effect due to core polarization is sufficient to explain the small observed values of the static moments. The breaking of l forbiddenness accounts for the large observed value of $B(M1, (\frac{5}{2}^-)_1 \to (\frac{3}{2}^-)_1)$. These results, together with the similar results obtained for Sn^{116},[10] indicate the $M1$ observables as quantities sensitive to the degree of configuration mixing in a strong but regular way.

Essential agreement with experiment is obtained for one-nucleon transfer reaction spectroscopic factors. The ambiguity related to the two possible definitions of spurious vectors for $J^\pi = 0^+$ indicates that calculations in a number conserving approximation to exact shell model would be desirable.

ACKNOWLEDGMENTS

One of us (MG) is grateful to Professor Abdus Salam, Professor P. Budini, and the International Atomic Energy Agency for hospitality at the International Centre for Theoretical Physics, Trieste.

All the numerical computations were performed on the IBM 7044 computer of the University of Trieste. The authors wish to acknowledge the helpful cooperation of the staff of the Centro di Calcolo.

PHYSICAL REVIEW VOLUME 185, NUMBER 4 20 SEPTEMBER 1969

Decay of the 6.18-MeV $J^\pi = 0^+$ Level of Be^{10} †

D. E. Alburger and E. K. Warburton
Brookhaven National Laboratory, Upton, New York 11973
and
A. Gallmann
Institut de Recherches Nucléaires, Strasbourg, France
and
D. H. Wilkinson
Brookhaven National Laboratory, Upton, New York 11973 and *Nuclear Physics Laboratory, Oxford, England*

(Received 14 April 1969)

The reaction $Be^9(d, p)Be^{10}$ (at $E_d = 3.25$ MeV) has been used to investigate the decay of the 6.18-MeV $J^\pi = 0^+$ level of Be^{10}. Both of the γ-ray transitions 6.18→5.96 and 6.18→3.37 have been observed by means of γ-γ coincidence experiments using Ge(Li) and NaI(Tl) detectors. The mean life of the 6.18-MeV state is found to be $1.1_{-0.3}^{+0.4}$ psec from a Doppler-shift measurement on the 6.18→5.96 transition. It is concluded that the 6.18→5.96 transition takes place mainly to the $J^\pi = 1^-$ component of the $J^\pi = (1^-, 2^+)$ 5.96-MeV doublet and has an energy of 219.4±0.3 keV. The intensities of proton groups leading to levels of Be^{10} in the (d, p) reaction at $E_d = 3.25$ MeV were determined with a Buechner spectrograph By combining the present results with previous measurements on the 6.18-MeV $E0$ ground-state transition, the branching ratios (in %) from the 6.18-MeV state to the states at 5.96 MeV ($J^\pi = 1^-$), 3.37 MeV ($J^\pi = 2^+$), and 0 MeV ($J^\pi = 0^+$) are found to be 4.6±1.5, 95±2, and 0.24±0.08, respectively. The significance of these results is discussed. Incidental results are a value of 169.25±0.04 keV for the C^{13} 3.85→3.68 transition and a meanlife of 2.0±0.6 psec for the B^{10} 2.15-MeV level.

I. INTRODUCTION

The $J^\pi = 0^+$ state at an excitation energy of 6.18 MeV in Be^{10} is thought to be an interloper in the $1p$ shell; that is, one of those states which, although of the "correct parity" $(-)^A$, does not belong to the $(1s)^4(1p)^{A-4}$ configuration. Other examples are the $J^\pi = 0^+$ states at 7.65 MeV in C^{12}, 6.59 MeV in C^{14}, and 6.05 MeV in O^{16}.[1] The Be^{10} state is thought[2] to be predominantly $(1p)^{A-6}(2s, 1d)^2$ as is the C^{14} state.[3] The interloper states in even-even nuclei are almost certainly considerably more complicated.[4,5] One reason for this is that 4-particle–4-hole states are energetically favored in even-even nuclei considerably more than in odd-odd nuclei.

Available evidence indicates that the well-known enhancement of $E2$ transition rates between states of $(1p)^{A-4}$ is present to about the same extent for transitions between interloper states in the $1p$ shell. An example is the $E2$ transition between the $J^\pi = 5^+$ and 3^+ states of N^{14} at 8.96 and 6.44 MeV, respectively. These states are identified as interlopers[3] involving

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

[1] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).
[2] W. W. True and E. K. Warburton, Nucl. Phys. **22**, 426 (1961).
[3] W. W. True, Phys. Rev. **130**, 1530 (1963).
[4] G. E. Brown and A. M. Green, Nucl. Phys. **75**, 401 (1966).
[5] A. P. Zucker, B. Buck, and J. B. McGrory, Phys. Rev. Letters **21**, 39 (1968).

2-particle excitation from $(1p)^{10}$ into the $(2s, 1d)$ shell. The $E2$ transition between them has an experimental strength of about 8.5 W.u.[6] (Weisskopf units, using $r_0=1.2$ F throughout this paper) which is about 4 times the strength[7] deriving from True's[3] 2-particle–2-hole wave functions. This is just the same factor as that by which the $(1p)^{A-4}$ wave functions typically fail to describe the $E2$ transitions between the states whose relative excitations are well described by those wavefunctions.

This $E2$ enhancement is one of the puzzles which must be better understood before we can claim an understanding of light nuclei. Another puzzle is the appearance at quite low excitation energies of states of the "wrong parity," $(-)^{A+1}$, and the connected appearance of the interloper states already referred to.

The great success of the $(1p)^{A-4}$ picture in accounting for so much of what we know about the $1p$ shell has led us to hope that our two puzzles can be understood by some process of patching up the simple "spherical" $(1p)^{A-4}$ wave functions. An attractive possibility is that a successful "patching" may consist of introducing, through a Hartree-Fock minimization procedure, a quadrupole deformation which, in turn, lowers the excitation energies of the $(1p)^{A-5}(2s, 1d)$ states and of interlopers of the "correct parity" and introduces the $\Delta N=2$ admixtures necessary to explain $E2$ enhancements,[8] those enhancements being qualitatively understood in terms of rotations of the deformed states. In order to test this hypothesis, we need more experimental information on matrix elements connecting the $(1p)^{A-4}$ states with the interlopers. These matrix elements, which are particularly scarce deep within the $1p$ shell, can provide information on the degree of mixing of the interlopers and the $(1p)^{A-4}$ states. $E2$ matrix elements connecting interloper states with each other will also provide tests of current ideas on $E2$ enhancements.

