuch as the subsequent gamma-ray deexcitation conforms to the known decay of the 6.80-MeV level but not to the decay properties of the 6.75-MeV level.

Other experimental work on the 6.8-MeV doublet levels of B^{11} includes an angular-distribution measurement[4] on the protons in the $Be^9(He^3,p)B^{11}$ reaction leading to the 6.804-MeV state, which, together with the gamma-ray branching of this state measured by Ferguson *et al.*,[5] shows that this level is $\frac{1}{2}^+$ or $\frac{3}{2}^+$. The gamma-ray measurements[5] also suggest that the 6.75-MeV lower member of the doublet has a spin and parity of $\frac{7}{2}^-$.

Since the beta-ray branches to the 6.75–6.80- and 7.99-MeV levels are both allowed, then in order to obtain evidence for the parity of Be^{11} experimentally, one may either determine directly which member of the 6.75–6.80-MeV doublet is fed in the beta decay of Be^{11}, or fix the parity of the 7.99-MeV level in B^{11}. Both objectives have been pursued in the present work. In one case an accurate energy measurement of the 6.8-MeV gamma ray in the Be^{11} decay was made with a lithium-drifted germanium detector, and the result was compared with the level energies previously established on the basis of reaction Q-value measurements. In the other case, the characteristics of the B^{11} 7.99-MeV transition were determined by means of a magnetic pair spectrometer.

ENERGY OF THE 6.8-MeV GAMMA RAY FROM Be^{11} DECAY

The Be^{11} and N^{16} activities were produced in the $B^{11}(n,p)Be^{11}$ and $O^{16}(n,p)N^{16}$ reactions by irradiating samples with the 15.5-MeV neutrons from the $t+d$ reaction. As the source of neutrons a Zr-T target was bombarded with 600-keV deuterons from a Van de

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

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Graaff accelerator, and at the beam current of 50 μA usually employed, the total yield from the target was $\sim 10^{10}$ neutrons/sec.

Whereas in the previous Be^{11} decay-scheme studies[1] it was important to avoid the interfering radiations from N^{16} by procuring a crystalline boron sample free of oxygen, in the present work the N^{16} gamma rays were desirable to serve as reference standards. Samples of boron carbide and amorphous boron were tested by activation analysis for their oxygen content, and it was found that amorphous boron contained the proper amount of oxygen to produce the N^{16} gamma rays in desirable intensities relative to the Be^{11} gamma rays. Because of the very low efficiency of the detector for high-energy gamma rays, the sample to be irradiated was fairly large, i.e., it contained about 100 g of amorphous boron in a 3-in.-diam polyethylene bottle. This was placed adjacent to the Zr-T target and was irradiated for 30 sec. After turning off the Van de Graaff beam, the sample was carried in $\sim$6 sec to the Li-Ge detector, located in the control room, and the activity was counted for 30 sec. This procedure was repeated in order to accumulate a spectrum with suitable statistics. A description of the detecting system is given elsewhere.[6]

The calibration gamma-ray spectrum of N^{16} by itself was obtained with better statistics and in a much shorter time by irradiating a similar polyethylene bottle (about 1-pint capacity) filled with distilled water. In this case the irradiation and counting intervals were 15 sec each. Tests made by irradiating the empty polyethylene bottle showed that there were virtually no counts in the region of interest arising from the bottle or from room background.

Figure 1 shows the Li-Ge counter pulse-height spectra resulting from the $\mathrm{Be}^{11}+\mathrm{N}^{16}$ activities obtained in one of the final runs consisting of 120 irradiate-count cycles. The energies of the reference gamma rays emitted in the decay of N^{16} were taken to be 6.132 ± 0.003 and 7.116 ± 0.003 MeV. These values are a weighted mean of the O^{16} energy-level values given by Ajzenberg-Selove and Lauritsen,[7] and by Browne and Michael.[8] The lines identified in Fig. 1 as the two-escape and one-escape peaks associated with pair production in the detector by the 6.132-MeV O^{16} transition in N^{16} decay and the two-escape peak of the O^{16} 7.116-MeV transition were observed in the same pulse-height positions and with the same relative intensities in the data taken with the irradiated water sample. The latter spectrum was practically identical in shape to Fig. 1 except that the 6.8-MeV line was absent. Since there was no other line in the spectrum that could be associated with the peak at channel 197, we assign this as the two-escape peak of a transition of 6.8 MeV. Although a half-life determination was not made on the decay of this line, the counting rate at this peak was qualitatively observed to decrease at a slower rate than the N^{16} lines, but to be considerably slower towards the end of the 30-sec counting interval than at the start. Since a 6.8-MeV gamma ray had already been seen[1] in Be^{11} decay, there can be no doubt that the peak at channel 197 is the two-escape line of the Be^{11} gamma ray in question. The procedures followed to extract a gamma-ray energy from data such as that shown in Fig. 1 and the method of analyzing the errors are described in detail elsewhere.[6] The present data gives a value of 6.792 ± 0.006 MeV for the gamma ray produced in the Be^{11} decay.

