PHYSICAL REVIEW C VOLUME 26, NUMBER 6 DECEMBER 1982

Influence of 1p-1h-excited α particles on elastic α-α scattering

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(Received 13 July 1982)

The influence of channels with 1p-1h-excited α particles with $S=T=0$ on elastic α-α scattering is studied in the framework of the Feshbach projection operator formalism. Calculated phase shifts and transmission coefficients for α-α scattering are compared to experimental data for c.m. energies between 15 and 35 MeV. The effect of positive parity α-α^* rotational states is discussed.

[NUCLEAR REACTIONS Excited α particles in elastic α-α scattering microscopic absorptive potential. Feshbach projection operator formalism. Phase shifts and transmission coefficients.]

I. INTRODUCTION

Some years ago attempts were made to study the influence of the α-α^* channel on the elastic α-α channel,[1-3] α^* denoting the first excited (0^+) state of ^{4}He.[4] These theoretical studies met with experimental investigations[5-7] on high-lying ^{8}Be states with possible α-α^* cluster structure. Although there is experimental evidence for a resonancelike bump in the ^{7}Li$(p,\alpha^*)\alpha$ and ^{6}Li$(d,\alpha^*)\alpha$ cross section at about 25 MeV excitation energy in ^{8}Be, there is yet no clear evidence for this bump being due to a specific member of a possible α-α^* rotational band.[7] The existence of such an α-α^* rotational band has been predicted by Hackenbroich *et al.*[2]; however these authors described the α^* particle as an extremely large breathing mode [the ratio of root mean square (rms) radii being $r_\alpha^*/r_\alpha \approx 1.7$]. As a consequence of this model the interaction between α and α^* turned out to be relatively small, which can be seen from the calculated α-α^* phase shifts which exhibit only a very weak resonant behavior.[2] This is somewhat contradictory to the assumption that the α-α^* resonances should be almost as sharp as the resonances of the α-α ground state band.[8] Moreover, the model of the α^* being a breathing mode is not well established in the literature, cf. Ref. 9. Instead the α^* should be described in terms of particle-hole excitations, namely approximately as a $(2s)(1s)^{-1}$ state, coupled to $S=T=0$.[4,10] Such a particle hole excitation model would, in oscillator shell model terms, lead to a considerably different ratio $r_\alpha^*/r_\alpha \approx 1.15$ and thus the relative interaction between the α^* particle and other nuclei should be of a very different character for both models. To illustrate this we recall that in many cases the main contribution of the attractive part of the relative interaction between two nuclei is the double folding potential, which depends sensitively on the density of the nuclei involved: If the density distribution of the α^* is assumed to be comparable with that of the α particle, resonances in the α-α^* system are expected to be almost as sharp as in the α-α system; if on the other hand the α^* is assumed to be of very large size, the relative interaction will be rather shallow and resonances will occur only very weakly, as turned out in the calculations of Hackenbroich *et al.*[2] The interpretation of the α^* in terms of particle-hole excitations is supported by an investigation of $A=5$ levels with nucleon-α^* cluster structure.[11] From this investigation it has been concluded that the attraction between $p_{3/2}$ nucleons and an α^* is stronger than the one between $p_{3/2}$ nucleons and an α particle. Clearly such a conclusion would be inconsistent with the picture of the α^* being a very extended breathing mode state, since in this case the resulting p-α^* potential would be very shallow. This is confirmed by a calculation of Heiss and Hackenbroich[12] for the ^{5}Li system, where the inclusion of a p-α^* channel (with the α^* being described as a breathing mode), although producing a noticeable effect, only leads to very weak resonances.

With this in mind new theoretical investigations on the scattering of excited α particles seem necessary. Such studies should account for the particle-

hole character of the excited α particles. Since recently methods have been established for the microscopic description of scattering of composite nuclei which even may be in excited states,[13,14] calculations of this kind are now possible with acceptable numerical effort.[15] This paper is a step in this direction.

We study here the effect of channels with 1p-1h-excited α particles on *elastic* α-α scattering. Since the ^{4}He excitations are entirely continuous, one basically deals with three-fragment breakup channels. The model space is restricted to channels with one 1p-1h-excited α particle coupled to $S=T=L=0$. This truncation is reasonable in a rather narrow energy region above the breakup threshold.[4] The dominant α^* state which decays into $p+t$ (Refs. 4 and 16) can be approximately described as a resonance in the $p+t$ excitation spectrum and is therefore contained within this model. The present investigation is *not* performed on the basis of a multichannel calculation; instead, the influence of the channels with excited α particles is taken into account *globally* via an absorptive-dispersive potential in the framework of the Feshbach projection operator formalism.[17] Since the underlying theory of calculating this potential and the properties of this potential are given elsewhere[14] in some detail, we just give in Sec. II a short review of the model and the approximations within this model. In Sec. III the results of our calculations, i.e., scattering phase shifts and transmission coefficients of the α-α system for energies between 15 and 35 MeV in the c.m. system above α-α threshold, are presented. These results are related to the existing experimental data.