As yet very little is known about $E2$ transitions involving interlopers in the $1p$ shell and the $(1p)^{A-4}$ states; some discussion is given later. A prime objective of the present work was to measure the speed of the $E2$ transition from the $J^{\pi}=0^+$ interloper in Be^{10} at 6.18 MeV to the $J^{\pi}=2^+$ $(1p)^6$ state at 3.37 MeV, which itself has an $E2$ strength for its ground-state transition of 7.5 ± 0.8 W.u.[9] Companion objectives were the measurements of the $E0$ width with which the 6.18-MeV state deexcites to the ground state and the $E1$ width of the transition that takes it to the $J^{\pi}=1^-$ component of the $J^{\pi}=1^-, 2^+$ doublet at 5.96 MeV[10,11]; the latter state has a large s-wave neutron width for the ground state of Be^9, being one of the class of "wrong parity" states that may have configurations close to $(1p)^{A-5}(2s, 1d)$.

These objectives demand a determination of the lifetime of the 6.18-MeV state and a determination of its branching ratios; this has been accomplished following the population of the level by the reaction $Be^9(d, p)Be^{10}$.

II. EXPERIMENTAL METHODS

The choices of target characteristics and beam energy used in most of the present studies on the 6.18-MeV level of Be^{10}, excited in the $Be^9(d, p)Be^{10}$ reaction, were made on the basis of earlier work in which the $6.18\rightarrow0$ transition was first observed[12] and its multipolarity determined[13] as $E0$. Since those measurements were carried out with a 3.7-mg/cm^2-thick Be target and a deuteron beam energy of 3.25 MeV, the same target material and beam energy were used for the present coincidence experiments.

γ-γ coincidence measurements were made with a conventional arrangement consisting of a 5×6-in. NaI(Tl) detector at 90° to the beam on one side of the target and a Ge(Li) detector on the other side. Pb, $\frac{3}{8}$-in. thick, was placed between the target and the NaI(Tl) detector in order to reduce the coincidence yield of low-energy Compton-scattered γ rays in the NaI(Tl) detector. Several sizes of Ge(Li) detector, with volumes ranging from 8–30 cc, were employed depending on the particular experiment. The Ge(Li) detector was placed at 90° to the beam and close to the target for branching-ratio measurements, or was moved back to a distance of 7 cm from the target for the Doppler-shift lifetime measurements at 30° and 127° (to be described later). Pulse-height spectra from the Ge(Li) detector, in coincidence with one or more pulse-height windows imposed on the spectrum from the NaI(Tl) detector, were recorded in separate 1024-channel sections of a 16 384-channel analyzer by the use of a "spectrum sorter."

For the Doppler-shift measurements on the $6.18\rightarrow5.96$ transition, reference γ-ray lines were needed. In

[6] A. Gallmann, F. Haas, and B. Heusch, Phys. Rev. **164**, 1257 (1967).

[7] The equation for the $E2$ strength of this transition given in Ref. **6** did not properly take into account antisymmetrization of the wave functions. It should be, in the notation of Ref. 6.

$$\Lambda(E2)=2[C^5{}_{5/2,5/2}(1.414C^3{}_{1/2,5/2}+0.5000C^3{}_{3/2\cdot5/2}+0.5774C^3{}_{5/2,5/2})]^2\gamma^{-2}(1+2\beta)^2.$$

[8] D. Kurath, in *Nuclear and Particle Physics*, edited by B. Margolis and C. S. Lam (W. A. Benjamin, Inc., New York, 1968), pp. 199–272.

[9] T. R. Fisher, S. S. Hanna, D. C. Healey, and P. Paul, Phys. Rev. **176**, 1130 (1968).

[10] F. C. Young, P. D. Forsyth, M. L. Roush, and W. F. Hornyak, in *Nuclear Spin-Parity Assignments*, edited by N. B. Gove and R. L. Robinson (Academic Press Inc., New York, 1966), p. 179; M. L. Roush, F. C. Young, P. D. Forsyth, and W. F. Hornyak, Nucl. Phys. **128**, 401 (1969).

[11] E. K. Warburton and D. E. Alburger, in *Nuclear Spin-Parity Assignments*, edited by N. B. Gove and R. L. Robinson (Academic Press Inc., New York, 1966), p. 224.

[12] E. K. Warburton, D. E. Alburger, and D. H. Wilkinson, Phys. Rev. **132**, 776 (1963).

[13] E. K. Warburton, D. E. Alburger, A. Gallmann, P. Wagner, and L. F. Chase, Jr., Phys. Rev. **133**, B42 (1964).

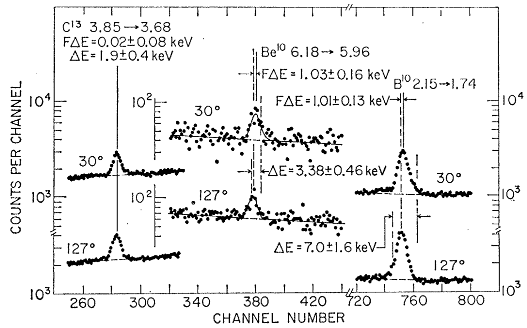

FIGURE 1

FIG. 1. Doppler-shift measurement of the Be^{10} 6.18→5.96 t ransition. The figure shows portions of Ge(Li) γ-ray spectra observed at 30° and 127° to the deuteron beam ($E_d=3.25$ MeV) and 7 cm from the target. The spectra were observed in coincidence with γ rays viewed by a 5×6-in. NaI(Tl) crystal at 90° to the beam and 3 cm from the target. The center spectra (Be^{10} peak) were observed in coincidence with γ rays with $5.3<E_\gamma<6.1$ MeV; and the other two spectra in coincidence with γ rays with $2.9<E_\gamma<3.8$ MeV. The deuteron beam impinged on a split target, one-half of which was Be^9 and the other half C^{12}. The C^{13} 3.85→3.68 transition arises from C_{12}+d and the Be^{10} and B^{10} peaks from Be^9+d. The solid curves drawn through the B^{10} peaks are least-squares fits (see text) with the assumed backgrounds which are indicated by the dashed lines. For each peak the full (kinematical) Doppler shift is indicated by ΔE. The uncertainty on ΔE arises from the kinematics of the reaction (see text). The actually observed Doppler shift, extracted from the centroids of the peaks, are indicated by $F\Delta E$. Lifetimes are extracted from $F(=F\Delta E/\Delta E)$, as discussed in the text.

the Be^9+d reaction the 411-keV line occurring in the B^{10} 5.16→2.15→1.74 cascade following the $Be^9(d,n)B^{10}$ reaction served as one such line. In order to generate another reference γ-ray line at an energy lower than the Be^{10} 219-keV transition, the $C^{12}(d,p)C^{13}$ reaction was used to produce the 169-keV γ ray occurring in the C^{13} 3.85→3.68→0 cascade. These simultaneous measurements on the Be+d and $C^{12}(d,p)C^{13}$ reactions were accomplished by the use of a split target consisting of a 1-mm-thick slice of graphite attached to the target holder adjacent to a Be foil. An external screw allowed the position of the target holder to be varied so that the 3-mm-diam collimated beam could strike the adjacent edges of both samples at the same time. Relative intensities of radiations from the two targets were adjusted as desired.