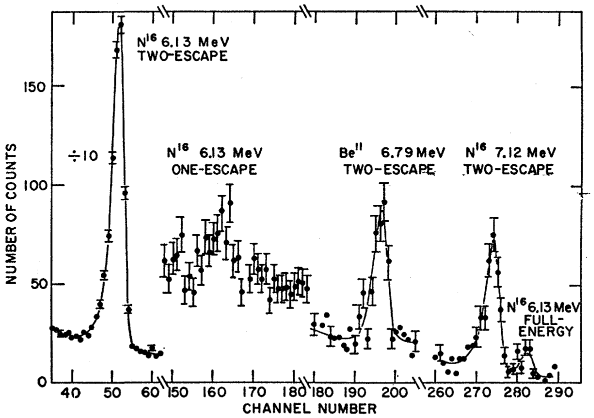

FIG. 1. Composite pulse-height spectrum for the N^{16} and Be^{11} gamma rays. The two-escape peaks of the 6.13- and 7.12-MeV N^{16} gamma rays were used for the energy calibration. The full-energy peak of the 6.13-MeV gamma ray can be seen very weakly just above the two-escape peak of the 7.12-MeV N^{16} gamma ray at channel 282. The energy calibration is about 4.43 keV per channel.

PARITY OF 7.99-MeV STATE IN B^{11}

The procedure followed in these experiments was to excite the 7.99-MeV level in the $\mathrm{Be}^9(\mathrm{He}^3,p)\mathrm{B}^{11}$ reaction, and to examine the electron pair spectra with an intermediate-image magnetic pair spectrometer. This instrument has been modified with a special spiral baffle system,[9] with which it is possible to determine the multipolarities of nuclear electromagnetic transitions. Measurements are made on the intensities of an internal-pair conversion line, first with the baffle in place and than with the baffle removed, and the reduction ratio is compared with calibration curves. Corrections must be applied to the ratio if there is an anisotropy in the corresponding gamma radiation.

The target consisted of a 4-mg/cm²-thick Be foil located at the normal spectrometer-source position. This was bombarded with a 1.4-μA beam at $E_{\mathrm{He}^3}=3.2$ MeV. Transitions of 7.99 and 5.86 MeV are known[7] to

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take place from the 7.99-MeV level of B^{11} to the ground state (55%) and to the $\frac{1}{2}^-$ first excited state (45%) at 2.13 MeV. Survey runs showed that both of the corresponding internal-pair conversion lines were well resolved from other lines occurring in the $Be^9(He^3,p)B^{11}$ and $Be^9(He^3,n)C^{11}$ reactions. After locating the peak positions, ratio measurements were made by taking points at the peaks and at the background levels above the lines with the baffle in and out. Ratios of the net peak yield for baffle-in/baffle-out were as follows:

$$R_{7.99}=0.090\pm0.007\,;$$

$$R_{5.86}=0.114\pm0.008\,.$$

Separate measurements on the gamma-ray spectrum were made with a three-crystal pair spectrometer when bombarding the same target material with a 3.2-MeV He^3 beam. Procedures for determining gamma-ray angular distributions with this device have been described previously.[10] By writing the angular distribution in the usual form,

$$W(\theta)=A_0+A_2P_2(\cos\theta)\,,$$

the experimental ratio A_2/A_0 is found to be 0.10 ± 0.05 for the 7.99-MeV gamma ray and -0.14 ± 0.04 for the 5.86-MeV gamma ray. These measurements alone show that $J\geqslant\frac{3}{2}$.

