Lowest negative parity state of ^{8}Be

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(Received 16 April 1979)

Shell model and multichannel cluster model calculations yield different predictions for the lowest negative parity state of ^{8}Be. Several shell model calculations predict a 1^- state below about 18.5 MeV which has the same quantum numbers as an α-α^* cluster state near 22 MeV. The experimental situation pertaining to this problem is examined.

[NUCLEAR STRUCTURE ^{8}Be structure, ^{7}Li$(p,p)^7$Li phase shifts.]

I. INTRODUCTION

Several years ago, Brown *et al.*[1] reported the results of a phase shift analysis of elastic scattering cross section and analyzing power data for protons on ^{7}Li. The analysis covered the energy range from 0.4 to 2.5 MeV. Two sets of phase shift solutions were found in the energy range below 2.2 MeV; they differ approximately by a sign change in the $^3S_1$ phase that is compensated by small changes in the magnitude of this phase and the other active phases. Only one of these two sets was reported in detail in Ref. 1. The purpose of this paper is to reexamine the phase shift analysis and to discuss the results for the 1^- partial wave in light of new information on the spectroscopy of ^{8}Be.

II. SPECTROSCOPY

The motivation for this paper is evidence which indicates that there may be a 1^- state in ^{8}Be lower in energy than the well-known 2^- state at 1.88 MeV proton energy (E_x = 18.91 MeV). This 2^- state has been considered to be the lowest non-normal parity state of ^{8}Be on the basis of numerous experimental studies[2] which have revealed the structure shown in Fig. 1. In a recent study of the ^{7}Li$(p,\gamma)^8$Be reaction with polarized protons, Ulbricht *et al.*[3] suggest the possibility of a 1^- state at 0.5 MeV proton energy (E_x= 17.7 MeV) with a width of about 180 keV. However, as noted by one of us,[4] and also by Barker,[5] the expression for the analyzing power quoted in Ref. 3 is incorrect.[6] Moreover, the existing cross section data for ^{7}Li$(p,\gamma)^8$Be, while suggesting the presence of enhanced $E1$ radiation, seem to be inadequate for the purpose of a definitive analysis with the correct analyzing power expression. The state suggested by Ulbricht *et al.* is a viable possibility nevertheless.

Shell model studies of the non-normal parity states of the A = 8 nuclei provide a striking counterpoint to the experimental studies. In the first of such studies, Aswad *et al.*[7] predicted a 1^- T = 0 state 0.9 MeV below the 2^- state. Their result has been confirmed by Kurath[8] and by Darema-Rogers[9] who find the lowest 1^- state of ^{8}Be to be several MeV below the 2^- state. Different residual interactions have been used in each of these calculations; they have been applied to the study of non-normal parity states throughout the $1p$ shell with good results. The predicted T = 0 state would be

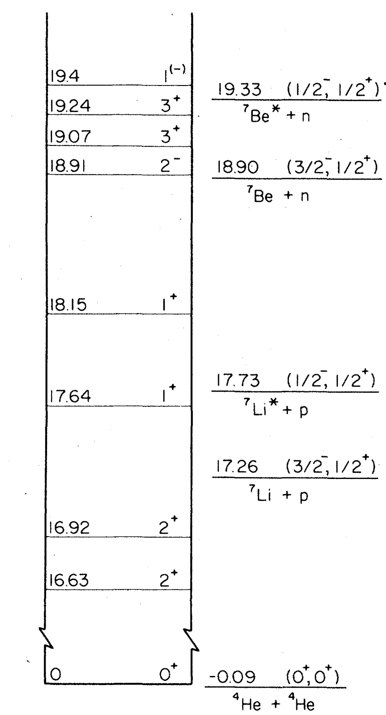

FIG. 1. Energy levels of ^{8}Be between 16.0 and 19.5 MeV excitation and thresholds for particle emission channels. The positive parity levels are isospin mixed pairs of T = 0 and T = 1 levels.

observable in the $^7Li(p,\gamma)^8Be$ reaction on the basis of isospin mixing with the $S=0$, $T=1$ giant dipole resonance at 21.6 MeV. The 1^- $T=0$ shell model state predicted to be below the 2^- state is also predominantly $S=0$.[9]

