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Nuclear molecular resonances in $\alpha + {}^{12}C$ and $\alpha + {}^{16}O$ systems

P SARANGI and L SATPATHY
Institute of Physics, Bhubaneswar 751 005, India

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Abstract. The nuclear molecular resonances observed in $\alpha + {}^{12}C$ and $\alpha + {}^{16}O$ systems are described in a diatomic-like molecular picture using a Morse-type bonding potential. The depths of the bonding potentials are found to be 11·5 MeV and 11 MeV respectively, with long range of about 15 fm. Both the bound and resonance states of these potentials are calculated which compare quite well with the observed states. The diatomic-like rotational and vibrational picture of the quasi-molecular states proposed earlier for $^{12}C + {}^{12}C$ system system is found to be quite valid for $\alpha + {}^{12}C$ and $\alpha + {}^{16}O$ systems. In these two systems, the rotational vibrational characteristics are equally well pronounced as in the $^{12}C + {}^{12}C$ system.

Keywords. Nuclear molecular resonances; nuclear molecule; diatomic-like rotational and vibrational picture.

PACS No 25·70

1. Introduction

The discovery of isolated, narrow resonances in $^{12}C + {}^{12}C$ system in 1960 by Bromley *et al* (1960), has opened up a new domain of nuclear physics in which a combination of two nuclei exhibits behaviour similar to a di-atomic molecule. Over the years, after the advent of heavy-ion reactions, such narrow resonances have been observed in many other combinations of light and medium heavy nuclei. These resonances referred to as nuclear molecular resonances (NMR) or sometimes as quasi-molecular resonances, now constitute an established exotic nuclear phenomenon, in which molecular degrees of freedom are prominently manifested by nuclear dynamics. Unlike in the case of atoms where the interaction is long range, atomic molecules are found rather very easily, the interaction between two nuclei is short range and hence nuclear molecules are not found in nature. Therefore, the understanding of the mechanism of the nuclear molecular resonances which are short-living nuclear molecules, has remained a challenging problem, although, more than 30 years have passed, since they were first discoverd. Many phenomenological and microscopic attempts have been made over the years to describe these states and unearth its mechanism, but with meagre success. Microscopic calculations (Vogt and McManus 1960; Imanishi 1968, 1969; Scheid *et al* 1971, 1972) carried out in the framework of coupled channel formalism using the usual optical potential, can qualitatively describe few states, whose numbers are often comparable to the number of parameters of the potential. However, experimentally, sometimes the number of resonances exceeds fifty in a system like $^{12}C + {}^{12}C$. The phenomenological models (Iachello 1981; Cindro and Greiner 1983) succeed, in only showing the existence of clear and simple regularity in the resonances which show

rotation and vibration characteristics. During the last several years, we have developed a quantum mechanical model based on diatomic-like molecular picture in which the dipole degree of freedom is the essential collective co-ordinate. Therefore, the inter-nuclear potential $V(R)$, where R is the distance between the two nuclei will govern the physics of these states. Thus, in this model rotation-vibration characteristics of the resonances are of dipole origin, rather than of quadrupole origin, normally seen in low energy nuclear spectra. We have developed a method of determining the potential directly from the resonance data itself, by supposing a combination of a constant and the Morse potential to represent $V(R)$ properly. Then the bound and resonance states of this potential have been shown to describe all the states in the $^{12}C + {}^{12}C$ (Satpathy *et al* 1986, 1990), $^{12}C + {}^{16}O$ and $^{16}O + {}^{16}O$ (Satpathy *et al* 1991) systems. We would like to apply the same model to $\alpha + {}^{12}C$ and $\alpha + {}^{16}O$ systems, which have the unique feature of having one of the partners to be very rigid and stable i.e. the α particle. It is known that α-nucleus is a unique nucleus, being very rigidly bound, it has the first excited state at 17 MeV. Thus, it cannot be easily excited and hence the inelastic channels pertaining to this nucleus will be mostly inaccessible. So, these two systems are quite different compared to the other three systems studied earlier. Therefore, it will be interesting to see if the dynamics of these two reactions are quite similar to that of $^{12}C + {}^{12}C$, $^{12}C + {}^{16}O$ and $^{16}O + {}^{16}O$ and thereby to find if all these reactions have a common physical scenario. Further it will provide a good testing ground of our model.