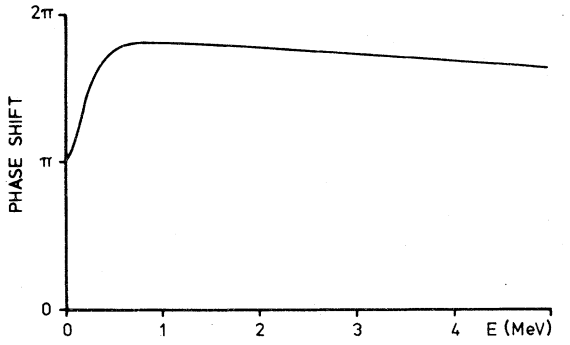

FIG. 1. Scattering phase shifts ($L=0$) generated by the separable potential of rank 2 which describes the relative motion of the 3 + 1 nucleon system.

II. THE MODEL SPACE OF CHANNELS WITH EXCITED PARTICLES AND APPROXIMATIONS WITHIN THIS MODEL

The current investigation is based on Feshbach's projection operator formalism,[17] i.e., we take into account the influence of the channels with excited α particles on the elastic α-α channel globally via the effective absorptive dispersive potential

$$PHQ\frac{1}{E^+-QHQ}QHP\ . \tag{1}$$

Here P denotes the projector onto the elastic α-α channel, Q denotes the projector onto all inelastic channels considered here (with $PQ=0$), E is the energy of the scattering system, and H is a microscopic model Hamiltonian of the form

$$H=\sum_i \frac{p_i^2}{2m}-T_{\text{c.m.}}+\tfrac{1}{2}\sum_{i\neq j}V(i,j)\ , \tag{2}$$

where $T_{\text{c.m.}}$ is the center-of-mass kinetic energy operator and the two particle interaction $V(i,j)$ in our model contains a simple, schematic nuclear interaction which has been used previously in the α-α system by Thompson *et al.*[18] On more formal grounds, the P space contains all antisymmetrized eight-particle states, which in coordinate space take the form

$$\mathcal{A}\{\phi_1^\alpha(\xi_1)\phi_2^\alpha(\xi_2)g(x)\}\ , \tag{3}$$

$\phi_i^\alpha(\xi_i)$ being the intrinsic wave function of the respective α particle in its ground state and $g(x)$ being an arbitrary wave function of relative motion. For the intrinsic ground state ϕ_i^α we have taken the same model state as Thompson *et al.*[18] ($b_\alpha=0.43^{-1/2}$ fm).

The model Q space contains states which in coordinate space take the form

$$\mathcal{A}\{\phi_1^\alpha(\xi_1)\phi_2(q,\xi_2)g(x)\}\ , \tag{4}$$

where now $\phi_2(q,\xi_2)$ is an (intrinsic) excited ^{4}He state and q denotes the quantum numbers of this excited state. We here only consider 1p-1h excitations preserving the $S=T=0$ symmetry of the ground state. Moreover, since the ^{4}He excitation spectrum is entirely continuous, q is a continuous parameter. For low excitation energies it seems sufficient to include just $L=0$ excitations, so in this case q may be taken to denote the relative (asymptotic) momentum in the 3+1 particle system with symmetry $S=T=L=0$. This truncation of the model space is of course only reasonable in a rather narrow energy region above the excitation threshold, however,

the α^* resonance which actually dominates the positive parity excitation spectrum around 0.2 MeV above particle-hole threshold[4] is contained within this model.

The eight-particle states of the form (3) and (4) as well as the excited intrinsic four-particle states $\phi_i(q,\xi_i)$ are constructed via momentum projection techniques.[13] q parametrizes the relative motion between the excited nucleon and the remainder nucleus which consists of three bound nucleons. For simplicity, we here assume threshold degeneracy for the n-^{3}He and p-^{3}H system.[19] The relative motion of the $3+1$ system is constructed using a separable potential of rank 2 for the relative interaction such that one bound state and a resonance in the continuum is generated, according to experimental evidence. The two form factors and the coupling constants of this separable potential are chosen in such a way that, first, the α-particle ground state $\phi_i^{\alpha}(\xi_i)$ is generated with the correct binding energy (i.e., bound state energy below $p+{}^3$H threshold) and second, the excitation spectrum for $L=0$ contains a sharp resonance which is approximately a $(2s)$ state with energy and width being in accordance with experimental data.[4,16] This (α^*) resonance is illustrated by the scattering phase shifts of the separable potential and is shown in Fig. 1. For the details of the separable potential (form factors and coupling constants), see Ref. 14. This approach automatically guarantees orthogonality between the ground states and all excited states.