In contrast to the shell model studies, a multichannel cluster model calculation by Stöwe and Zahn[10] predicts a 2^- assignment for the lowest negative parity state of ^8Be; a 1^- state and a 0^- state are predicted to be about 1 MeV above the 2^-. The shell model calculations also predict a 1^- and a 0^- state about 1 MeV higher than the 2^- shell model state. These three states $(2^-, 1^-, 0^-)$ may be identified schematically with $S=1$, $T=0$ states from the shell model configurations $(1s)^3(1p)^5$ and $(1s)^4(1p)^3(2s)$. It seems likely that the $1^- S=0$, $T=0$ state, automatically included in the shell model calculations, is absent from the cluster model calculations due to truncation of the number of cluster channels. The possibility is realized as follows: The cluster channels included in the Stöwe and Zahn calculation are $^4He+^4He$, ^7Li+p, $^7Li^*+p$, ^7Be+n, $^7Be^*+n$, and ^6Li+d; the $^4He+^4He^*(0^+, 20$ MeV) cluster channel is omitted from this calculation. A cluster model calculation by Hackenbroich *et al.*[11] which includes only the $^4He+^4He$ and $^4He+^4He^*$ clusters predicts a 1^- $S=0$, $T=0$ state near 22 MeV excitation energy in ^8Be. This 1^- state must be formed from the $^4He+^4He^*$ cluster omitted from the Stöwe-Zahn calculation since a 1^- state cannot be formed from the $^4He+^4He$ cluster. The lowest $1^- S=0$, $T=0$ cluster model state can be identified on the basis of quantum numbers with the shell model state predicted to be below 18.9 MeV. Coupling to the nucleon channels could alter the excitation energy of the cluster model state. Stöwe and Zahn[10] have indicated that the coupling is weak, but this point should be reexamined in light of the shell model studies[7-9] which indicate a 4–6 MeV energy downward shift from the 22 MeV uncoupled excitation energy of the 1^- $S=0$, $T=0$ cluster model state.

The preceding remarks about the shell and cluster models suggest that some importance can be attached to identifying a 1^- $S=0$, $T=0$ state in the spectrum of ^8Be. The results of studies with the $^7Li(p,\alpha)\alpha^*$, $^6Li(d,\alpha)\alpha^*$, and $^2H(^6Li,\alpha)\alpha^*$ reactions have been reported recently.[12,13] While evidence for negative parity compound nucleus structure above 20 MeV excitation has been observed in these studies, no definite statements have been made which relate this structure to the 1^- cluster state.[14] The experimental situation is much simpler at lower energies. There have been numerous studies of reactions leading to final state of ^8Be in the 16–19 MeV range of excitation energies.[2] The motivation for most of these studies has been an understanding of the isospin structure of the positive parity states shown in Fig. 1. However, Piluso *et al.*[15] have looked for other states and have found no evidence for additional states below 18 MeV that might be expected on the basis of systematics. This study, among others, appears to rule out the possibility that a 1^- state could be below the 17.26 MeV ^7Li+p threshold or at an energy just above threshold where the decay of a 1^- state by S-wave proton emission would be hindered by the Coulomb barrier. It is only for energies appreciably above threshold that the possibility of identifying an S-wave emitting state diminishes for these reactions. For example, the 2^- state at 18.91 MeV is obscured by background in the $^{10}B(d,\alpha)^8Be$ reaction. In contrast, this state shows up strongly in the $^7Li(p,p)^7Li$ phase shift analysis[1] and in the $^7Li(p,n)^7Be$ reaction owing to its proximity to the ^7Be+n threshold.[16] Elastic scattering of protons on ^7Li and nucleon induced reactions may afford the best possibility of locating a 1^- state in ^8Be for the energy range above 17.4 MeV. In the regard, Barker[17] has noted that the ambiguity of two $^3S_1$ phase shift solutions reported in Ref. 1 might be obscuring a 1^- state of the type predicted by Aswad *et al.*[7]

In the $^7Li(p,p)^7Li$ phase shift analysis reported previously,[1] we determined the phase shifts over the 17.6 to 19.5 MeV range of excitation in ^8Be from an analysis of elastic scattering cross section and analyzing power data. Total cross sections for the reactions $^7Li(p,p')^7Li^*$, $^7Li(p,\alpha)^4He$, and $^7Li(p,n)^7Be$ were used as a constraint on the imaginary parts of the phase shifts where this was possible. At the lower energies, the phase shift analysis was supplemented with an effective range analysis[18] of the cross section data. We found that the two sets of phase shifts obtained from the phase shift analysis could not be eliminated by the more restrictive effective range analysis. The origin of these two sets is discussed in the Appendix.

At the higher energies, the phase shift analysis was terminated because the number of active phases became too large to obtain meaningful results from the available data. Some evidence was obtained for a 1^- state near or above 19.4 MeV, but multiple minima in the chi-squared surface did not allow confirmation of the 1^- state reported[19] at this energy. The pronounced threshold behavior of the $^7Li(n,n')^7Li^*$ and $^7Li(p,n')^7Be^*$ reactions is rather strong evidence for at least one 1^- state above 19.3 MeV. Both shell model[7-9] and multichannel cluster model[10] calculations predict two 1^- states between 19.3 and 21 MeV excitation; the cluster model calculations show that these states have a pronounced effect on the threshold behavior of the $^7Li(n,n')^7Li^*$ and $^7Li(p,n')^7Be^*$ reactions even though they may be somewhat higher in energy than 19.4 MeV. Recently, Fisher *et al.*[20] have questioned the parity assignment of the 19.4 MeV state and have noted that shell model calculations[21,22] of the positive parity states predict a 1^+ state near this energy. This possibility cannot be ruled out by the phase shift analysis of Ref. 1. In fact, the presence of a 1^+ state, one or more 1^- states, and other states predicted by shell model calculations to be in the energy range from 19.4 to 21 MeV, as well as known levels in this energy range[2] could account for the difficulties we encountered in attempting to extend the phase shift analysis above 2.5 MeV proton energy. There are just too many levels between 19.4 and 21 MeV for an elastic scattering phase shift analysis to be fruitful. The results of Fisher *et al.*[20] on the parity of the 19.4 MeV state do not appear to be in conflict with previous work[19] which has revealed the presence of a broad 1^- state above the ^{7}Be* $+n$ threshold; both 1^+ and 1^- states appear to be necessary for an understanding of all available data.