Some of the calculations of branching ratios required a knowledge of the efficiency-times-solid-angle for detecting low-energy γ rays in the Ge(Li) detector. For this purpose a carbon target by itself was used to make efficiency measurements on the 169-keV γ rays occurring in the $C^{12}(d,p)C^{13}$ reaction.

It was also found desirable to determine the energy of the C^{13} 169-keV γ ray more accurately than had been reported in the literature. An accurate energy value was obtained for this γ ray by intercomparisons with reference γ rays emitted from a source of Ta^{182}.

The 6.18→3.37 transition was detected by means of γ-γ coincidence measurements using the general arrangement already described. When several previous and unsuccessful attempts had been made to observe the 6.18→3.37 transition, it was believed that independent measurements of relative proton-population intensities would be needed in order to assign limits to the various branching ratios from the 6.18-MeV level. For this purpose magnetic analysis measurements were made on the $Be^9(d,p)Be^{10}$ reaction by means of a Buechner-type spectrograph.

III. EXPERIMENTAL RESULTS AND ANALYSIS

A. Observation of the 6.18→5.96 Transition

When the present work was started, it was known[10,11] that the 5.96-MeV level of Be^{10} actually consists of a doublet (separation 1.6±0.5 keV) having spin parities of $J^\pi=1^-$ and 2^+; the $J^\pi=1^-$ (upper) member decays predominantly to the $J^\pi=0^+$ ground state, whereas the $J^\pi=2^+$ (lower) member decays predominantly to the $J^\pi=2^+$ 3.37-MeV first-excited state. It was expected that the 6.18-MeV $J^\pi=0^+$ level would decay preferentially by an $E1$ transition to the $J^\pi=1^-$ member of the 5.96-MeV doublet rather than by an $E2$ transition to the $J^\pi=2^+$ member. In the initial search for the 6.18→5.96 transition, the output of an 8-cc Ge(Li) detector was displayed in coincidence with a pulse-height channel encompassing the full-energy and one-escape peaks of the 5.96-MeV γ rays in the spectrum from the 5×6-in. NaI(Tl) detector. A weak 219-keV coincidence line was observed.

In a second experiment five pulse-height gates were set on the γ-ray spectrum from the 5×6-in. NaI(Tl) detector, and the Ge(Li) spectrum in coincidence with each was displayed. The 219-keV line was again observed, but only in coincidence with the 5.96-MeV γ ray. However, the 3.37-MeV γ ray from direct feeding of the 3.37-MeV level in the $Be^9(d,p)Be^{10}$ reaction was too intense to allow a significant limit to be placed on the intensity of 6.18 ($J^\pi=0^+$)→5.96 ($J^\pi=2^+$)→3.37→0 cascades relative to 6.18 ($J^\pi=0^+$)→ 5.96 ($J^\pi=1^-$)→0 cascades. Thus, this limit was inferred from the lifetime measurement described below.

B. Lifetime Measurement

The lifetime of the Be^{10} 6.18-MeV level was measured by observing the Doppler shift of the 6.18→5.96 transition. As shown in Fig. 1, the full-energy peak of this transition was observed in the Ge(Li) detector at 30° and 127° to the 3.25-MeV deuteron beam in coincidence with a channel on the 5.96-MeV full-energy and one-escape peaks in the NaI(Tl) detector. By using the "spectrum sorter" and the split-target technique described earlier, the C^{13} 169-keV transition and the B^{10} 411-keV transition were recorded in coincidence with the region $2.9<E_\gamma<3.8$ MeV. These transitions arise from the C^{13} 3.85→3.68→0 and B^{10}

5.16→2.15→1.74 cascades, respectively, and are also shown in Fig. 1 for both detector angles.

The full (kinematical) Doppler shifts for these three transitions were calculated assuming angular distributions for the reactions involved characterized by $\langle\cos\theta_{c.m.}\rangle=0.0\pm0.33$, where $\theta_{c.m.}$ is the angle to the beam of the reaction products. The values of ΔE shown in Fig. 1 result from these calculations. Any possible γ-γ correlation effects were neglected since the geometry was such that they were not expected to be important. The actually observed Doppler shifts were obtained from the shift in the centroids of the peaks. For this purpose the background under the peak was assumed to be given by a least-squares fit to the region, either side of the peak assuming an exponential form. These fits are shown by the dashed lines in Fig. 1. The observed centroid shifts calculated in this manner are indicated by $F\Delta E$ in Fig. 1. The ratio of observed to calculated shifts, $F=F\Delta E/\Delta E$, from this procedure are

$$F(C^{13})=0.01\pm0.05,$$

$$F(Be^{10})=0.30\pm0.06,$$

$$F(B^{10})=0.14\pm0.03.$$

These were analyzed using the procedure of Warburton *et al.*[14] to give mean lifetimes:

$$\tau(C^{13})>2.3 \text{ psec (two standard deviations)},$$

$$\tau(Be^{10})=1.1_{-0.3}^{+0.4} \text{ psec},$$

$$\tau(B^{10})=2.0\pm0.6 \text{ psec}.$$

The B^{10} and C^{13} results are in good agreement with previous work,[9,15] while the result for the Be^{10} 6.18-MeV level is consistent with the previous limit,[12] $\tau>0.5$ psec. The solid curves shown in Fig. 1 for the Be^{10} 6.18→5.96 full-energy peaks are the expected line shapes[14] for a 1.1-psec lifetime. These curves agree with the data within the statistical uncertainties.

The Weisskopf estimates for 219-keV $E1$ and $E2$ transitions in Be^{10} are $\tau=2\times10^{-13}$ and 1.2×10^{-6} sec, respectively. Thus the observation of a Doppler shift is incompatible with any observable 6.18 ($J^\pi=0^+$)→5.96 ($J^\pi=2^+$) contribution, and the 219-keV γ ray is assigned to the 6.18 ($J^\pi=0^+$)→5.96 ($J^\pi=1^-$) transition, as was expected.