The channels with excited α particles are made orthogonal to the elastic channel via a Schmidt orthogonalization procedure to ensure $PQ=0$. This is crucial for the application of the formula (1). The orthogonalization is necessary because due to antisymmetrization, two-cluster states are in general not orthogonal even if the respective intrinsic cluster states are.

When calculating the effective α-α interaction (1) it seems legitimate to treat the Q-space propagation approximately because the Feshbach potential (1) only globally takes into account the effect of all inelastic channels considered and thus many of the details of the Q-space propagation get lost anyhow. First, the dynamical coupling between different Q-space channels has been neglected, i.e., transitions between channels with different internal α excitations have not been considered. Second, the relative interaction between the α particle and the excited α particles, which enters into the energy denominator in (1), has been taken to be the same for all Q-space channels.

Since the α^* resonance is dominant in the α-excitation spectrum it is important to use an α-α^* interaction based on physically reasonable grounds. In the present calculation this is done, preserving the microscopic character of the relative α-α^* interaction: Following the arguments given in the Introduction, i.e., assuming the α^* particle to be a $(2s)(1s)^{-1}$ excitation, the extension of α and α^* in coordinate space should be of comparable order ($r_{\alpha}^*/r_{\alpha}\approx 1.15$). Thus the local part of the relative interaction, which is in fact a double folding potential,[13,20] should be very similar to that of the α-α case. It has been shown by Saito *et al.* that for simple nucleon-nucleon forces (without a strong repulsive core) the main attractive part of the relative interaction is the double folding potential, while the repulsive effect of the Pauli principle is described by the redundant states of relative motion[21]; at least this is true for light systems such as the α-α system. In order to discuss these effects of the Pauli principle we note that in the ^{8}Be system only states with at least $4\hbar\omega$ (in oscillator shell model terms) are al-

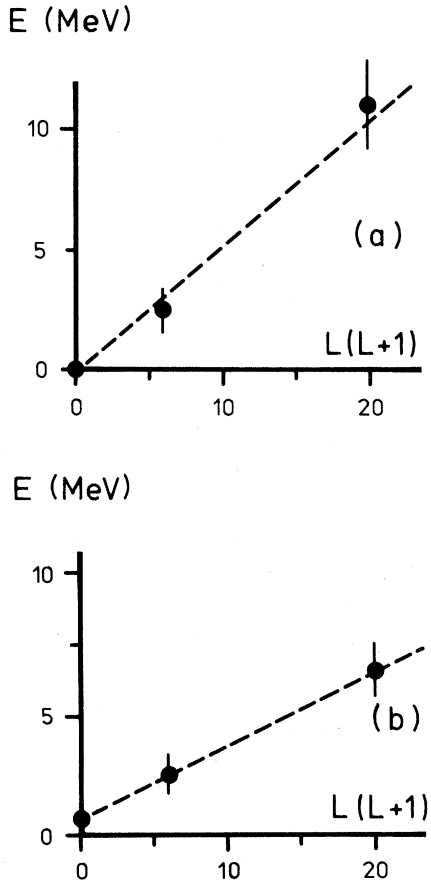

FIG. 2. α-α rotational band (top) and assumed α-α^* positive parity rotational band (bottom).