Anisotropy corrections to the experimental ratios R given above were made for various assumptions as to the multipolarities of the two transitions. The method, as described earlier,[9] is to make the appropriate correction for each assumed multipolarity and to compare the corrected ratios with the calibration curves which apply to nonaligned nuclei. In no case other than for electric-dipole radiation was it possible to make the corrected ratio for either of these transitions fit the calibration curves. For $E1$ on the other hand, there were good fits in both cases. Since the ground and first excited states of B^{11} both have odd parity, the 7.99-MeV level must therefore be even. Furthermore, the spin of this level cannot be $>\frac{3}{2}$ in order for an $E1$ transition to take place to the $\frac{1}{2}^-$ first excited state. Combining all of the results shows that the spin parity of the 7.99-MeV level is $\frac{3}{2}^+$. The angular-distribution data are consistent with this conclusion. Thus, the experimental ratio $(A_2/A_0)_{7.99}/(A_2/A_0)_{5.86}=-(0.7\pm0.4)$ is in agreement with the theoretical ratio of -0.8 which must obtain for a $\frac{3}{2}^+$ assignment to the 7.99-MeV level. The theoretical ratio is independent of the degree of alignment in this particular case. A more detailed report on the $Be^9(He^3,p)B^{11}$ and $Be^9(He^3,n)C^{11}$ reactions using the pair spectrometer will be published later.

DISCUSSION

In our data on the decay of Be^{11}, only one transition energy was observed in the vicinity of 6.8 MeV. Since it is known[7] that both members of the 6.752–6.804-MeV B^{11} doublet decay predominantly (83% and 79%, respectively) by ground-state gamma-ray transitions, it may be concluded that only one of the doublet levels is fed in Be^{11} decay, and that the branch to the other member must be relatively $<10\%$ as strong. As to which level is involved in the decay, our result of 6.792 ± 0.006 MeV for the transition energy is to be compared with the doublet level energies obtained from reaction Q values.

The first evidence for the 6.8-MeV doublet in B^{11} was obtained by Van Patter, Buechner, and Sperduto.[11] They found energies of 6.758 ± 0.013 and 6.808 ± 0.013 MeV and a separation of 50 ± 2 keV by means of magnetic analysis of the proton groups from the $B^{10}(d,p)B^{11}$ reaction. However, their results were based on an energy value of 5.2985 ± 0.0020 MeV for the Po^{210} alpha-particle calibration line,[12] a value no longer accepted as a standard. By adjusting the results of Van Patter *et al.* to conform with the revised Po standard[13] of 5.3043 ± 0.0006 MeV, the B^{11} doublet excitation energies would be 6.765 and 6.815 MeV, the separation between the levels remaining unchanged. Hinds and Middleton[4] investigated the $Be^9(He^3,p)B^{11}$ reaction and give the doublet energies relative to a lower state of B^{11} at 4.45 MeV. If the energy of the lower state is taken from a weighted average of the 4.463 ± 0.014- and 4.449 ± 0.008-MeV values for this state obtained by Van Patter *et al.*[11] (corrected for change in Po^{210} alpha energy) and by Jaidar *et al.*,[14] respectively, values of 6.748 ± 0.010 and 6.800 ± 0.010 MeV are obtained for the doublet values. It has recently been learned[15] that Browne and collaborators have obtained a new and preliminary excitation energy for the lower member of the B^{11} doublet. Photographic plates from magnetic spectrograph exposures that had been made in connection with experiments on the $B^{10}(d,\alpha)Be^8$ and $Be^9(He^3,\alpha)Be^8$ reactions were reanalyzed for the proton groups occurring in the $B^{10}(d,p)B^{11}$ and $Be^9(He^3,p)B^{11}$ reactions. In both cases Q values were obtained for the lower member of the doublet. A preliminary value for the excitation energy of 6.749 ± 0.010 MeV is obtained. Further work is planned[15] on the $B^{10}(d,p)B^{11}$ reaction in order to determine more precise energy values for the doublet levels. If the doublet spacing of 50 ± 2 keV found by Van Patter is added to Browne's result, then the energy of the upper member of the doublet is 6.799 ± 0.010 MeV. Taking a weighted average of the above data then gives values of 6.752 ± 0.006 and 6.804 ± 0.006 MeV

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for the doublet energies. It seems probable that the original values of Van Patter *et al.* are too high, and that the actual values for the doublet energies may be lower by about 5 keV than the average values including Van Patter's measurement.