In § 2, we determine the effective potentials using the resonance data of the two systems and analyse them. Section 3 contains the calculations of the exact solution of the bound states and the resonances. In § 4, discussion and conclusion are presented.

2. Determination of effective potential

To facilitate the discussion, we repeat the essential features of our model (Satpathy *et al* 1986, 1990). The effective potential between two ions is taken as a combination of the Morse potential and a constant

$$V_{\text{eff}}(R) = A + B[e^{(-2\beta x)} - 2e^{(-\beta x)}];\ x = \frac{R - R_0}{R_0}, \tag{1}$$

where A, B, β and R_0 are four constants. The corresponding radial Schrödinger equation for relative motion of the two ions is

$$\left(-\frac{\hbar^2}{2\mu}\frac{d^2}{dR^2} + V_{\text{eff}}(R) + \frac{\hbar^2}{2\mu R^2}L(L+1)\right)\chi_{nL}(R) = E_{nL}\chi_{nL}(R). \tag{2}$$

It can be analytically solved exactly for $L = 0$ state. However for $L \neq 0$ states, it can also be analytically solved using an approximation due to Flügge (1974) for the centrifugal potential, which is

$$\frac{\hbar^2}{2\mu R^2}L(L+1) \simeq \frac{\hbar^2}{2\mu R_0^2}L(L+1)[C_0 + C_1 e^{-\beta x} + C_2 e^{-2\beta x}] \tag{3}$$

where C_0, C_1 and C_2 are constants defined in Satpathy *et al* (1986).

The general eigen value expression using the above approximation can be written in terms of the four parameters of the potential as

$$E_{nL} = A - B + \frac{\hbar^2}{2\mu R_0^2}\left[2\beta\gamma(n+\tfrac{1}{2}) - \beta^2(n+\tfrac{1}{2})^2 + L(L+1) - \frac{3(\beta-1)}{\beta\gamma}(n+\tfrac{1}{2})L(L+1) - \frac{9(\beta-1)^2}{4\beta^4\gamma^2}L^2(L+1)^2\right] \quad (4)$$

where

$$\gamma^2 = 2\mu B R_0^2/\hbar^2.$$

The eigen functions χ_{nL} are given in terms of confluent hypergeometric function. It must be recalled that this effective ion-ion potential comprises both the nuclear and Coulomb parts which gives rise to all the states in the systems. The value of the parameters can be determined by fitting the known energy levels with (4).

(a) $\alpha + {}^{12}C$ system

In the $\alpha + {}^{12}$C system, the number of quasi-molecular states is much smaller compared to the $\alpha + {}^{16}$O system. The Coulomb barrier of this system is 3·43 MeV. Abbondanno *et al* (1990) have applied our model to determine the effective potential in $\alpha + {}^{12}$C. They have studied this system in the anharmonic vibration-rotation model also. Following them we have selected the data from table 16·12 of Ajzenberg-Selove (1986), using the criteria on total width Γ and the ground state partial width $\Gamma_{\alpha C}$ as $10\,\text{keV} \leqslant \Gamma \leqslant 500\,\text{keV}$ and $\Gamma_{\alpha C}/\Gamma \geqslant 0{\cdot}1$ respectively, and have presented them in the second column of table 1. There are about 25 states with well established spins. We have also used the same vibrational quantum numbers assigned by them to these 25 states. These data were fitted to expression (4) and the parameters of the effective potential obtained are $A = 11{\cdot}51$ MeV, $B = 10{\cdot}35$ MeV, $\beta = 0{\cdot}885$, and $R_0 = 7{\cdot}53$ fm.