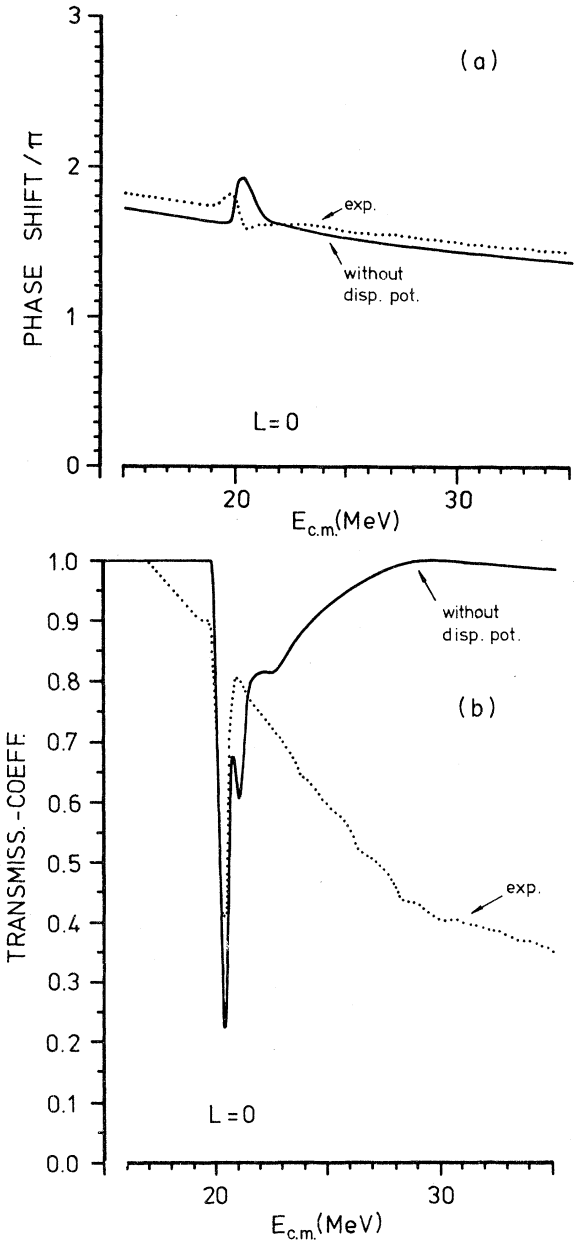

FIG. 3. Scattering data for the α-α system, calculated for $L=0$ with the *PHP*-Hamiltonian plus imaginary potential (solid lines): (a) scattering phase shifts and (b) transmission coefficients; dotted lines: experimental data.

lowed. Owing to the fact that the α particle is approximately a $(1s)^4$ state coupled to $S=T=0$, the $(1s)$, $(2s)$, and $(1d)$ states are forbidden in the α-α system (negative parity states do not occur). Since the α^* is approximately a $(2s)(1s)^3$ state, coupled to $S=T=0$, one should expect only the $(1s)$-relative state to be forbidden in the α-α^* system of positive parity. However, the α-α^* relative states with $2\hbar\omega$ relative energy and good angular momentum are the same as those α-α states with $4\hbar\omega$ relative energy. In both cases one has ^{8}Be states with $S=T=0$, $4\hbar\omega$ energy, and sharp angular momentum, and these states are nondegenerate. Therefore, after orthogonalizing the α-α^* channel to the α-α channel, both systems have the same (positive parity) redundant states. This ultimately means that the relative interaction between α-α and α-α^* should indeed be very similar.

The α-α interaction leads to the well-known rotational band of the ^{8}Be ground states [Fig. 2(a)]. Owing to the similarity of the α-α and α-α^* interaction which thus stems from the above argument, one should expect a similar rotational band to exist in the α-α^* system. The bandhead should be shifted by the α^* excitation energy, i.e., about 20 MeV and, caused by the larger size of the α^* particle, the slope of this rotational band should be somewhat smaller [Fig. 2(b)]. This assumption is confirmed by a calculation of Arickx *et al.*[22] who predicted an excited ^{8}Be band with a similar bandhead and a slope which is smaller than that of the ground state band. The energies of the positive parity rotational states are the same as those predicted by Hackenbroich *et al.*[2] Owing to the similar relative interaction, in the present paper we take the widths of these α-α^* resonances to be of comparable order as those of the α-α ground states. The width of the $L=4$ state is even taken somewhat smaller than that of the $L=4$ low lying state. These assumptions are in accordance with the finding of Schröder *et al.*[11] revealing that the nucleon-α^* interaction is as strong or even stronger than the nucleon α interaction, at least for the nucleon being in a $p_{3/2}$ state, which is the state of largest attraction.

All the considerations just stated are consistent with using basically the (microscopic) α-α interaction in order to describe the α-α^* interaction but with slight modifications such as to reproduce the α-α^* rotational band. We here omit the details and refer the reader to Sec. II 4 of Ref. 14. The rotational bands of α-α and α-α^* which enter in our calculation via this treatment are given in Fig. 2.