C. Energies of the Be^{10} 6.18→5.96 and C^{13} 3.85→3.68 Transitions

Additional information which may be obtained from the Doppler-shift data described above is the energy of the 219-keV transition corresponding to the unshifted position of the peak, as indicated by the vertical dashed lines in the upper and lower parts of Fig. 1. The 169-, 411-, and 511-keV (not shown) lines served to establish the energy scale. The C^{13} 169-keV γ-ray energy was reported[1] previously as 169.5 ± 0.4 keV. It was felt desirable to establish its energy with greater accuracy before using it as a standard for the Be^{10} 219-keV transition energy.

The 169-keV line from the $C^{12}(d,p)C^{13}$ reaction was measured in a Ge(Li) detector at 90° to the beam in a separate experiment when a source of Ta^{182} was superposed. Numerous γ rays are present in the Ta^{182} spectrum and the energies of several of these are known[16] with very high accuracy. For the present purposes the γ-ray lines at 152.435 ± 0.004 keV and 179.393 ± 0.003 keV were the most useful. The deuteron beam current was adjusted so that the C^{13} 169-keV line intensity was about the same as that of the Ta^{182} 179-keV line. The spectrum of the Ta^{182} source alone was also recorded. In the latter case it was noted that a weak peak corresponding to a γ ray of about 167.6 keV is also emitted from the source. Since in the combined spectrum this line was not resolved from the C^{13} 169-keV peak, it was necessary to first subtract the normalized 167.6-keV peak (~10% as strong as the C^{13} 169-keV peak) from the total spectrum before making the centroid analysis on the 169-keV line. An additional Ta^{182} line at 222.110 ± 0.003 keV was also fitted in order to check the over-all linearity of the analyzing system. The analyzer dispersion for these measurements was about 0.22 keV per channel. As a check on local nonlinearities in the system, a similar experiment was done at a slightly different amplifier gain setting. Nonlinearities were found to be completely negligible.

The final result for the energy of the γ ray due to the C^{13} 3.85→3.68 MeV transition is 169.25 ± 0.04 keV. This is in agreement with the earlier measurement,[1] but is very much more accurate. Because of its very small Doppler shift and the ease of producing this γ ray, it can serve as a useful low-energy standard. Since the recoil energy in the emission of the 169-keV γ ray is only 0.001 keV, and therefore negligible, the energy of the γ ray is also the separation energy between the 3.85- and 3.68-MeV levels in C^{13}.

There have been several accurate measurements of the energy of the C^{13} 3.68-MeV γ ray emitted in the $C^{12}(n,\gamma)C^{13}$ reaction. Prestwich *et al.*[17] obtained a γ-ray energy of 3683.94 ± 0.17 keV, which corresponds to a level energy of 3684.50 ± 0.17 keV when corrected for recoil. More recently, Spilling *et al.*[18] reported a level

[14] E. K. Warburton, J. W. Olness, and A. R. Poletti, Phys. Rev. **160**, 938 (1967).
[15] F. Riess, P. Paul, J. B. Thomas, and S. S. Hanna, Phys. Rev. **176**, 1140 (1968).
[16] J. B. Marion, University of Maryland Technical Report No. 656 (revised), 1967 (unpublished).
[17] W. V. Prestwich, R. E. Coté, and G. E. Thomas, Phys. Rev. **161**, 1080 (1967).
[18] P. Spilling, H. Gruppelaar, H. F. De Vries, and A. M. J. Spits, Nucl. Phys. **A113**, 395 (1968).

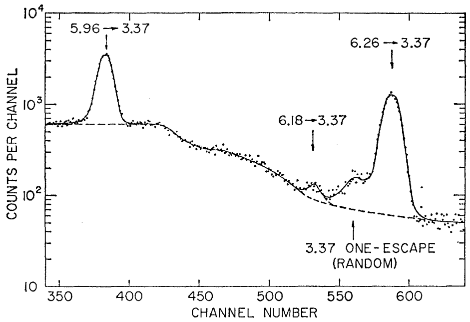

FIG. 2. Pulse-height spectrum from a 30-cc Ge(Li) detector recorded in coincidence with a pulse-height channel on the full-energy peak of 3.37-MeV γ rays detected in a 5×6-in. NaI(Tl) scintillator. The peaks are due to the Be^{10} γ-ray cascade transitions indicated following excitation of the levels in the $Be^9(d, p)Be^{10}$ reaction at $E_d = 3.25$ MeV.

energy of 3684.28±0.14 keV. We adopt a weighted mean value of 3684.37±0.14 keV for the C^{13} level. By adding this to our value for the energy separation between the 3.85- and 3.68-MeV levels, we obtain a value of 3853.62±0.15 keV for the energy of the third excited state of C^{13}.

Based on the above result for the C^{13} 3.85→3.68 MeV γ ray, the analysis of the Doppler-shift data of Fig. 1 leads to a value of 219.4±0.3 keV for the Be^{10} transition energy between the $J^{\pi}=0^+$ 6.18- and $J^{\pi}=1^-$ 5.96-MeV states.

D. Observation of the 6.18→3.37 Transition

The arrangement for observing the Be^{10} 6.18→3.37 transition was similar to that used for finding the 219-keV transition, except that a 30-cc Ge(Li) detector with a resolution of ~3 keV for Co^{60} γ rays was employed. Figure 2 shows the spectrum in coincidence with a pulse-height channel placed on the photopeak of the 3.37-MeV γ rays occurring in the spectrum from the 5×6-in. NaI(Tl) detector. In addition to the strong peaks corresponding to the cascade decays of the 5.96(2+)- and 6.26-MeV states to the 3.37-MeV level, the sought-for 6.18→3.37 γ-ray peak is also present, as well as the one-escape peak of the 3.37-MeV γ rays resulting from random coincidences.

The expected position of the 6.18→3.37 peak was calculated from the positions of the 5.96→3.37 and 6.26→3.37 peaks in Fig. 2, together with the values for the excitation energies of the Be^{10} levels (given in Fig. 3 and discussed later). As may be seen in Fig. 2, the observed peak agrees very well with the position, indicated by an arrow, calculated for the 6.18→3.37 γ ray. The calculated position of the 3.37-MeV one-escape peak is also shown by an arrow and serves to confirm the identity of this line.

