PHYSICAL REVIEW VOLUME 120, NUMBER 2 OCTOBER 15, 1960

$Be^9(\alpha,n)C^{12}$ Reaction and the Parameters of the 7.66-Mev State of C^{12}†

F. Ajzenberg-Selove
Haverford College, Haverford, Pennsylvania

AND

P. H. Stelson
Oak Ridge National Laboratory, Oak Ridge, Tennessee

(Received June 6, 1960)

The $Be^9(\alpha,n)C^{12}$ reaction has been studied at $\bar{E}_\alpha=5.6$ and 5.78 Mev. Neutron groups have been observed to the first three states of C^{12}. The ratio of the population of the 4.43- and 7.66-Mev states has been determined to be 8.1 ± 1 at $\bar{E}_\alpha=5.6$ Mev. This value, together with information from a number of other sources, demonstrates that the 7.66-Mev state has $J^\pi=0^+$, that its width for alpha emission is approximately the Wigner limit ($\Gamma\sim8$ ev) and that in $\sim10^{-3}\%$ of the cases the state decays to the ground state of C^{12} by pair emission. It is also estimated that the 7.66-Mev state can decay by γ emission via the 2^+, 4.43-Mev state with a probability of 1/5000. This information reinforces the proposal that the 7.66-Mev state has the necessary properties to participate in the buildup of the elements in red giant stars.

I. INTRODUCTION

It was proposed[1–3] several years ago that the $3\alpha\rightarrow C$ reaction plays a key role in energy generation and element synthesis in red giant stars. The surmise is that the fusion takes place as a resonance reaction via the 7.66-Mev state[4] of C^{12}. The reaction rate depends critically[3] both on the difference between the mass of C^{12} in its 7.66-Mev state and the mass of the $(Be^8+\alpha)$ system, and on the ways in which the 7.66-Mev state decays. Thus two questions are of extreme importance: (1) Can the 7.66-Mev state be formed as a resonance by $Be^8+\alpha$? (2) If it can be, does the state decay in any way other than by α emission, and to what extent do such alternate modes of decay occur? It is obvious that if the C^{12} excited state, once formed, never decays to the C^{12} ground state, it will be of no importance as a link in the buildup of the elements.

Because of the short life of the Be^8 ground state ($\sim10^{-16}$ sec), the question of the formation of the 7.66-Mev state may be determined more easily, on a terrestrial time scale, by studying $C^{12*}\rightarrow Be^8+\alpha$ and, through the principle of reversibility, applying the results to $Be^8+\alpha\rightarrow C^{12*}$. It has been clearly and elegantly demonstrated by Cook, Fowler, Lauritsen, and Lauritsen[5] that the 7.66-Mev state breaks up predominantly into three α particles, with $(Be^8+\alpha)$ as an intermediate stage in the process. The Q value of the breakup $C^{12*}\rightarrow Be^8+\alpha$ was determined to be 278 ± 4 kev. Although Cook *et al.* emphasized the likely 0^+ character of the 7.66-Mev state, the α decay by itself only indicated that the J^π of the state was either even-even or odd-odd.

If the 7.66-Mev state has $J^\pi=0^+$, then the only way in which it might decay directly to the 0^+ ground state of C^{12} would be by emission of $E0$ nuclear pairs. The state could also decay via an $E2$ cascade through the 2^+ first excited state of C^{12} at 4.43 Mev. The cascade decay of the 7.66-Mev state has not been observed: It occurs in $<0.1\%$ of the decays of the state.[6] The nuclear pairs have recently been observed by Alburger[7] by means of the $Be^9(\alpha,n)C^{12}$ reaction, using an intermediate-image spectrometer. He determined the ratio of the number of 7.7-Mev $E0$ pairs to the number of 4.4-Mev $E2$ pairs to be $(5\pm1.5)\times10^{-4}$. This number permits calculation of the ratio of the width of the 7.66-Mev level for pair emission to the total width of the state ($\Gamma_{e\pm}/\Gamma$) if one knows relatively how often the 7.66-Mev and the 4.43-Mev states were formed. That is,