The lowest negative parity state of ^{8}Be obtained from the phase shift analysis is the well-known 2^- state at the 18.9 MeV ^{7}Li$(p,n)^7$Be threshold. For energies near this threshold the phase shift analysis was supplemented with a multichannel scattering length analysis[16] of cross section data for the various open reaction channels. We found that the 2^- S-wave phase shift is compatible with this data. The behavior of the ^{7}Li$(p,n)^7$Be cross section rises rapidly from threshold and within 100 keV approaches the unitary limit for a 2^- state.[23] There is not much tolerance for an additional contribution to the cross section from a 1^- state in the vicinity of this threshold. In addition, the ^{7}Be$(n,p')^7$Li* cross section for thermal neutrons[24] is smaller than the ^{7}Be$(n,p)^7$Li cross section by a factor of 50. An anomaly observed[23] in the ^{7}Li$(p,p')^7$Li* reaction at the (p,n) threshold, while pronounced, is also small in magnitude. These small effects are consistent with a 2^- state and a D-wave proton coupled to ^{7}Li*.

Experimental information on the nucleon channels indicates that there are no 1^- states in ^{8}Be between about 18.5 and 19.3 MeV excitation. A 1^- state above 19.3 MeV appears to be required by the threshold behavior of the ^{7}Li$(n,n')^7$Li and ^{7}Li$(p,n')^7$Be* reactions and is consistent with both shell model and multichannel cluster model calculations. Numerous studies of reactions which populate final states of ^{8}Be between 14.5 and 19 MeV appear to rule out a 1^- state below about 17.4 MeV. This leaves a rather small range of energies from 17.4 to 18.5 MeV where there is insufficient information to eliminate the possibility of a 1^- state. It is worth noting that the 1^- state suggested by Ulbricht *et al.*[3] occurs at 17.7 MeV, roughly in the middle of this range of energies. In the following section we reexamine the ^{7}Li$(p,p)^7$Li phase shift analysis to see if a 1^- state is present in this energy range.

III. ^{7}Li$(p,p)^7$Li PHASE SHIFT ANALYSIS

In our previous phase shift analysis[1] three partial waves were found to be important in the region from 0.4 to 1.4 MeV proton energy (17.6 to 18.5 MeV excitation). These are the two S waves $^5S_2$ and $^3S_1$ and the 1^+ partial wave which consists of $^5P_1$ and $^3P_1$ phase shifts and a mixing parameter. Other P-wave phase shifts, D- wave phase shifts, and S-D mixing parameters did not respond to the data in any significant manner. The S-wave phase shifts are important throughout the region while the 1^+ partial wave contributes in the vicinity of the 17.64 and 18.15 MeV resonances. Further, the 1^+ partial wave parameters obtained from the analysis correspond to these resonances being nearly pure $p_{1/2}$ states in the j-j coupling representation. The $p_{1/2}$ character of the 17.64 MeV resonance was first noted by Christy.[25] The $p_{1/2}$ character of the 18.15 MeV resonance can be inferred from shell model considerations[26]: The $(1p_{3/2})^4$ shell model configuration does not contribute to an isospin zero 1^+ state. Thus, the ^{7}Li$(p,p)^7$Li data are well described by three phase shifts in the energy range of interest.

Since the purpose of this reexamination of the ^{7}Li$(p,p)^7$Li phase shifts is to determine the possible presence of a 1^- state, we did not attempt a better fit to the data than was given in Ref. 1. Rather, we modified the analysis of Ref. 1 to see if it is possible to put upper and lower limits on the values of the $^3S_1$ phase shift in the energy range of interest. Exploratory calculations revealed that the 5% uncertainty in the absolute normalization of the cross section data is unimportant for the purpose of determining these limits. In addition, the effect of a modest $p_{3/2}$ contribution in the 1^+ partial wave was found to be small. The data set used in this analysis consists of the cross section data of Warters *et al.*[27] as modified according to Ref. 1 and the analyzing power data of Brown *et al.*[1] Since the cross section data is much more extensive than the analyzing power data, the calculations were done with the cross section data alone, with the analyzing power data used as a check. Somewhat tighter limits on the value of the $^3S_1$ phase shift could be obtained at those energies where both cross section and analyzing power data exist. However, the limits given below for the cross section data alone are adequate for the purposes of this work.