The solid curve in Fig. 2 is a hand fit to the data and the dashed lines are estimates of the underlying backgrounds. A qualitative feature of the spectrum is that the 6.18→3.37 peak has a full width at half-maximum only about half as great as the half-widths of the other three peaks. Although no detailed calculations have been carried out on the Doppler broadening expected for the various γ rays, the data are consistent with previously determined lifetime information[19,20] on the 5.96- and 6.26-MeV states, together with the measurements reported above on the lifetime of the 6.18-MeV level.

E. Branching Ratios from the 6.18-MeV State

The following sequence of measurements and calculations was followed in order to determine the relative intensities of the three branches from the Be^{10} 6.18-MeV level:

(a) From the coincidence measurements described in Sec. III A, the ratio of intensities of 219-keV and 5.96-MeV γ rays was determined. This required supplementary experiments on the $C^{12}(d, p)C^{13}$ reaction in order to establish the Ge(Li) efficiency times solid angle for detecting the 219-keV γ rays.

(b) The data discussed in Sec. III D were analyzed to find the relative intensities of the three cascade transitions to the 3.37-MeV level, which are indicated in Fig. 2.

(c) A supplementary experiment was performed with a NaI(Tl) detector in order to determine the intensity ratio of the 5.96→3.37 and 5.96→0 transitions.

(d) By combining the results of steps (b) and (c), the intensity ratio of the 6.18→3.37 and 5.96→0 γ rays was found.

(e) Previous pair-line measurements[13] on the 6.18→0 and 5.96→0 transitions were corrected for spectrometer transmission[21] to obtain the intensity ratio of these two transitions.

(f) Having established the intensity of each transition from the 6.18-MeV state relative to the number of 5.96-MeV γ rays, measured in every case with the same target and beam energy, the results of steps (a), (d), and (e) were combined to determine the relative intensities of the 6.18→5.96, 6.18→3.37, and 6.18→0 transitions, respectively. Fractional transition intensities from the 6.18-MeV level were then derived.

In step (a), the supplementary experiments on the $C^{12}(d, p)C^{13}$ reaction were done in the same geometry as had been used for the measurements of the Be^{10} 219-keV γ rays in coincidence with 5.96-MeV γ rays. A 550-μg/cm²-thick carbon target was installed, and

[19] E. K. Warburton, J. W. Olness, K. W. Jones, C. Chasman, R. A. Ristinen, and D. H. Wilkinson, Phys. Rev. **148**, 1072 (1966).

[20] H. Lancman, F. S. Rosenthal, J. Beyea, M. Nessin, and L. J. Lidofsky, Bull. Am. Phys. Soc. **13**, 606 (1968).

[21] D. H. Wilkinson, D. E. Alburger, E. K. Warburton, and R. E. Pixley, Phys. Rev. **129**, 1643 (1963).

the deuteron beam energy was set at 2.51 MeV, since the various characteristics of this reaction have been throughly investigated[22] under these conditions. The efficiency times solid angle for detection of the 169-keV γ rays in the Ge(Li) detectors was determined in two ways. In the first the singles spectra in the Ge(Li) and NaI(Tl) detectors were recorded during the same bombardment time. From the area under the 3.85-MeV full-energy-loss peak in the NaI(Tl) spectrum, the total number of 3.85-MeV γ rays emitted from the target was found by correcting for peak-to-total ratio, total efficiency at the target-to-crystal distance used, absorption, and analyzer dead time. The known branching[23] of the C^{13} 3.85-MeV state, i.e., $(37\pm4)\%$ for the 3.85→3.68 transition and 63% for the ground-state transition, was used to calculate the corresponding total number of 169-keV γ rays emitted from the target. Together with the area under the 169-keV peak, this led to a value for the efficiency times solid angle of the Ge(Li) detector at 169 keV.

In the second method the 169-keV γ-ray peak was measured in coincidence with a channel on the NaI(Tl) detector including the photo-peaks of the 3.68- and 3.85-MeV γ rays. An analysis of the pulse-height spectrum within the channel gave that fraction of total counts in the channel corresponding to 3.68-MeV γ rays, and also gave an intensity ratio of the two γ rays which agreed very well with the work of Poletti *et al.*[22] By using the branching ratio data[23] on the 3.85-MeV state, the fraction of the total 3.68-MeV γ rays that follow the 3.85→3.68 transition was obtained. Finally, from the area under the 169-keV peak the number of coincidences per 3.68-MeV cascade γ ray was calculated; this is simply the efficiency times the solid angle.

Results from the above two measurements agreed within their errors, and their average was 0.0158 $(\pm11\%)$ for the efficiency times solid angle for detecting 169-keV γ rays in the Ge(Li) detector. A previously determined[24] curve of efficiency versus γ-ray energy for this particular Ge(Li) detector was then used to obtain an efficiency-times-solid-angle value of 0.0108 $(\pm12\%)$ at 219 keV. The ratio of 219-keV γ rays to 5.96-MeV γ rays was then calculated from the results of step (a) in a straightforward manner based on the total number of counts in the channel on the 5.96-MeV γ rays, suitably corrected for background. The result for the intensity ratio of 219-keV to 5.96-MeV γ rays is $(1.7\pm0.3)\times10^{-3}$.

In the analysis of the data in Fig. 2, the areas under the 5.96→3.37, 6.18→3.37, and 6.26→3.37 peaks were corrected according to the curve of efficiency versus γ-ray energy obtained[25] at Chalk River for a 25-cc Ge(Li) detector. The ratio of transition intensities was found to by 0.0159 ± 0.003 for the (6.18→3.37)/(5.96→3.37) ratio [step (b)], and 0.027 ± 0.006 for the (6.18→3.37)/(6.26→3.37) ratio.

The γ-ray singles spectrum from Be+d at $E_d=$ 3.25 MeV, measured with the 5×6-in. NaI(Tl) detector, was analyzed to find the intensity ratio (5.96→3.37)/(5.96→0) [step (c)]. This was done by correcting the intensities of the 2.59- and 5.96-MeV full-energy-loss peaks for the relative peak efficiency.[26] The measured ratio was (5.96→3.37)/(5.96→0) = 2.20. By combining this with the result given in the preceding paragraph, the intensity ratio (6.18→3.37)/(5.96→0) was found to be 0.035 ± 0.007 [step (d)].

The ratio of the intensities of the 6.18→0 to 5.96→0-MeV lines measured[13] earlier in the magnetic spectrometer was $(3.5\pm0.7)\times10^{-2}$. According to the transmission calculations,[21] the spectrometer efficiencies for normal operation are in the ratio (6.18 $E0$)/(5.96 $E1$) = 392. This leads to a value of $(0.89\pm0.20)\times10^{-4}$ for the intensity ratio of the 6.18→0 and 5.96→0 transitions [step (e)].