$$\Gamma_{e\pm}/\Gamma=(5\pm1.5)\times10^{-4}\times\alpha\times E\times R, \qquad (1)$$

where $\alpha=1.3\times10^{-3}$ is the internal pair conversion coefficient of the 4.43-Mev transition[8]; $E=1.26$ is the $E2/E0$ pair-line efficiency; and $R=N_{4.43}/N_{7.66}$ is the ratio of the neutron population to the two levels. In order to determine $\Gamma_{e\pm}/\Gamma[=(8.2\pm2.5)\times10^{-7}\times R]$ it is therefore necessary to know R at the $\bar{E}_\alpha$ (~5.5 Mev) employed by Alburger in determining the pair ratio value of 5×10^{-4}.

At the time of Alburger's experiment very little was known about R. The only knowledge of the neutron population derived from an experiment by Guier, Bertini, and Roberts[9] at $E_\alpha=5.3$ Mev. They obtained $R\sim8$ (no error indicated) at 0°. Recently, McCallum[10]

---

† Work performed under the auspices of the National Science Foundation and the U. S. Atomic Energy Commission.

[1] E. J. Öpik, Proc. Roy. Irish Acad. A54, 49 (1951).

[2] E. E. Salpeter, Astrophys. J. **115**, 326 (1952).

[3] E. E. Salpeter, Phys. Rev. **107**, 516 (1957).

[4] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).

[5] C. W. Cook, W. A. Fowler, C. C. Lauritsen, and T. Lauritsen, Phys. Rev. **107**, 508 (1957). See this paper also for a complete summary of the pre-1957 information and conjectures on the 7.66-Mev state.

[6] R. W. Kavanagh, Bull. Am. Phys. Soc. **3**, 316 (1958); S. F. Eccles and D. Bodansky, Phys. Rev. **113**, 608 (1959).

[7] D. E. Alburger, Phys. Rev. **118**, 235 (1960).

[8] M. E. Rose, Phys. Rev. **76**, 678 (1949).

[9] W. H. Guier, H. W. Bertini, and J. H. Roberts, Phys. Rev. **85**, 426 (1952).

[10] G. J. McCallum (private communication).

determined $R(0°)$ at $E_\alpha=5.8$ Mev as <14, and Retz-Schmidt et al.[11] have measured the relative yields of the neutron groups in the range $E_\alpha=2$ to 5.6 Mev. We decided to accurately measure R, integrated over all angles, to permit calculation of $\Gamma_{e\pm}/\Gamma$ and from this to determine the decay characteristics of the 7.66-Mev state. The results are presented in this paper.

II. EXPERIMENTAL PROCEDURES AND RESULTS

A. The Exposure of the Plates

Beryllium targets were bombarded by (5.81 ± 0.01)-Mev α particles from one of the Oak Ridge Van de Graaff generators. Two targets were used. The "thin" target, target A, consisted of an evaporated layer of Be^9 on approximately 0.010-inch thick platinum. The target weight was (50 ± 5) micrograms/cm^2 but it was positioned at 45° to the α beam so that its effective thickness corresponded to an energy loss of $\sim$50 kev for the α particles. Thus the average α energy $(\bar{E}_\alpha)$ in the "target A" exposure was 5.78 Mev. The "thick" target, target B, was a Bradner foil[12] mounted on 0.008-inch thick platinum. The foil was one of the $\sim$0.1-mil foils used by Alburger.[7] It was positioned at 0° to the α beam. The weight of the foil corresponded to an energy loss of approximately 0.35 Mev for the α particles, and thus $\bar{E}_\alpha=5.6$ Mev for exposure B. In both cases, the total exposure, 1900 microcoulombs, was the same.

The emitted neutrons were detected by observing proton recoil tracks in Ilford C-2 nuclear emulsions, 400 microns thick, mounted at 10 angles (0° to 135°) to the incident α beam. The plates were processed and scanned in a standard manner.[13] A shorter background run was also carried out with plates exposed to neutrons from the α bombardment of the target backing, and from the room background.