The procedure used to determine limits on the $^3S_1$ phase shift is as follows. Angular distributions

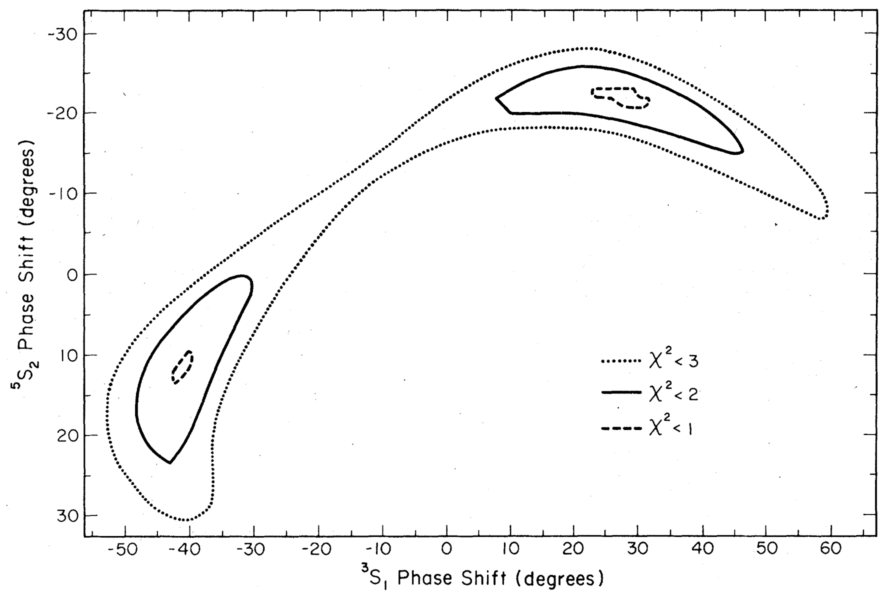

FIG. 2. Chi-square contour plot as a function of the $^5S_2$ and $^3S_1$ phase shifts for 1.0 MeV proton energy and a $p_{1/2}$ phase shift value of 15°.

of cross section data were constructed from the excitation functions of Warters *et al.*[27] for a number of energies in the range from 0.4 to 1.4 MeV proton energy. At each energy the value of the $p_{1/2}$ phase shift was varied from 0° to 180° in 5° steps. A chi-square contour plot showing the goodness of fit to the cross section data as a function of the $^5S_2$ and $^3S_1$ phase shifts was constructed for each step. The sequence of contour plots for all steps was then examined to determine the maximum and minimum values of these phase shifts at a given energy independent of the value of the $p_{1/2}$ phase shift. These maxima and minima represent limits on the $^5S_2$ and $^3S_1$ phase shifts allowed by the data for a specified goodness of fit. The form of the contour plots obtained in this analysis is such that all phase shift values between the maxima and minima are permissible, although values near the maxima and minima appear to be most reasonable.

A typical contour plot is shown in Fig. 2. The plot shows two distinct minima in the chi-square surface which correspond to the two sets of phase shifts mentioned in Ref. 1. The origin of these two sets is discussed in the Appendix. The two chi-square minima become an elongated valley as the chi-square parameter is increased. Within this valley the size and shape of the two minima, as well as the width of the neck connecting them, are somewhat sensitive to the cross section normalization. However, the extremal values of the phase shifts in the upper right and lower left corners of the plot are insensitive to either the normalization or the neglect of a $p_{3/2}$ contribution in the 1^+ partial wave. Note that the phase shift values in each of the two chi-square minima are close to the extremal values. The S-wave phase shifts for the lower left chi-square minimum are such that the $^5S_2$ phase shift is positive while the $^3S_1$ is negative. This minimum corresponds to the preferred phase shift set in Ref. 1. For the upper right chi-square minimum the $^3S_1$ phase shift is positive; the $^5S_2$ phase shift is negative at the lower energies, but turns positive as the energy is increased above 1 MeV. The 2^- state at the $^7Li(p,n)^7Be$ threshold (1.89 MeV) is responsible for this behavior.

The upper and lower limits for the $^5S_2$ phase shift are shown in Fig. 3. A chi-square parameter val-

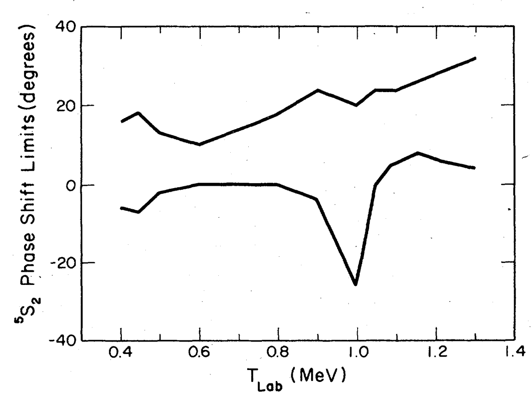

FIG. 3. Uncorrelated maximum and minimum values of the $^5S_2$ phase shift between 0.4 and 1.3 MeV proton energy for a chi-square parameter value of 1.2. Allowed values of this phase shift fall between the two curves.