All of the above results may be combined to obtain branching ratios (in %) from the 6.18-MeV level to the levels at 5.96 MeV ($J^\pi=1^-$), 3.37 MeV ($J^\pi=2^+$), and 0-MeV ($J^\pi=0^+$) levels of 4.6 ± 1.5, 96 ± 2, and 0.24 ± 0.08, respectively.

Since the intensities of the various transitions from the 6.18-MeV level were all measured with respect to the number of 5.96-MeV γ rays, the relative proton-population intensities of the 6.18-MeV level and the 5.96-MeV doublet may be calculated. This was done by combining the data on the above branching ratios with the singles results on the 5.96- and 2.59-MeV γ-ray intensities mentioned earlier and with the branching information[11] on the two components of the 5.96-MeV doublet. The relative population intensities of the 6.18- and 6.26-MeV levels may be obtained directly from the analysis of Fig. 2, since it is known[1] that the 6.26-MeV state decays 100% by γ decay to the 3.37-MeV level. If the population intensities are designated as p_2, p_3, p_4, and p_5, for the $J^\pi=2^+$ 5.96-, $J^\pi=1$- 5.96-, $J^\pi=0^+$ 6.18-, and $J^\pi=2^-$ 6.26-MeV levels, respectively, then we find that $p_4/(p_2+p_3)=0.0116\pm0.002$ and $p_4/p_5=0.028\pm0.006$.

F. Buechner-Spectrograph Measurements

Measurements on the $Be^9(d,p)Be^{10}$ reaction were carried out with a Buechner-type magnetic spectrograph in order to determine the relative proton population intensities of the various Be^{10} levels. This was done prior to experiments in which the 6.18→3.37

[22] A. R. Poletti, J. W. Olness, and E. K. Warburton, Phys. Rev. **151**, 812 (1966).
[23] S. Gorodetzky, R. M. Freeman, A. Gallmann, and F. Haas, Phys. Rev. **149**, 801 (1966).
[24] S. Hechtl (private communication).
[25] T. K. Alexander (private communication).
[26] J. W. Olness (private commnuication).

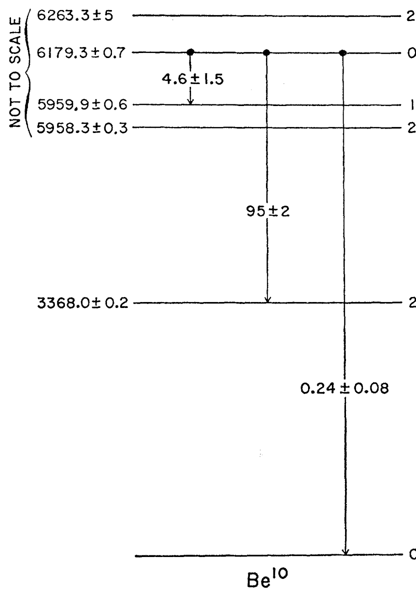

FIG. 3. Energy-level diagram of Be^{10} showing the branching ratios (in %) from the 6.18-MeV level as obtained in the present work. Results reported in the literature as well as in the present paper were combined to derive the excitation energies (in keV) shown for the bound levels of Be^{10}.

transition was finally detected, as described in Sec. III D.

The target used in the spectrograph was a 30-μg/cm^2-thick Be layer evaporated onto a 15-μg/cm^2-thick carbon backing. The beam energy was 3.25 MeV, and spectra were recorded at 30° and at 60° to the beam. Because of its low intensity, the 6.18-MeV proton group could be observed only in long exposures—which resulted in saturation of the strong groups. Short runs were therefore made to measure the intensities of the strong groups; the runs were normalized according to the total yields observed in a Si proton monitor counter mounted so as to view the target.

Results for the ratio p_4/p_5, where in this case p represents a differential cross section rather than a proton-population intensity and where the subscripts 4 and 5 correspond to the $J^\pi=0^+$ 6.18-MeV and $J^\pi=2^-$ 6.26-MeV levels, respectively, were 0.007 ± 0.002 at 30° and 0.031 ± 0.004 at 60°.

It is evident from these results that the angular distributions of the protons leading to the 6.18- and 6.26-MeV states differ considerably, and hence an accurate ratio of the proton population intensities probably cannot be obtained on the basis of these measurements. However, the ratio $p_4/p_5=0.028$ derived in the preceding section lies between the two spectrograph results quoted above. We may therefore consider the spectrograph measurements as giving a rough confirmation of the relative proton population intensities as derived from the γ-γ coincidence work.

G. Summary of Branching Ratios from the 6.18-MeV Level—Energies of States of Be^{10}

Figure 3 summarizes the branching ratios of the 6.18-MeV level based on the present work.

Accurate values for the energies of the Be^{10} 3.37→0 and 5.96 (2^+)→3.37 transitions have been reported by Greenwood.[27] His results, including recoil corrections, are 3368.0 ± 0.2 and 2590.3 ± 0.25 keV, respectively, for these two transition energies. Other information that may be combined with Greenwood's results to derive energies for various levels of Be^{10} include the 5.96-MeV doublet separation[10] of 1.6 ± 0.5 keV, our present result of 219.4 ± 0.3 keV for the 6.18→5.96 $(J^\pi=1^-)$ transition, and the separation between the 6.26- and 6.18-MeV levels obtained by Jung and Bockelman.[28] According to their Q values, the separation between the 6.18- and 6.26-MeV levels is 84 keV. Since no error has been given on the separation energy, we have estimated this as ±5 keV. The energies of the first five excited states of Be^{10} are shown in Fig. 3.

IV. DISCUSSION

Before entering into a consideration of the radiative widths resulting from the present measurements, a short discussion of the level energy spectrum of Be^{10} is worthwhile. As well as the bound states of Be^{10} shown in Fig. 3, the four lowest unbound states are also of some interest to the present discussion. These are a $J^\pi=3^-$ level at 7.38 MeV, a $J^\pi=2^+$ level at 7.55 MeV, and probable $J^\pi=4^-$ and 2^+ levels at 9.27 and 9.4 MeV, respectively.[29] It is probable that the $J^\pi=3^-$ and $J^\pi=4^-$ levels are predominantly composed of $1d_{5/2}$ neutrons coupled to $(1p)^5$ states of Be^9, and so are rather similar to the $J^\pi=1^-$ 5.96- and $J^\pi=2^-$ 6.26-MeV levels which, from $Be^9(d,p)Be^{10}$ results, are at least partially $(Be^9{}_{g.s.}\times 2s_{1/2})$.[10,29]

The effective interaction calculations of Cohen and Kurath[30] predict the three lowest $(1p)^6$ levels of Be^{10} above the $J^\pi=0^+$ ground state all to be $J^\pi=2^+$ states with excitation energies of 4.16, 5.81, and 9.16 MeV. The first is identified with the 3.37-MeV level. The second is almost certainly identifiable with the $J^\pi=2^+$ member of the 5.96-MeV doublet.