The Coulomb interaction, which is relatively small in the α-α and α-α^* system (and which we consider not to be crucial for understanding the effect we are interested in), has been neglected.[19]

It should be stressed that the approximations discussed above only affect the Q-space propagation and the energy denominator in (1). The P-space motion as well as the dynamic coupling between P space and Q space, which enters into the potential

(1) via the coupling matrix elements *PHQ*, *QHP*, have been treated consistently within our microscopic model.[23]

III. NUMERICAL RESULTS AND DISCUSSION

In order to calculate the effective absorptive-dispersive potential (1) it is convenient to write P in the form

$$P=\int d^3k\,|\psi(\vec{k})\rangle\langle\psi(\vec{k})|\ , \tag{5}$$

where $\vec{k}$ is a parameter of (free) relative motion in the α-α system which can be interpreted as the asymptotic relative momentum, and where the states $|\psi(\vec{k})\rangle$ form a basis of the P space such that $P^2=P$, cf. Ref. 14. Then the (nonlocal) kernel

$$V(E;\vec{k},\vec{k}')\equiv\langle\psi(\vec{k})|\,HQ\frac{1}{E^+-QHQ}QH\,|\psi(\vec{k}')\rangle \tag{6}$$

can be inserted into an effective Schrödinger equation of relative motion for the elastic α-α scattering. Since the properties of this potential are amply discussed elsewhere,[14] we here just present scattering phase shifts and transmission coefficients calculated for partial waves $L=0$, 2, and 4. Higher partial waves only yield negligible contributions to the potential (6) within our model. For comparison, the transmission coefficients and phase shifts have been calculated twice:

(i) with the (direct) *PHP*-Hamiltonian plus the imaginary (i.e., the absorptive) part of the potential (6) and

(ii) with the entire potential (6) (i.e., including the dispersive part).

Figures 3(a) and (b) show the real phase shifts and transmission coefficients obtained from the *PHP*-Hamiltonian plus absorptive potential for c.m. energies in the α-α system between 15 and 35 MeV. At about 20 MeV there is a resonancelike bump, which is due to the lowest state of the α-α^* rotational band. Such a bump also appears in the experimental data which have been determined by Bacher *et al.*[24] However, the experimental transmission coefficient steadily decreases for increasing energy in the inelastic region, whereas the theoretical values almost return to unity. Clearly this behavior is due to the truncation of our model space: Experimentally, above 22 MeV more and more inelastic channels not considered within our model open, and more and more partial waves of these channels will take away flux from the incident α-α scattering system.[25]

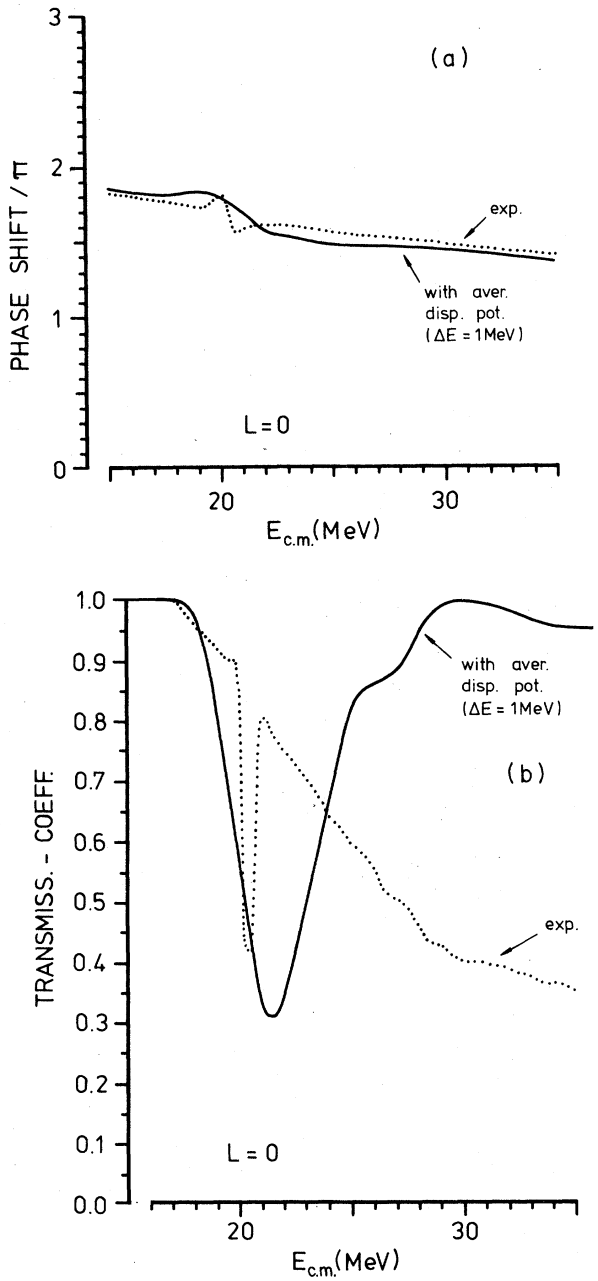

FIG. 4. Scattering data for the α-α system, calculated for $L=0$ with the full energy averaged Feshbach potential (averaging interval $\Delta E=1$ MeV).