ue of 1.2 was chosen as a criterion for determining these limits. The effect of relaxing this criterion can be gauged from Fig. 2. The limits are uncorrelated in the sense that they are independent of the value of the $p_{1/2}$ phase shift at each energy. As noted above, the permissible values of the $^5S_2$ phase shift fall between these curves although there is a definite preference for values just below the maximum or just above the minimum; the contour plot in Fig. 2 indicates the degree of preference. The curve for the lower limit of the $^5S_2$ phase shift has a pronounced downward excursion in the vicinity of the 1^+ resonance at 1 MeV. This dip is due to the inclusion of all values of the $p_{1/2}$ phase shift in determining the limit. The $p_{1/2}$ phase shift values corresponding to the dip are small, whereas the value of this phase shift in the vicinity of the 1^+ resonance is likely to be in the neighborhood of 90°. The downward excursion at 1 MeV represents an adjustment of the $^5S_2$ and $^3S_1$ phase shifts to describe the resonant features of the cross section data associated with the 1^+ resonance. Note that the curve for the upper limit of the $^5S_2$ phase shift is not affected by the 1^+ resonance at 1 MeV. This distinction between the two curves for the upper and lower limits, which carries over to the values of the $^5S_2$ phase shift at the chi-square minima, is the basis for the choice made in Brown *et al.*[1] for a preferred phase shift set.

Upper and lower limits for the $^3S_1$ phase shift are shown in Fig. 4. The preceding remarks for the

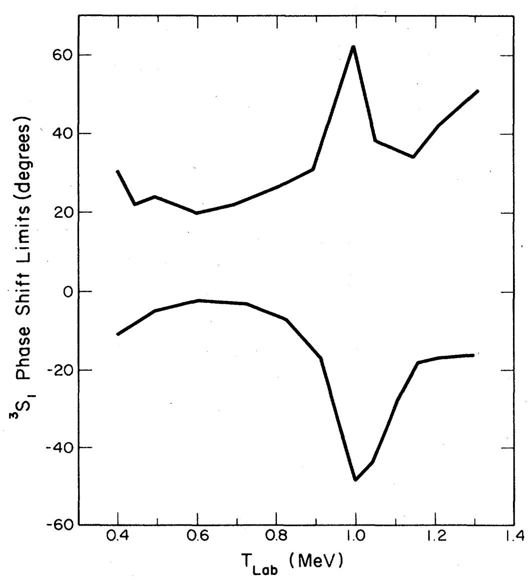

FIG. 4. Uncorrelated maximum and minimum values of the $^3S_1$ phase shift between 0.4 and 1.3 MeV proton energy for a chi-square parameter value pf 1.2. Allowed values of this phase shift fall between the two curves.

$^5S_2$ phase shift also apply here, except that both limits show excursions in the vicinity of the 1^+ resonance at 1 MeV. In addition, the limits for the $^5S_2$ and $^3S_1$ phase shifts are correlated. The lower limit for the $^3S_1$ phase shift corresponds to the upper limit for the $^5S_2$ phase shift and vice versa. The upper limit for the $^3S_1$ phase shift shows a general tendency to increase from about 20° to about 60° in the interval from 0.4 to 1.4 MeV. The lower limit, which corresponds roughly to the preferred solution of Ref. 1, decreases from −5° to −20° in the same interval. The permissible values of the $^3S_1$ phase shift fall between the curves shown in Fig. 4. Note that $^3S_1$ phase shift values between 60° and 120°(−60°) are excluded by the cross section data at all energies in the range from 0.4 to 1.4 MeV. If the excursions in the limits at 1 MeV are eliminated, the region of excluded $^3S_1$ phase shift values extends from 60° to 160° at 1.4 MeV and is larger at lower energies. The range of $^3S_1$ phase shifts allowed by the cross section data shows no obvious tendency to exhibit resonant behavior.

In the next section, we examine the possibility that there is a 1^- state between 0.4 and 1.4 MeV which results in a phase shift that is compatible with the limits shown in Fig. 4. We summarize this section by repeating the restrictions associated with this analysis. First, we have neglected a $p_{3/2}$ contribution in the 1^+ partial wave. Exploratory calculations revealed this to be a small effect. We have neglected all other partial waves on the basis of the analysis in Ref. 1. We have also neglected inelasticity associated with the ^{7}Li$(p,p')^7$Li* channel. These effects were shown to be small in Ref. 1. However, we have attempted to compenstate for these omissions by considering the cross section data only. Inclusion of the analyzing power data results in somewhat tighter limits than the ones shown in Figs. 3 and 4.

IV. RESONANT PHASE SHIFTS

There are several aspects of resonant phase shift behavior which need to be considered in determining whether the limits on the $^3S_1$ phase shift are compatible with a resonance. In this section we consider the situation for a single-particle resonance first, then generalize these results to include the influence of coupling to other channels.

Tombrello[28] has proposed a simplified single-particle model of the positive parity states of ^{8}Be between 16.5 and 18.5 MeV. In this model these states are assumed to be nucleon plus core configurations where the interaction between the nucleon and core is taken to be a Woods-Saxon potential. The model has been extended to the $^3S_1$ and $^5S_2$ partial waves for ^{8}Li.[29] It is a particularly convenient model for S-wave single-particle resonances where the absence of an angular momentum barrier results in a severe distortion of the typical picture of a resonant phase shift.[30] The model is relevant in the present context because Aswad *et al.*[7] find that the lowest shell model 1^- state is dominated by nucleon plus core configurations with the $2s$ particle plus ground state core being most prominent.