How do the observed electromagnetic decay modes of the $J^\pi=2^+$ 5.96-MeV level agree with the predictions of Cohen and Kurath? The radiative widths predicted by the (8-16) POT form[30] of the effective interaction for the decay of the lowest two $A=10$, $J^\pi=2^+$, $T=1$ states are presented in Table I. In this table $T_z=(N-Z)/2$, $\epsilon(\Delta T)$ is the enhancement of the $\Delta T=0$ (isoscalar) and $\Delta T=1$ (isovector) parts of the $E2$ matrix elements, and the transition strengths were

[27] R. C. Greenwood, Phys. Letters **23**, 482 (1966).
[28] J. J. Jung and C. K. Bockelman, Phys. Rev. **96**, 1353 (1954).
[29] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **78**, 1 (1966).
[30] S. Cohen and D. Kurath, Nucl. Phys. **73**, 1 (1965).

TABLE I. The (8-16)POT results of Cohen and Kurath[a] for the decay of the lowest two $(J^{\pi}, T)=(2^{+}, 1)$ states of $(1p)^6$.

Transition	Multi-polarity	Transition strength[b] (W.u.)	Γ_{γ} (meV) for Be^{10}
$(2^+,1)_2\rightarrow(2^+,1)_1$	$M1$	$[0.0044+0.3824T_z]^2$	54.61
$(2^+,1)_2\rightarrow(2^+,1)_1$	$E2$	$[1.8518\epsilon(0)-0.1174T_z\epsilon(1)]^2$	1.58
$(2^+,1)_2\rightarrow(0^+,1)_1$	$E2$	$[-0.0948\epsilon(0)+1.1566T_z\epsilon(1)]^2$	7.41
$(2^+,1)_1\rightarrow(0^+,1)_1$	$E2$	$[1.5925\epsilon(0)+0.0584T_z\epsilon(1)]^2$	4.81

[a] Calculated from the results of Ref. 30 by Dr. I. S. Towner.
[b] The phase convention is that of Rose and Brink [H. J. Rose and D. M. Brink, Rev. Mod. Phys. **39**, 306 (1967)].

calculated using $\langle 1p|r^2|1p\rangle=7.06$ F^2. In calculating the Be^{10} $E2$ rates, we have taken $\epsilon(0)=2$, $\epsilon(1)=1$, which would result from an effective-charge formalism with $e_p=(1+0.5)e$, $e_n=0.5e$. The transition energies used were those of Fig. 3. From these results the branching ratios of the $J^{\pi}=2^{+}$ Be^{10} 5.96-MeV level are predicted to be 88% to the 3.37-MeV level and 12% to the ground state. The predicted lifetime is 1.0×10^{-14} sec and the predicted $E2/M1$ mixing ratio in the 5.96→3.37 transition is +0.17. By comparison, the observed ground-state branching ratio is <10%[11] and the lifetime is less than 8×10^{-14} sec.[20] The former is not a strong disagreement, especially since the isoscalar part of the $(2^+,1)_2\rightarrow(0^+,1)_1$ $E2$ rate is small and therefore probably rather uncertain.

The third $J^{\pi}=2^{+}$ $(1p)^6$ state, expected at 9.16 MeV, we tentatively identify as that observed at 9.4 MeV. Thus, we are left with the $J^{\pi}=2^{+}$ 7.55-MeV level as an interloper.[31,32] This identification is rather speculative; however, we certainly expect a $J^{\pi}=2^{+}$ state to be associated with the $J^{\pi}=0^{+}$ 6.18-MeV level and to lie within several MeV above it.

In the Introduction we gave as a major purpose of these experiments the determination of the $E2$ rate between the interloping non-$(1p)^6$ $J^{\pi}=0^{+}$ 6.18-MeV state and the $J^{\pi}=2^{+}$ state at 3.37 MeV. This transition is of particular interest for the $E2$ enhancement problem, as well as for a measure of the mixing between the interloper states and the $(1p)^6$ states. The problem is, of course, that these two points are intertwined and difficult to separate. Certainly not much can be said without a detailed theoretical study. However, a brief and crude comparison of this $E2$ rate with expectation and with the similar $E2$ rate in C^{12} is of some interest. An extremely crude estimate of the degree of mixing goes as follows: If an interloper of a given J mixes with the $(1p)^{A-4}$ states of the same J with amplitude ϵ ($\epsilon^2\ll1$), and if the in-band matrix elements for the interloper's $E2$ transitions are f times those for the pure intra-$(1p)^{A-4}$ $E2$ transitions, then the mixing will enhance the intra-$(1p)^{A-4}$ radiative widths by a factor of about $(1+f\epsilon^2)^2$—assuming that there is no transition between the pure interloper and pure $(1p)^{A-4}$ states. The $E2$ transitions between the interlopers and the $(1p)^{A-4}$ states will then be expected to have speeds of order $\epsilon^2(1-f)^2$ in terms of those of the "pure" intra-$(1p)^{A-4}$ transitions. Now, from the considerations advanced in the Introduction, our speculation is for $|f|\sim1$ to pertain on the average, so that $(1+f\epsilon^2)^2\approx1$ and the intra-$(1p)^{A-4}$ $E2$ transitions are usually not much affected by mixing with the interlopers. On the other hand, $\epsilon^2(1-f)^2\approx4\epsilon^2$ or 0, depending on the sign of f. An example of the effect of the ambiguity in the sign of f may be that involving the N^{14} $E2$ transitions from the $J^{\pi}=3^{+}$ interloper at 6.44 MeV to the $J^{\pi}=1^{+}$ $(1p)^{10}$ ground-state and 3.95-MeV level. These $E2$ strengths are $\sim4.5\times10^{-2}$ and ~1.4 W.u., respectively.[33,34] The large difference in these two strengths could conceivably result from destructive and constructive interference, respectively, as outlined above.