A similar behavior is apparent in the transmission coefficients and phase shifts that have been calculated with inclusion of the dispersive part. However, since the calculation of the dispersive part requires one additional (principle value) integration and since for $L=0$ both in the ^{4}He-excitation spectrum as well as in the relative motion of the channels with excited fragments sharp resonances occur, only an *energy-averaged* dispersive potential could

be calculated with acceptable numerical effort and reliable accuracy for energies above ≈ 22 MeV. Accordingly, in this calculation also the absorptive part of the potential (6) has been subject to the same energy averaging. The averaging interval was chosen as 1 MeV. The resulting phase shifts and transmission coefficients are shown in Figs. 4(a) and (b). Owing to the energy averaging the resonancelike bump has considerably broadened.

For $L=2$ two resonancelike bumps occur in the calculated phase shifts and transmission coefficients both without and with dispersive potential (this time *not* energy averaged), cf. Figs. 5 and 6. These bumps are located at about 22 MeV and about 24 MeV. These two absorption maxima coincide with maxima in the strength of the absorptive potential.[14] Experimentally there is a lot more structure for $L=2$ in both phase shifts and transmission coefficients in the energy region considered here. The two very sharp resonances just below 17 MeV and the resonance at about 20 MeV can be well explained[26,27]: These are ^{8}Be states with internal symmetry other than the one considered within our model states. Therefore at most the experimental bumps at about 22.5 and 25 MeV can probably be identified with the two calculated absorptive maxima.

For $L=4$ again two resonancelike bumps occur in the present calculation, one at about 25 MeV, the other at about 29 MeV. The calculations with and without dispersive potential yield very similar results [Figs. 7(a) and (b)]. It is interesting to note that for energies below the absorption threshold the dispersive potential, which is here a purely attractive polarization potential, lowers the energy of the $L=4$ member of the ground state band by about 1 MeV.[28] Apart from the resonant behavior at 20 MeV, which is due to an excited ^{8}Be state not considered within our model space,[27] the agreement with the experimental data between 20 and 30 MeV energy is astonishingly good, since experimentally also two bumps, one at about 25 MeV and one at 29.5 MeV, occur.

The appearance of a double structure in the transmission coefficients is surprising, at first sight. However, a closer examination of the formula for the energy-dependent part of the potential shows that its calculation is highly nontrivial. From Ref. 14, Eq. (2.28) we recall

$$\langle k'0 \mid V^L_{\text{eff}}(E) \mid k0 \rangle = \int_0^\infty dq \int_0^\infty dp \frac{\langle k' \mid V^L_q \mid p \rangle \langle p \mid V^{L+}_q \mid k \rangle}{E+i0-\epsilon_q - p^2/4} \quad (7a)$$