A Woods-Saxon potential with radius 2.95 F and diffuseness 0.52 F was used in Refs. 28 and 29, and the Coulomb potential was determined from a uniform charge distribution of the same radius as the Woods-Saxon potential. These parameters are retained in the present work. The strength of the Woods-Saxon potential for the positive parity states was obtained by fitting the observed energies of the 1^+ and 2^+ states shown in Fig. 1. Strengths ranging from 28 to 34 MeV were required. Somewhat smaller strengths, say 26 MeV, would be needed to describe the 3^+ states in this model. Thus a relatively small range of values for the strength parameter in the vicinity of 30 MeV is adequate to describe the positive parity states of ^{8}Be between 16.5 and 19.5 MeV. The behavior of the scattering length as a function of the potential strength reveals that the ^{7}Li + n scattering lengths require values near 40 MeV.

Potential model S-wave phase shifts for protons on ^{7}Li are shown in Fig. 5. Starting from the bottom of the figure, the phase shift at each energy increases as the strength of the Woods-Saxon potential is increased from zero. The energy dependence of the phase shift begins to show features of a single-particle resonance at a strength of about 9 MeV. These resonant features become more pronounced between 10 and 12 MeV as the energy of the resonance decreases toward threshold and its width becomes smaller. The resonance becomes a bound state at a strength of about 12 MeV. This bound state corresponds to a $1s$ single-particle configuration. The analogous situation for a $2s$ single-particle configuration occurs for a range of strengths between 54 and 57 MeV. Thus, within the framework of the potential model, potential strengths in the neighborhood of 55 MeV are required in order to have a $2s$ single-particle resonance. This feature is similar to Tombrello's results in that a relatively small range of potential strengths is needed to describe resonances for a given partial wave in the 16.5 to 19.5 MeV region of ^{8}Be excitation; it is similar to Aurdal's results in that the magnitude of the potential strength needed to put a $2s$ single-particle resonance in this energy range is nearly a factor of 2 larger than the strength needed for a $1p$ resonance. Another feature of the $2s$ single-particle resonance is that it is very broad for resonance energies more than 400 keV from threshold. A $2s$ single-particle

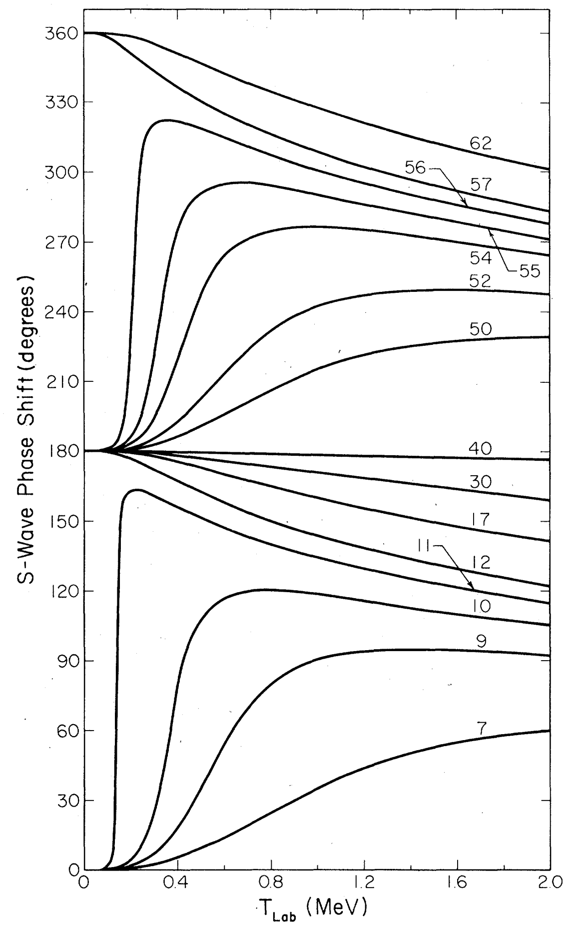

FIG. 5. Proton single-particle S-wave phase shift for a Woods-Saxon potential of strength as indicated and geometrical parameters from Ref. 28. Potential strength in the range from 30 to 40 MeV gives a good account of the positive parity states of ^{8}Be between 16.5 and 19.5 MeV.

resonance which has the characteristics of a typical resonance, where the phase shift changes from near 0° to near 180° in a small energy interval, is confined to a region between threshold and about 400 keV.

The potential model S-wave phase shifts in Fig. 5 show that there is a large range of potential strengths from about 12 to 52 MeV where the phase shift does not exhibit resonance behavior. This range includes the region of 30 MeV potential strength for $1p$ single-particle resonances in ^{8}Be and of 40 MeV for the ^{7}Li + n scattering lengths. Note that the 1^- phase shift limits given in the previous section correspond roughly to this 12 to 52 MeV range of potential strengths and that the 1^- phase shift preferred in Ref. 1 corresponds to a strength in the neighborhood of 30–40 MeV. A basic feature of the range of potential strengths between 12 and 52 MeV is that a rather large change in the potential strength yields a small change in the S-wave phase shift. As a result, rather substantial changes in the average potential determined from Tombrello's study of the P-wave single-particle configuration have a very small effect on the S-wave phase shift behavior.