The $E2$ 6.18→3.37 transition of 3.1±0.9 W.u. (see Table II) is to be compared to the 7.5±0.8 W.u. for the $E2$ 3.37→0 transition. However, we first divide the former by 5 in order to express it as a $J^{\pi}=2^{+}\rightarrow J^{\pi}=0^{+}$ strength. The resulting ratio is 0.08. We then find $\epsilon^2\approx0.08/4=0.02$ (we discard the other solution as unreasonable) and the strength of the Be^{10} 6.18→3.37 transition is consistent with mixing between the interloper and $(1p)^{A-4}$ states of the order of a few percent. Let us compare this result to the similar case of C^{12}. The $E2$ transition from the $J^{\pi}=0^{+}$ interloper at 7.65 MeV in C^{12} to the $J^{\pi}=2^{+}$, 4.43-MeV level has a strength of 6±2 W.u. as compared to 5.0±0.2 W.u. for the ground-state transition from the $J^{\pi}=2^{+}$ state. Thus, $4\epsilon^2\approx(1/5)(6\pm2)/(5.0\pm0.2)$, and $\epsilon^2\approx0.06$, which is somewhat larger than but of the same order as the Be^{10} case. This crude estimate of the mixing in Be^{10} and C^{12} is of the same order as found by True[3] for the mixing in N^{14} between the $(1p)^{10}$ states and interlopers of the type $(1p)^8(2s,1d)^2$.

[31] The very small neutron reduced width observed for this level (Ref. 29) cannot be used as an argument for this assignment since Cohen and Kurath (Ref. 32) predict a small neutron reduced width for the third $J^{\pi}=2^{+}$, $T=1$ state of $(1p)^6$.

[32] S. Cohen and D. Kurath, Nucl. Phys. **A101**, 1 (1967).

[33] J. A. Becker and E. K. Warburton, Phys. Rev. **134**, B349 (1964).

[34] S. Gorodetzky, R. M. Freeman, A. Gallmann, and F. Haas, Phys. Rev. **149**, 801 (1966).

TABLE II. Radiative widths and transition strengths for the decay of the Be^{10} $J^{\pi}=0^{+}$ 6.18-MeV level.

Transition (MeV)	Measured branching ratio (%)	Multi-polarity	$\Gamma\gamma$ (10^{-4} eV)	$\Gamma\gamma$(s.p.)[a] (10^{-4} eV)	Transition strength[a] (single-particle units)
6.18→5.96	4.6±1.5	$E1$	0.28±0.12	33.6	$(8.3\pm3.6)\times10^{-3}$
6.18→3.37	95±2	$E2$	5.7±1.7	1.9	3.1±0.9
6.18→0	0.24±0.08	$E0$	0.014±0.006	0.061	0.23

[a] For the E1 and E2 transitions the single-particle radiative widths and transition strengths are from the Weisskopf estimate. The single-particle unit for E0 transitions is discussed in the text and in Ref. 35.

The confrontation of the $E2$ transition rate from the 6.18-MeV state with our crude expectation invites an examination of the strength of the $E0$ transition connecting the $J^{\pi}=0^{+}$ interloper with the $J^{\pi}=0^{+}(1p)^{A-4}$ ground state. In Table II the transition strengths for the $E1$ and $E2$ decays are in Weisskopf units, while the $E0$ strength is expressed in a unit defined similarly to the Weisskopf unit as follows[35]: The unit is defined as that of a $2s\rightarrow1s$ transition in an infinite spherical square well. The size of the well is adjusted so that the matrix element M for such a transition approximates that to be expected for the dominant single-particle $E0$ transition in the range $A<100$ or so. This yields $|M|=0.65\times A^{2/3}$ F^2 as the single-particle unit. We may note that the nearby $E0$ transitions in C^{12}, C^{14}, O^{16}, and O^{18}, involving the interlopers at 7.65, 6.59, 6.05, and 3.63 MeV in the four nuclei, respectively, have strengths of roughly 2.7, <0.9, 0.9, and 0.7 such single-particle units. These strengths are somewhat greater than our present one of 0.23, again indicating that the mixing may be somewhat smaller here than, say, in C^{12}. We note that the $E0$ rates in the $T_z=0$ nuclei, C^{12} and O^{16}, are larger than those in the $T_z=1$ nuclei, Be^{10}, C^{14}, and O^{18}. This may reflect the fact that the valence particles are predominantly neutrons in these latter cases. That is, in so far as neutrons cannot contribute to the $E0$ transitions, we expect *a priori* the $E0$ rates to be smaller in these nuclei.

As was implied in the Introduction, it seems probable that a considerable fraction of the Be^{10} 6.18-MeV level wave function arises from $(1p)^4(2s,\ 1d)^2$, while the $J^{\pi}=1^{-}$ 5.96-MeV level arises mainly from $(1p)^5(2s,\ 1d)$. Assuming this is so, the $E1$ transition between these components is allowed, while the $E0$ and $E2$ decays to the $(1p)^6$ ground, and first-excited states are forbidden in first order, as has been assumed. We now consider this $E1$ decay. As a standard of comparison for the observed strength, we use the decay between the two hypothetical states $[Be^8{}_{g.s.}\times(2s_{1/2})^2]_{0^+,1}$ and $[Be^9{}_{g.s.}\times(2s_{1/2})]_{1^-,1}$ with $Be^9{}_{g.s.}=\alpha[Be^8{}_{g.s.}\times(p_{3/2})]_{3/2,1/2}$ plus other terms. The overlap factor α^2 we take to be 0.58, this value being taken from the (8-16)POT predictions of Cohen and Kurath.[32] We also assume an effective neutron charge of $-(4/10)e$ and a radial integral $\langle 2s_{1/2}|r|1p_{3/2}\rangle$ of -1.68 F. The resulting transition strength is 0.27 W.u. The observed strength of the 6.18→5.96 transition is smaller than this by a factor of 33; thus it appears that the wave functions of the two states are more complicated than the simple ones used in this calculation, which is certainly not surprising. The situation here is similar to that in C^{14}, where the $J^{\pi}=0^{+}$ interloper at 6.59 MeV decays mainly by an $E1$ transition to the $(1p)^9\ (2s,\ 1d)\ J^{\pi}=1^{-}$ state at 6.09 MeV. In this case the observed $E1$ strength is at least three times weaker than the strength predicted for a transition between $[C^{12}{}_{g.s.}\times(2s_{1/2})^2]_{0^+,1}$ state and a $[C^{12}{}_{g.s.}\times(1p_{1/2}2s_{1/2})]_{1^-,1}$ state.[36]

[35] D. H. Wilkinson, Nucl. Phys. **A133**, 1 (1969).

[36] D. E. Alburger, A. Gallmann, J. B. Nelson, J. T. Sample, and E. K. Warburton, Phys. Rev. **148**, 1050 (1966).