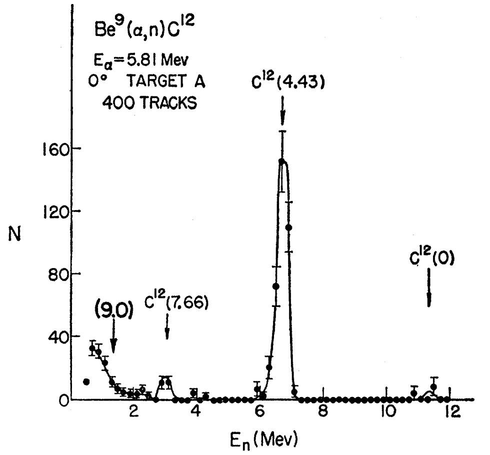

FIG. 1. Data at 0° (in the laboratory system) for $\bar{E}_\alpha=5.78$ Mev ("thin" target). N is the corrected number of neutrons per 200-kev interval. E_n is the neutron energy. The arrows label the states in C^{12} to which the neutron groups correspond.

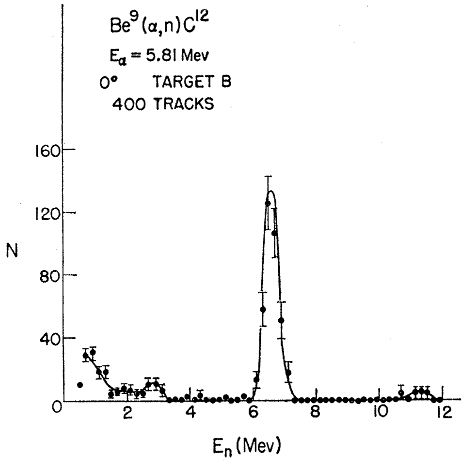

FIG. 2. Data at 0° for $\bar{E}_\alpha=5.6$ Mev ("thick" target). N is the corrected number of neutrons per 200-kev interval. E_n is the neutron energy.

B. The Data

A total of 4850 tracks was measured on plates exposed to neutrons from both the "thin" and the "thick" targets. Measurements were made at nine angles in each exposure. Typical spectra are shown in Figs. 1–5. It may be observed from Figs. 1 and 2, that the neutron groups observed in the "thick" target exposure (target B) are broader and shifted to lower energy by approximately 0.2 Mev relative to the "thin" target groups, as may indeed be expected. The calculated locations of known[4] states of C^{12} are shown on the target A spectra. The ground-state Q value for the $Be^9(\alpha,n)C^{12}$ reaction was taken to be 5.704 Mev.[14]

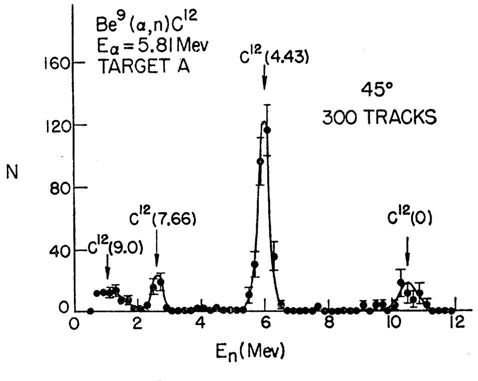

FIG. 3. The 45° data ($\bar{E}_\alpha=5.78$ Mev) (see also caption of Fig. 1)

---

[11] T. Retz-Schmidt, T. W. Bonner, G. U. Din, and J. L. Weil, Bull. Am. Phys. Soc. **5**, 110 (1960).

[12] The foil was kindly loaned to us by Dr. D. E. Alburger and Dr. R. E. Benenson.

[13] A. G. Rubin, F. Ajzenberg-Selove, and H. Mark, Phys. Rev. **104**, 727 (1956).

[14] F. Everling, L. A. König, J. H. E. Mattauch, and A. H. Wapstra, Nuclear Phys. **15**, 342 (1960).