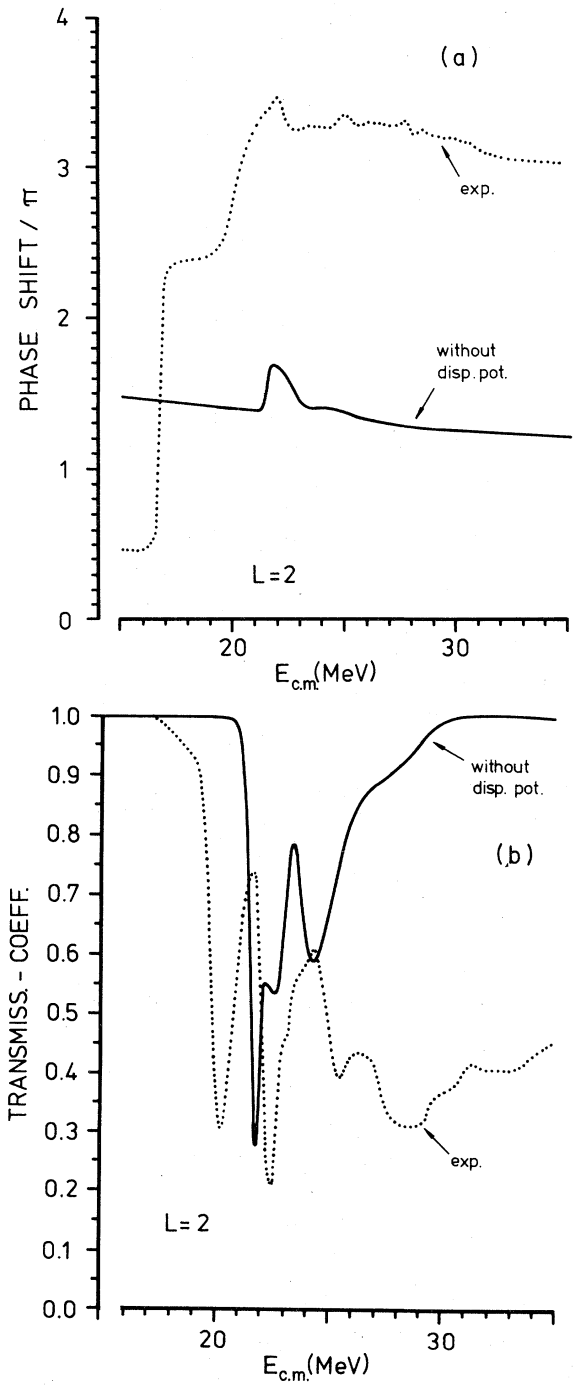

FIG. 5. Scattering data for the α-α system, calculated for $L=2$ with *PHP*-Hamiltonian plus imaginary potential.

for the effective potential (in momentum space). Here $|k0\rangle$ denotes the state of two α particles in their ground state with relative momentum $\vec{k}$. Furthermore

$$\epsilon_q = 19.8 \text{ MeV} + q^2/(2\times\tfrac{3}{4}) \quad (7b)$$

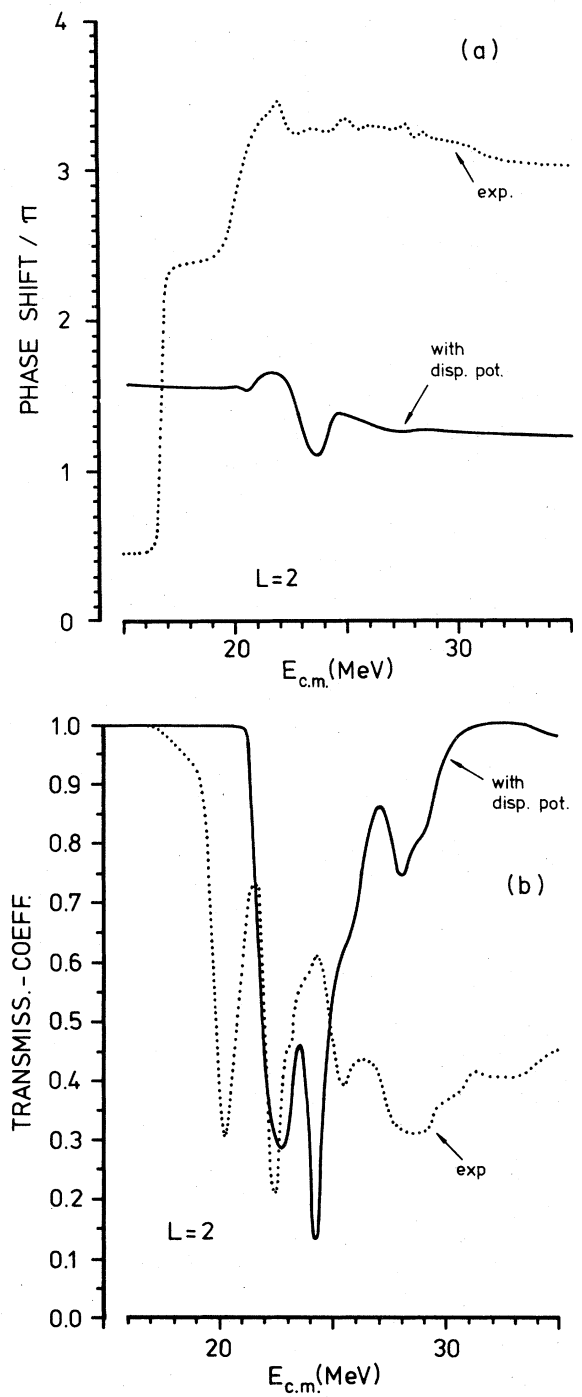

FIG. 6. Scattering data for the α-α system, calculated for $L=2$ with the full Feshbach potential.

and

$$\langle k' \mid V_q^L \mid p \rangle = \int_0^\infty dk \langle k'0 \mid V^L \mid kq \rangle \langle k \mid \psi_*^L(p) \rangle \ . \quad (7c)$$

In the k integrand we encounter the matrix element of the microscopic interaction between the systems α-α and α-α^* with relative momenta k' and k, respectively, and q characterizes the relative motion of the $3+1$ system α^* described by a plane wave (orthogonalized to the α-ground state). The dynamics of the $3+1$ system enter via the wave function $\langle k \mid \psi_*^L(p) \rangle$ which corresponds to the phase shifts shown in Fig. 1. Hence two resonant structures, namely from the $3+1$ system and the $4+(3+1)$ system (rotational band), enter into the formula for the effective potential. Thus a complicated interference is to be expected in the double integral (7a), and apparently it occurs.