An extension of the single-particle description given above to include coupling to other channels requires an elaborate coupled channel computation such as Ref. 10 for a detailed analysis. However, qualitative features associated with this coupling can be seen from a much simpler analysis based on R-matrix theory. The R-matrix formula for a single level is appropriate for this extension since coupling to other channels such as the ^{7}Be$+n$ channel appears to be a more important perturbation of the ^{7}Li$+p$ single-particle model than the presence of additional 1^- states higher in energy. The single level formula for the elastic S-matrix element in channel c is

$$S_{cc}=e^{2i\delta_c^b}\left\{1+2iP_c\gamma_c{}^2\Big/\left[E_0-E-\sum_{c'}(S_{c'}-B_{c'}+iP_{c'})\gamma_{c'}{}^2\right]\right\}, \qquad (1)$$

where the notation of Ref. 17 is followed. In this expression, δ_c^b is the background phase shift, P_c is the penetration factor, γ_c is the reduced width amplitude, E_0 is the resonance energy, S_c is the shift function, and $B_c=S_c(E_0)$ by choice.

If coupling to channels other than ^{7}Li$+p$ S-wave channel is neglected, the phase shift in this channel obtained from Eq. (1) is given by

$$\delta_p=\delta_p^b+\tan^{-1}[P_p\gamma_p{}^2/(E_0-S_c+B_c-E)]\,. \qquad (2)$$

The potential model phase shifts shown in Fig. 5 may be parametrized in this form using conventional formulas for P_p, S_p, and δ_p^b, a nominal single-particle value for $\gamma_p{}^2$, and a suitable choice for E_0. The value of E_0 for a given potential strength depends on the background phase shift through the condition $\delta_p(E_0)-\delta_p^b(E_0)=\pi/2$. Some results using Coulomb hard sphere background phase shifts for selected values of the hard sphere radius are given in Table I. The phase shift shown in Fig. 5 for a 52 MeV potential strength is consistent with a resonance energy as low as 1.06 MeV if a hard sphere radius of 5.22 F is used to calculate the background phase shift. The potential model phase shift at 1.4 MeV for this potential strength is 69°, somewhat higher than the upper limit of 60° obtained in the previous section for the $^3S_1$ phase shift. A 50 MeV potential strength is uniformly compatible with the upper limit on the $^3S_1$ phase shift shown in Fig. 4 over the energy range from 0.4 to 1.4 MeV. This yields a resonance energy of 1.64 MeV for the same hard sphere radius. A nominal value of the hard sphere radius, $R_c=1.45(7^{1/3}+1^{1/3})=4.22$ F, results in $E_0=2.11$ MeV for the 50 MeV potential strength. These results show that the energy E_0 for a single level, single channel R-matrix formula that yields a phase shift compatible with the upper limit on the $^3S_1$ phase shift lies above 1.4 MeV.

TABLE I. R-matrix resonance energies corresponding to the potential model described in the text for selected values of the potential strength and background phase shift hard sphere radius.

V_0 (MeV)	R_c (F) = / δ_p(1.4 MeV) (deg)	3.22	4.22 $E_0(R_c)$ (MeV)	5.22
50	45°	>3	2.11	1.64
51	56°	2.47	1.63	1.34
52	69°	1.54	1.21	1.06

The effect of coupling to closed channels such as ^{7}Li$(p,n)^7$Be is to shift the eigenenergy from its single-particle value E_0 and to decrease the width of the resonance $\Gamma_p=2P_p\gamma_p{}^2$ from the single-particle limit. The latter is most important in the context of this work since it implies that the phase shift changes more rapidly with energy. The extreme limit of a compound resonance where $\gamma_p{}^2$ is much smaller than the single-particle value would result in a π change of the phase shift over a small energy interval, a behavior that is excluded by the results of the previous section. Coupling to closed channels would result in a 1^- state which would be more readily observed in ^{7}Li$+p$ elastic scattering than a pure single-particle resonance.

There is only one open channel ^{7}Li*$+p$ other than elastic scattering in the energy range of interest. Measurements of the ^{7}Li$(p,p')^7$Li* cross section between 0.9 and 2.0 MeV show no trace of resonance features which could be attributed to a 1^- state in this energy range.[19,31] The magnitude of this cross section is about 30 mb at 1.25 MeV, increases to about 75 mb at the ^{7}Li$(p,n)^7$Be threshold, and continues to increase at higher energies. For energies below 1.25 MeV, the cross section, after subtraction of the resonant 1^+ cross section, decreases rapidly to zero. An analysis of these measurements, done in conjunction with the phase shift analysis of Ref. 1, reveals that $\Gamma_{p'}$ is much smaller than Γ_p throughout the energy range of interest. Thus, coupling to the ^{7}Li*$+p$ channel does not alter the conclusions of the single-particle model analysis in the energy range of interest.

The results of this section suggest that the limits on the $^3S_1$ phase shift obtained in the previous section are incompatible with a 1^- state in the energy range between 0.4 and 1.4 MeV. A predominantly single-particle resonance with an R-matrix energy between 1.4 and 2.0 MeV cannot be excluded by the analysis in this section if the positive $^3S_1$ phase shift solution is the correct one. Experimental studies on the nucleon channels reveal no information which can be interpreted at this time as definite evidence for a 1^- state in this energy range.