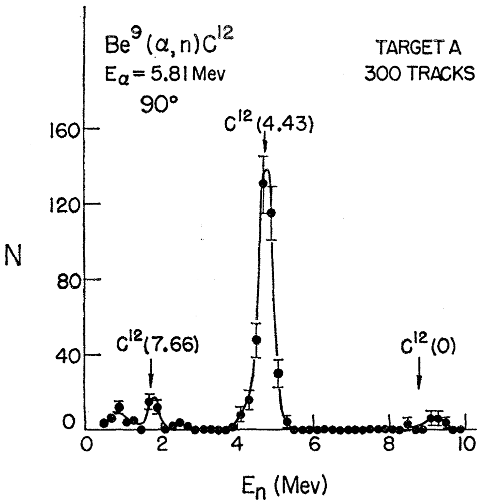

FIG. 4. The 90° data ($\bar{E}_\alpha = 5.78$ Mev) (see also caption of Fig. 1).

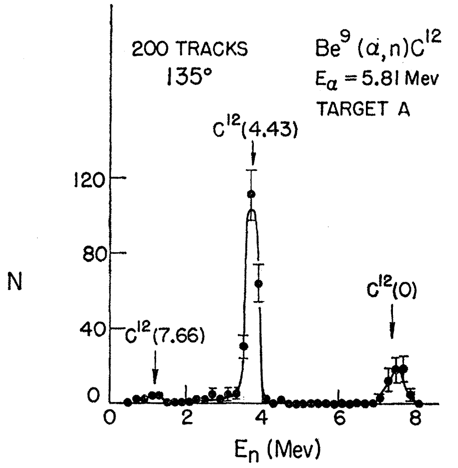

FIG. 5. The 135° data ($\bar{E}_\alpha = 5.78$ Mev) (see also caption of Fig. 1).

With varying intensities but appearing at all angles, neutrons with energies less than those of the 7.66-Mev state neutron groups are also observed. These are presumably due to one or more of the following reactions: $\mathrm{Be}^9(\alpha,n)3\mathrm{He}^4$ ($Q = -1.57$ Mev), $\mathrm{Be}^9(\alpha,n\alpha)\mathrm{Be}^8$ ($Q = -1.67$ Mev) or $\mathrm{Be}^9(\alpha,n)\mathrm{C}^{12}$ to the states at 9.0[15] and 9.63 Mev, and to the 2-Mev broad state at 10.1 Mev. These low-energy neutrons contribute a background of noise which leads to an average uncertainty of 8% in the assignment of neutrons to the 7.66-Mev groups.

Fortunately, no other background difficulties arise. The background plates showed that the room background was essentially nil. Neutrons from possible contamination of the target system or the target itself were not observed. The $\mathrm{C}^{12}(\alpha,n)\mathrm{O}^{15}$ reaction is highly endoergic. Computations were carried out on the locations of possible groups from the $\mathrm{C}^{13}(\alpha,n)\mathrm{O}^{16}$ reaction ($Q = 2.21$ Mev). No neutrons were observed at any angle from the reaction to the ground state of O^{16}. It is only at a few of the forward angles that neutrons from the 6- and 7-Mev states might have appeared, with very low energies. It is unlikely that the contribution of these states was appreciable. Another common contaminant is oxygen. Here again the Q value of the $\mathrm{O}^{16}(\alpha,n)\mathrm{Ne}^{19}$ reaction is prohibitively endoergic.

C. Experimental Results

The angular distributions in the center-of-mass system are shown in Figs. 6–9. The angular distributions are based on the following numbers of tracks: Ground

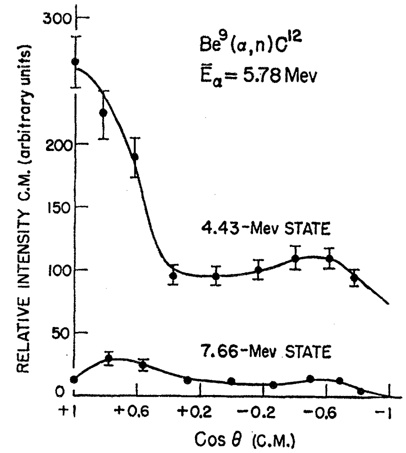

FIG. 6. Angular distributions of the neutrons to the 4.43-Mev and 7.66-Mev states of C^{12}, in the center-of-mass system, at $\bar{E}_\alpha = 5.78$ Mev. The intensity units are arbitrary but are the same as in Fig. 8.