IV. CONCLUDING REMARKS AND OUTLOOK

The agreement between our calculated results and the experimental data just above absorption threshold may be termed encouraging in view of our limited model space. The results presented here are not sufficient to conclude that the resonantlike bumps

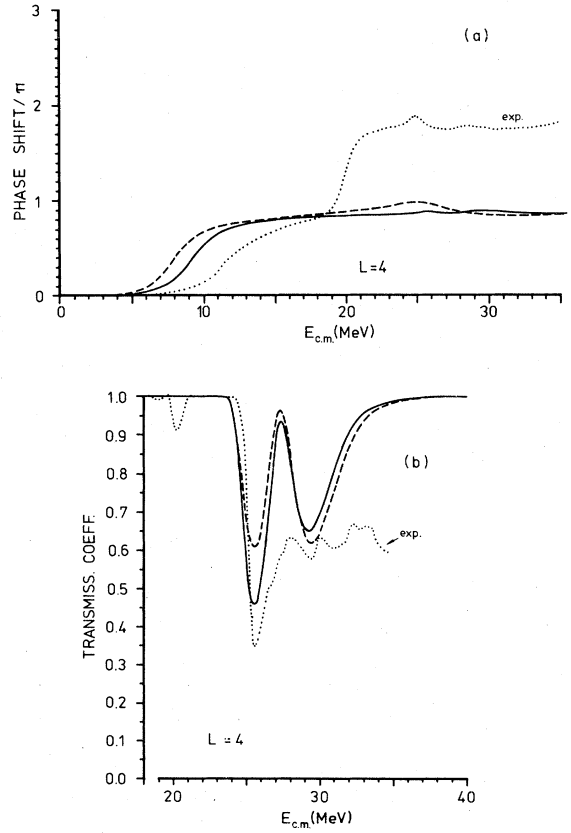

FIG. 7. Scattering data for the α-α system, calculated for $L=4$; solid lines: calculations with *PHP*-Hamiltonian plus imaginary potential; dashed lines: calculations with the full Feshbach potential.

are exclusively due to specific members of an α-α^* rotational band, except maybe for $L=0$. For $L=2$ and $L=4$ two absorptive maxima occur, whereas only one α-α^* resonance was assumed to exist in each partial wave. This effect is probably due to the coupling to a continuous $L=0$ ^{4}He-excitation spectrum with a resonant structure.

The maximum found by Warner *et al.*[6] in the cross section of the $d(^6\text{Li},\alpha)\alpha^*$ and by Čaplar *et al.*[7] also in the $^7\text{Li}(p,\alpha)\alpha^*$ reaction at 25 MeV probably is an overlap effect of $L=2$ and $L=4$ contributions (aside from negative parity effects), as is suggested by the present results for the α-α system.

It should be interesting to perform a new α-α^* calculation treating the α^* as a discrete state in terms of particle-hole excitations. Such a calculation should be possible with the aid of momentum projection techniques[13,14] and it should substantiate the assumptions about the positive parity α-α^* rotational band. Perhaps more interesting is that such a calculation should yield information about an α-α^* negative parity band. In contrast to the calculation of Hackenbroich *et al.*[2] this band is not expected to coincide with the positive parity band: Since the lowest lying negative parity relative states, which are allowed by the Pauli principle in the α-α^* system, have $3\hbar\omega$, the 1^- and 3^- members of this band should have $5\hbar\omega$ in oscillator shell model terms. The α-α ground state band has $4\hbar\omega$, whereas the α-α^* positive parity band has $6\hbar\omega$, therefore the negative parity band should be located between those two bands. Moreover, one should expect its slope to lie between the slopes of those two bands. One may therefore be allowed to speculate that the α-α^* 1^- state is located between 10 and 15 MeV and that the 3^- state is located between 15 and 21 MeV. Calculations in this direction appear to be highly desirable, since until now only little is known about the relative interaction between excited nuclei.

Finally, we would like to mention that the structure of the α^* particle is controversial. Some authors propose other models rather than a $(2s)(1s)^{-1}$ description.[29] Admittedly, the picture of a nucleon moving in the mean field of only three others can be true only in a rough, approximate sense. However, to the best of our knowledge, the treatment of the α^* in Ref. 14 and in this work employs more details of the α^* structure into a microscopic calculation of an effective α-α potential than any other work before. In view of the numerical effort apparent in Eqs. (7) we must leave further improvements to the future.

ACKNOWLEDGMENTS

The authors are greatly indebted to Prof. M. Stingl for many helpful discussions and comments. This work was supported in part by USDOE Contract DE-AC02-76ER13001.

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