These values are close to those of Abbondano *et al* (1990). In their application of our model to both $\alpha + {}^{16}$O and $\alpha + {}^{12}$C systems, they had assumed the value of R_0 and fitted only for the remaining three parameters. Therefore, there are some slight discrepancies between two sets of parameters. The result of the fit is shown in figure 1(a) as full curves. The full dots are the experimental points. It can be seen that the fit of the data is quite good. Thus all the states can be well accounted for in this description. Using these parameters, the effective potential was calculated which is shown in figure 2. It has a depth of 11·5 MeV, range of about 15 fm and a soft core of about 25 MeV.

(b) $\alpha + {}^{16}O$ system

In the $\alpha + {}^{16}$O system, large number of resonances have been observed. The Coulomb barrier for this system is 4·32 MeV. Abbondano *et al* (1990) have studied this system in the anharmonic vibration-rotation model. They have also applied our model to determine the effective potential. There are about 63 states which can qualify to be well defined quasi molecular states. Following Abbondano *et al* (1990), we have selected the states adopting the criteria on the total width Γ and ground state partial

Table 1. Resonances obseved in $\alpha + {}^{12}C$ and $\alpha + {}^{16}O$ systems. Odd states are of negative parity and even states are of positive parity. (from Ajzenberg-Selove (1986, 1987.)

	E_{cm}(MeV)			E_{cm}(MeV)	
L	$\alpha + {}^{12}C$	$\alpha + {}^{16}O$	L	$\alpha + {}^{12}C$	$\alpha + {}^{16}O$
0	7·90	9·21	6	7·43	7·85
1	5·28	9·13		9·11	8·37
	5·93			13·89	9·19
	10·35			14·48	9·56
	11·61				10·03
2	2·72	2·69			12·14
	4·36	4·76			12·81
	5·86	6·11			14·01
	9·27	7·86			14·55
	10·01	8·01			14·92
	12·09	9·17			15·11
	12·36				15·29
	12·59		7		8.96
	12·89				10·58
3	5·97	4·12			10·63
	8·25	6·51			11·85
		7·23			13·69
		8·10			14·03
		8·51			15·15
		8·77			15·56
		9·09			16·22
4	7·46	5·23			16·57
	10·85	5·82			17·07
	11·44	6·07	8		12·01
	12·21	7·52			12·56
		9·54			13·88
		11·59			14·23
		12·48			14·99
		13·03			18·67
		13·35	9		12·69
5	13·38	5·53			15·95
		7·98			16·34
		10·02			18·11
		10·44			
		13·12			
		13·76			

width $\Gamma_{\alpha O}$ to be $5\,\text{keV} \leqslant \Gamma \leqslant 500\,\text{keV}$ and $\Gamma_{\alpha O} \geqslant 0{\cdot}1$ respectively. The 63 states selected on this basis from table 20·18 of Ajzenberg-Selove (1987) are presented in the third column of table 1. The spin of these states varies from 0 to 9. We have also used the same vibrational quantum number assigned by Abbondano *et al* (1990) to these 63 states. As before, these data have been fitted to (4) and the parameters of the effective potential so obtained are $A = 11{\cdot}02$ MeV, $B = 9{\cdot}48$ MeV, $\beta = 0{\cdot}945$, and $R_0 = 7{\cdot}66$ fm.

These values are close to those of Abbondano *et al* (1990). The result of the fit is shown in figure 3(a) for both the odd and even states. We find that the fit is quite