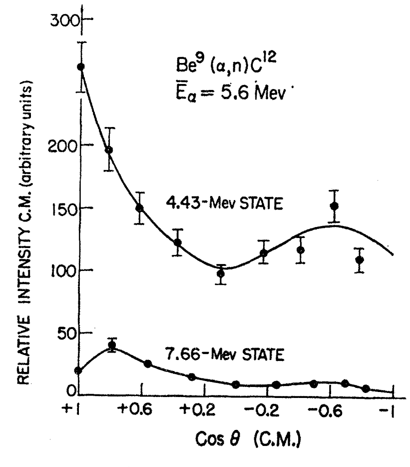

FIG. 7. Angular distributions of the neutrons to the 4.43- and 7.66-Mev states of C^{12}, in the center-of-mass system, at $\bar{E}_\alpha = 5.6$ Mev. The intensity units are arbitrary but are the same as in Fig. 9.

---

[15] D. E. Alburger and R. E. Pixley, Phys. Rev. 119, 1970 (1960). While, energetically, we should have been able to observe neutron groups to the new 9.0-Mev state, we did not observe the state. The intensities of the corresponding neutron groups appear to be very low.

state, 93 tracks (target *A*), 90 tracks (target *B*); 4.43-Mev state, 1394 tracks (target *A*), 1395 tracks (target *B*); 7.66-Mev state, 279 tracks (target *A*), 295 tracks (target *B*).

The differential cross section for formation of the 4.43-Mev state at $\bar{E}_\alpha=5.78$ Mev, and at 0°, was calculated to be 75 mb/sr. The number includes an estimate of the attenuation of the neutrons in the emulsion. The uncertainty in this cross section is estimated to be $\pm 25\%$. This is an rms estimate based on the following uncertainties: 5% in volume of emulsion scanned (chiefly because of uncertainty in knowing the original thickness of the emulsion), 15% in the target thickness, 5% in the incident number of α particles, 8% statistical error, and 10% error in estimating the attenuation. The "total" cross section for formation of the 4.43-Mev state is then ~560 mb. Making allowances for the formation of the other C^{12} states, the total cross section for the $Be^9(\alpha,n)C^{12}$ reaction at $E_\alpha=5.78$ Mev, determined from these data, is in satisfactory agreement with the very accurate value obtained by Gibbons and Macklin[16] at the same energy: $\sigma=600$ mb ($\pm 5\%$).

The ratios of the populations of the 7.66- and 4.43-Mev states, and of the 7.66-Mev and ground states, obtained directly from Figs. 6–9 (by measuring the areas underneath the solid curves) are shown in Table I. The errors quoted involve estimates of the differences in the attenuation of the neutrons of different energies in the emulsion, and, in the case of the 7.66-Mev state, include an estimate of the uncertainties in assigning tracks to the 7.66-Mev state groups because of the background plateau. In addition, of course, statistical errors are taken into account.

Angular distributions of the neutron groups to the ground state of C^{12} and to the 4.43-Mev state have been determined previously at a number of energies in the range $E_\alpha=2.0$ to 5.2 Mev by Risser et al.[17] The distributions obtained in the present experiment are similar in appearance to those reported by Risser et al. at $E_\alpha=5.1$ Mev. It is interesting to note the very similar intensities and angular distributions (Figs. 8 and 9) of the neutrons to the ground state and the 7.66-Mev state of C^{12}; both are characterized by a 0^+ assignment.

TABLE I. Ratios of the populations of the first three states of C^{12} in the $Be^9(\alpha,n)C^{12}$ reaction.

$\bar{E}_\alpha$ (Mev)	Ratios of integrated intensities of neutrons groups, *R*, to the following states: Ground state/7.66-Mev	4.43-Mev/7.66-Mev
5.6	1.0±0.2	8.1±1
5.78	1.2±0.2	8.6±1

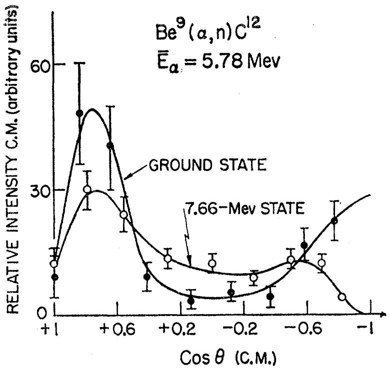

FIG. 8. Angular distributions of the neutrons to the ground and 7.66-Mev states of C^{12} in the center-of-mass system, at $\bar{E}_\alpha=5.78$ Mev (see also caption of Fig. 6).