V. SUMMARY

Several shell model calculations predict a 1^- state in ^{8}Be below about 18.5 MeV. This state, which has quantum numbers, $S=0$, $T=0$, is lower in energy than the well-known 2^- state at 18.9 MeV. It has the same quantum numbers as an α-α^* cluster state thought to be near 22 MeV. Multichannel cluster model calculations of the type which predict the α-α^* cluster 1^- state are in nominal agreement with the shell model calculations except for the 1^- state below 18.5 MeV. Since ^{8}Be is one of the few nuclei where a direct comparison of shell model and multichannel cluster model calculations is possible, this disagreement may be of general interest.

We have examined the experimental situation with regard to the possible presence of a 1^- state in the range from 14.5 to 19.5 MeV excitation. A 1^- state near or above 19.4 MeV is consistent with both shell model and multichannel cluster model calculations. Conventional interpretations of existing experimental data appear to rule out the possibility of a 1^- state over most of this energy range. In a small gap between 17.4 and 18.5 MeV, the possibility of a 1^- state cannot be ruled out on the basis of existing experiments. Ulbricht *et al.*[3] have suggested the possibility of a 1^- state at 17.7 MeV. We have reexamined the ^{7}Li$(p,p)^7$Li phase shift analysis for energies in the gap and have found no evidence which would suggest that there is a 1^- state between 17.6 to 18.5 MeV. Further, we have shown that a 1^- state with significant single-particle strength between 17.4 and 17.6 MeV would be broad enough to be seen in ^{7}Li$(p,p)^7$Li elastic scattering. Thus, there appears to be little or no possibility of a 1^- state in ^{8}Be between 17.4 and 18.5 MeV excitation.

Unless a 1^- state has been missed somehow in the interpretation of experimental studies, the results of this paper suggest that the shell model residual interaction for negative parity $S=0$, $T=0$ states of ^{8}Be is deficient. A similar deficiency for ^{14}N has been noted previously.[32,33] Kumar[22] has discussed a related problem for the positive parity $S=0$, $T=0$ states of ^{8}Be. We are hesitant to draw a firm conclusion as to this deficiency for several reasons. First, a firm conclusion of this type needs to be based on a systematic shell model study of several light p-shell nuclei. Second, the ^{7}Li$(p,\gamma)^8$Be data appear to show more $E1$ strength than is indicated by the ^{7}Li$(p,p)^7$Li 1^- phase shift limits; new experiments and analyses of this reaction are warranted. Third, the multichannel cluster model calculations are not as convincing as they could be, particularly in comparison with the systematic trend of three independent shell model calculations.

We are grateful to F. Ajzenberg-Selove, F. C. Barker, S. L. Blatt, L. Brown, F. Darema-Rogers, T. R. Donoghue, D. Fick, D. Kurath, J. Ulbricht, H. R. Weller, and W. Zahn for discussions on various topics pertaining to this work.

APPENDIX

The origin of the two phase shift solutions of Ref. 1 is described in this appendix. We consider the special case of S-wave proton scattering on a spin $\frac{3}{2}$ target as it contains the essential feature of the two solution ambiguity and is realized to a fairly good approximation for proton scattering on ^{7}Li between 0.4 and 1.4 MeV.

The cross section for S-wave proton scattering by a spin $\frac{3}{2}$ nucleus may be written

$$8k^2[\sigma(\theta)-\sigma_c(\theta)] = (5\sin^2\delta_2+3\sin^2\delta_1)(1-\eta\sin\delta_c\csc^2\theta/2) - (5\sin\delta_2\cos\delta_2+3\sin\delta_1\cos\delta_1)\,\eta\cos\delta_c\csc^2\theta/2\,,$$

where $\sigma_c(\theta)$ is the Rutherford cross section, η is the Coulomb parameter, and δ_c is the S-wave Coulomb phase shift. The nuclear phase shifts for $J=1$ and 2 are denoted by δ_1 and δ_2, respectively. The cross section is invariant to changes in the phase shifts which preserve the following relations:

$$5\sin^2\delta_2+3\sin^2\delta_1=C_a\,,$$

$$5\sin\delta_2\cos\delta_2+3\sin\delta_1\cos\delta_1=C_b\,,$$

where C_a and C_b are constants. The first of these equations describes an elliptical locus in the variables $\sin\delta_1$ and $\sin\delta_2$. The second may be written

$$5\sin\delta_2+3\sin\delta_1\approx C_b\,,$$

if δ_1 and δ_2 are sufficiently small. It describes a straight line in this approximation. Since a straight line and an ellipse intersect at two points, two combinations of δ_1 and δ_2 are allowed. Under very special conditions the two intersection points may degenerate to a single point. The case where the straight line and ellipse do not intersect is irrelevant. The two combinations of δ_1 and δ_2 allowed by the intersection of the straight line and the ellipse correspond to the two phase shift solutions of Ref. 1. In practice, the two solutions will not yield identical fits to the data owing to interference from other partial waves.

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