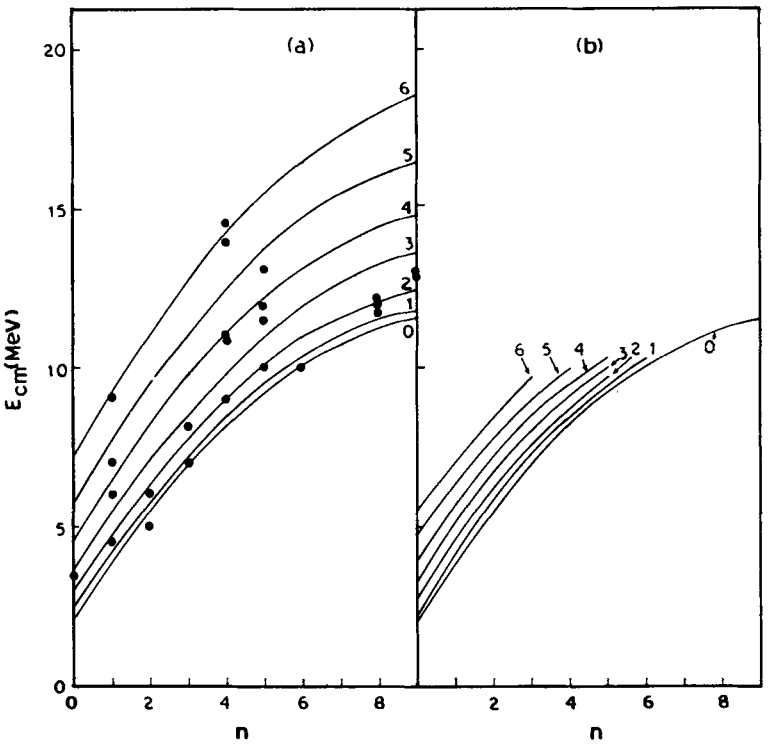

Figure 1. Comparison of $\alpha + {}^{12}C$ resonances for both odd and even values of L with the experiment and the calculation. (**a**) The full curves were calculated using the eigen-value expression (4) of the Schrödinger equation with the effective ion–ion potential. The full dots are the observed resonances. (**b**) The full curves are the bound states obtained by exact numerical solution of (2) (see text for details).

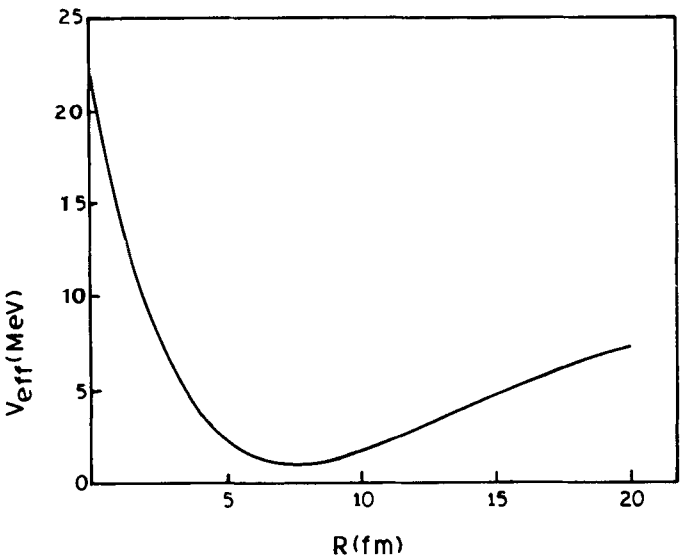

Figure 2. The effective potential (equation 1) for the $\alpha + {}^{12}C$ system, calculated from the set of parameters $A = 11{\cdot}51$ MeV, $B = 10{\cdot}35$ MeV, $\beta = 0{\cdot}885$ and $R_0 = 7{\cdot}53$ fm obtained through the fit of equation (4).