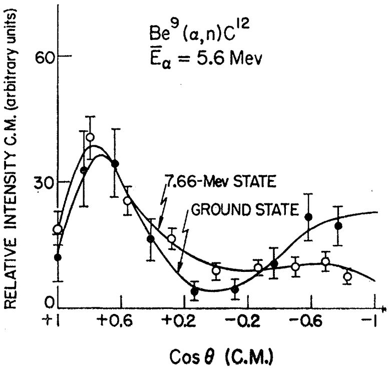

FIG. 9. Angular distributions of the neutrons to the ground and 7.66-Mev states of C^{12}, in the center-of-mass system, at $\bar{E}_\alpha=5.6$ Mev (see also caption of Fig. 7).

III. CONCLUSIONS

The average energy of the incident α particles in exposure *B* ($\bar{E}_\alpha=5.6$ Mev) was not precisely the same as that used by Alburger ($\bar{E}_\alpha=5.5$ Mev). *R* could not be determined by us at Alburger's energy because of difficulties in observing very low-energy proton recoil tracks (from the transition to the 7.66-Mev state). From a comparison of the *R* values at $\bar{E}_\alpha=5.78$ and 5.6 Mev, it appears that the *R*'s are the same at these two energies within the quoted errors. It is unlikely that *R* would change drastically over the next 0.1- or 0.2-Mev interval. Assuming then that $R=8.1\pm 1$,

$$\begin{aligned}\Gamma_{e\pm}/\Gamma &= (8.2\pm 2.5)\times 10^{-7}R\\ &= (6.6\pm 2.2)\times 10^{-6}.\end{aligned}\qquad (2)$$

$\Gamma_{e\pm}$ may be estimated[3,5] from the cross section of the $C^{12}(e,e')C^{12}$ reaction to the 7.66-Mev state, $\Gamma_{e\pm}\sim 5\times 10^{-5}$ ev;

$$\Gamma=\frac{\Gamma_{e\pm}}{(\Gamma_{e\pm}/\Gamma)}=\frac{5\times 10^{-5}}{(6.6\pm 2.2)\times 10^{-6}}=8\text{ ev.}\qquad (3)$$

This value of Γ is approximately the Wigner limit

---

[16] J. H. Gibbons and R. L. Macklin, Phys. Rev. **114**, 571 (1959).

[17] J. R. Risser, J. E. Price, and C. M. Class, Phys. Rev. **105**, 1288 (1957).

which, on the basis of a 0^+ assignment, is calculated[18] to be 7.5 ev. Ferrell[19] has calculated that the Γ_γ for the $7.66 \rightarrow 4.43$ ($0^+ \rightarrow 2^+$) transition is $\Gamma_\gamma = 0.0014$ ev (with an uncertainty of the order of a factor of two). Assuming this value of Γ_γ, one can calculate the percentage decay of the 7.66-Mev state by a γ cascade via the 4.43-Mev state:

$$\Gamma_\gamma/\Gamma = 0.0014/8 = 0.02\% \quad \text{(with an uncertainty of a factor of two).} \tag{4}$$

As has been mentioned earlier the best experimental upper limit[6] on this number is 0.1%. The 7.66-Mev state decays in $\sim 7 \times 10^{-4}\%$ of the cases [see (2)] by pair emission.

In summary, it is now clear from the width of the state and from its decay behavior that the 7.66-Mev state of C^{12} is a 0^+ state and that it can participate in the process of the buildup of the elements in red giant stars.

We are very much indebted to Dr. D. E. Alburger, to Leona Stewart and to Professor W. Selove and Professor W. A. Fowler for helpful discussions. We are also grateful to W. T. Newton for assisting us in the exposure of the plates and to B. J. Massey for preparing the thin beryllium target.