The value of 6.792 ± 0.006 MeV that we obtain for the energy of the Be^{11} gamma ray is in agreement with the excitation energy for the upper level based on the reaction Q-value data cited above. It is concluded that the beta decay of Be^{11} populates the upper member of the doublet.

The previous work of Wilkinson and Alburger shows that the beta-ray branches for the Be^{11} decay to the doublet and to the 7.99-MeV states of B^{11} are allowed. As discussed earlier, the 6.804-MeV state is $\frac{1}{2}^+$ or $\frac{3}{2}^+$, and the 7.99-MeV state is $\frac{3}{2}^+$ from the pair spectrometer and angular-distribution measurements discussed above. The parity of Be^{11} must therefore be even. This confirms the shell-model calculation of Talmi and Unna,[2] as well as their interpretation of the original Be^{11} decay-scheme data, and agrees with the conclusion of Donovan *et al.*[3]

The upper limit[1] on the beta-ray branch to the 6.752-MeV member of the B^{11} doublet corresponds to a lower limit of 6.9 on the logft value of this transition. This is consistent with a forbidden beta decay between the even-parity Be^{11} ground state and the 6.752-MeV level which is most probably $\frac{7}{2}^-$.

ACKNOWLEDGMENT

We are greatly indebted to Professor C. P. Browne for permission to quote the measurements by himself and his co-workers on the excitation energy of the 6.75-MeV state in B^{11} before publication.

PHYSICAL REVIEW VOLUME 136, NUMBER 4B 23 NOVEMBER 1964

Nuclear Transitions in Au^{197}†*

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(Received 18 June 1964)

The energy of the hardest gamma ray emitted following β^- decay of the ground state of Pt^{197} (18 h) has been measured in a lithium-drifted germanium detector to be 268 keV. A 279-keV gamma ray was resolved which decayed in intensity with the 78-min half-life of the isomeric level of Pt^{197}. The K-shell conversion coefficient of the 191-keV transition has been experimentally determined as 1.59 ± 0.07, suggesting an $E0$ component, and that the spin and parity of the 268-keV level in Au^{197} are $\frac{1}{2}+$. Previously reported gamma rays in the decay of these platinum isomers at 155 and 202 keV are shown to arise from the presence of Au^{199}, formed in the β^- decay of Pt^{199}.

INTRODUCTION

NUCLEAR states of Au^{197} are excited in β^- decay[1–4] of Pt^{197}, orbital electron capture decay[5–8] of Hg^{197} and Hg^{197m}, and by Coulomb excitation[9–12] of gold. The known data are summarized in the disintegration scheme of Fig. 1. The present investigation concerns the properties of the nuclear transitions in gold which follow β^- decay of Pt^{197}.

The 18-h Pt^{197} and its 78-min isomer were produced in successive irradiations of metallic platinum in the Kansas State University Triga Mark II reactor. Each exposure was of duration one hour, and the platinum targets were enriched in Pt^{196} to an extent of 65.55%. Owing to the short time of irradiation, long-lived platinum activities were suppressed.

268- and 279-keV Transitions

The unconverted quanta emitted in decay of Pt^{197} and Pt^{197m} were observed in a lithium-diffused germanium detector of depletion layer thickness two millimeters with a reverse bias of 50 V at the temperature of liquid nitrogen. The resolution was 5.5 keV, full width at half-maximum, this limitation imposed by the electronic system. The data so obtained are shown in Fig. 2, where full energy peaks at 268 and 279 keV are seen to be clearly resolved. The 268-keV peak was found to decay with a half-life of 18 h, while the

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† Supported in part by the National Science Foundation.

* The content of this paper constitutes portions of theses to be presented by E. B. Nieschmidt and D. D. Bornemeier to Kansas State University in partial fulfillment of requirements for the degree of Doctor of Philosophy.

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