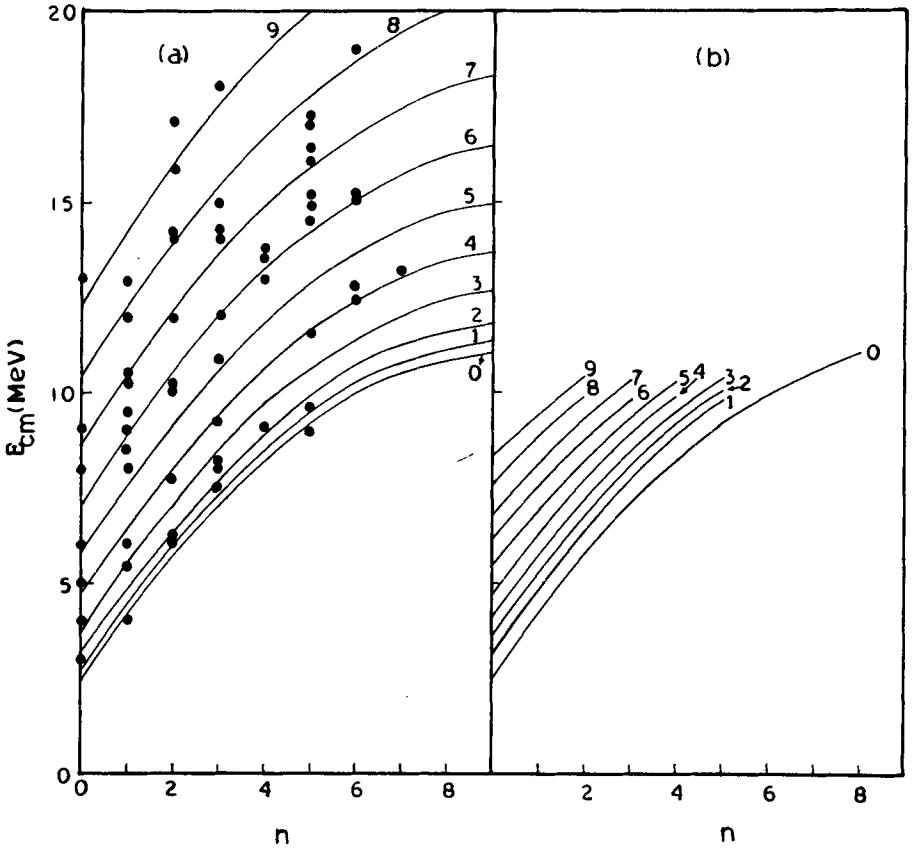

Figure 3. Same as figure 1 but for $\alpha + {}^{16}O$ system for all L.

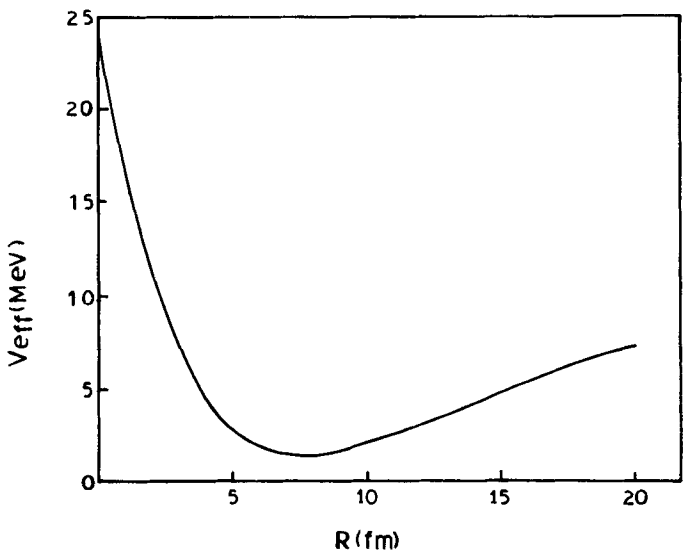

Figure 4. The effective potential for the $\alpha + {}^{16}O$ system, calculated from the set of parameters $A = 11{\cdot}02$ MeV, $B = 9{\cdot}48$ MeV, $\beta = 0{\cdot}945$ and $R_0 = 7{\cdot}66$ fm.

good. Thus all the states can be well described. Using these parameters, the effective potential was calculated which is presented in figure 4. The effective potential has a depth of 11 MeV, a long range of about 16 fm and a soft core of 22 MeV.