---

[18] W. A. Fowler and T. Lauritsen (private communication).

[19] R. A. Ferrell, private communication, quoted in Cook et al., see reference 5.

PHYSICAL REVIEW VOLUME 120, NUMBER 2 OCTOBER 15, 1960

Shell Model and Pb^{208}†

J. C. CARTER,* WILLIAM T. PINKSTON,‡ AND WILLIAM W. TRUE
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received May 23, 1960)

The lowest odd-parity excited energy levels of Pb^{208} have been calculated by a shell-model approach considering a single proton or a single neutron to be excited out of the Pb^{208} core. Both a singlet-even plus triplet-even force and a Rosenfeld force were used as the two-particle interaction. A zero-range force was also considered. There were no other arbitrary parameters. The results with the various forces indicate that it is impossible to get a 3− state low enough to be interpretated as the observed 2.615-Mev 3− level. The results, therefore, support the conclusion that the 3− level at 2.615 Mev in Pb^{208} is primarily the result of a collective octupole oscillation.

I. INTRODUCTION

RECENTLY there has been renewed interest in the low excited states of Pb^{208}. Several people have contributed to the position and spins of the experimentally determined levels.[1–3] Tauber[4] has tried to fit the excited states of Pb^{208} theoretically from a shell-model approach. He had difficulty in drawing any conclusions due to too many undetermined parameters. Tamura and Choudhury[5] have assumed shell-model configurations to explain some of the results of Cohen et al.[3] on the inelastic scattering of particles by heavy elements. They conclude that a collective octupole oscillation can affect their results for Pb^{208}. Lane and Pendlebury[6] have recently done some calculations which support the idea of C. Levinson that the first excited state of Pb^{208}, a 3− level at 2.615 Mev, is a surface vibration of the octupole type.

In the present paper, we calculate the energy spectrum of the lowest odd-parity energy levels of Pb^{208} according to the jj-coupling shell model with configuration mixing. The jj-coupling states included in our study are all those which can arise from promoting a $p_{1/2}$ or $f_{5/2}$ neutron into the $g_{9/2}$ or $i_{11/2}$ shell and from promoting an $s_{1/2}$ or $d_{3/2}$ proton into the $h_{9/2}$ or $f_{7/2}$ shell. The absolute positions of these jj configurations are obtained from empirical data; thus, the only arbitrary parameters in the calculation are those of the two-body potential between particles and of the nucleon radial wave functions. It is reasonable to take for these parameters values which have worked well in the past in theoretical calculations on nuclei in this mass region.[7–10]

[†] This work was supported in part by the U. S. Atomic Energy Commission and the Higgins Scientific Trust Fund.

[*] Now at Hans Sentmoring, Munster, Wesphalia, Germany.

[‡] Now at the Physics Department, Vanderbilt University, Nashville, Tennessee.

[1] L. G. Elliott, R. L. Graham, J. Walker, and J. L. Wolfson, Phys. Rev. **93**, 356 (1954).

[2] J. A. Harvey, Can. J. Phys. **31**, 278 (1953).

[3] B. L. Cohen and A. G. Rubin, Phys. Rev. **111**, 1568 (1958); B. L. Cohen and S. W. Mosko, Phys. Rev. **106**, 995 (1957); B. L. Cohen, Phys. Rev. **105**, 1549 (1957).

[4] G. E. Tauber, Phys. Rev. **99**, 176 (1955).

[5] T. Tamura and D. C. Choudhury, Phys. Rev. **113**, 552 (1959).

[6] A. M. Lane and E. D. Pendlebury, Nuclear Phys. **15**, 39 (1960).

[7] W. W. True and K. W. Ford, Phys. Rev. **109**, 1675 (1958).

[8] M. H. L. Pryce, Proc. Phys. Soc. (London) **A65**, 773 (1952).

[9] M. J. Kearsley, Phys. Rev. **106**, 389 (1957); Nuclear Phys. 4, 157 (1957).

[10] N. Newby and E. J. Konopinski, Phys. Rev. **115**, 434 (1959).