3. Bound and resonance states

In the preceding section, we have described all the states in $\alpha + {}^{12}C$ and $\alpha + {}^{16}O$ systems as bound states, since we have used the eigen value expression (4) to describe these states. The effective potentials determined through the fits have depths of 11·5 MeV and 11 MeV respectively. However from figures 1(a) and 3(a), we can see that many states lie above the top of the respective potential wells which obviously would not satisfy the criteria for bound states. However the states which lie within the potential well will have characteristics of bound states. It must be recalled here that using the Flügge approximation [equation (3)] for the centrifugal potential, we have been able to describe all the states as bound states. Thus there appears a contradiction quite similar to that found previously (Kato and Abe 1988) in our calculation of $^{12}C + {}^{12}C$ system. This was successfully countered by us (Satpathy and Sarangi 1990) by exactly solving the Schrödinger equation using numerical method for the bound states inside the well. We also calculated the resonances which lie above the top of the potential well following the method of phase shift analysis, and showed that, they lie in the vicinity of the experimental data thus vindicating the fact that most of the states which were inadvertently described as bound states earlier (Satpathy *et al* 1986) are in reality resonances. Following similar method, we will now calculate exactly the entire spectrum by dividing it into two parts: (i) the states within the potential well i.e. the bound states and (ii) the states above the top of the well i.e. resonances.

3.1 *The states inside the well*

We have to test how well the states given by (4) lying within the well agree with the exact numerical solution of the Schrödinger equation for various L values. This was done for both the systems. For $\alpha + {}^{12}C$ system, we found well defined bound states lie within the potential well i.e., within 11·5 MeV. These are plotted as full curves in figure 1(b) for both odd and even L values. Figure 1(a) depicts the approximate results obtained using the eigen value expression (4). It can be seen that the exact results agree quite well with the approximate ones up to $L = 3$. It is now found that there are 15 states lying within the well, qualify to be bound states which have been used in the fit of (4). The number of such states is much larger than the number of parameters (which is only four) to adequately determine them. Thus the nice agreement with the exact results obtained by numerical solution proves the validity of Flügge approximation for these states and reaffirms the goodness of the effective potential determined through the use of the data. Similar exact results for the bound states in $\alpha + {}^{16}O$ are also obtained by solving numerically the corresponding Schrödinger equation. Well-defined bound states are obtained within 11 MeV which is the depth of the effective potential for this system. In this case also, the number of states lying within the well is 28 which is much larger than the number of parameters. These are plotted as full curves in figure 3(b). It can be seen that these compare well up to $L = 4$ with

the approximate results of figure 3(a). The close agreement between the approximate results and the exact ones is due to the goodness of the Flügge approximation for this case also.

3.2 *States above the top of the well*

The states above the top of the well were described as bound states in §2, which could not be obtained in the exact solution of the Schrödinger equation above. For $^{12}C + ^{12}C$ system, it was shown by Satpathy and Sarangi (1990), that many of such states are resonances of the potential. Therefore we will like to calculate the resonances of the potential following the standard method of phase-shift analysis as done in $^{12}C + ^{12}C$. Since this potential is very long range, it is expected that it will have many resonances also. Before calculating the resonances, it is desirable to examine our effective potentials to see if they could support the existence of such states. In $\alpha + ^{12}C$ system, the highest angular momentum state observed is $L = 6$ at 20 MeV. In $\alpha + ^{16}O$ system, the state with angular momentum as large as 9 has been observed around 25 MeV. The most important criterion for a potential to sustain resonance with angular momentum L is that the total potential for this angular momentum ($V = V_{\text{eff}}(R) + (\hbar^2/2\mu R^2)\, L(L+1)$) must have a pocket. Hence, we would like to see if the effective potentials determined for the two systems would be able to support such high angular momentum states noted above. In figures 5 and 6, the total potential comprising of the effective potential and the centrifugal term for various L values in $\alpha + ^{12}C$ and $\alpha + ^{16}O$ systems are shown respectively. It is interesting to see that in

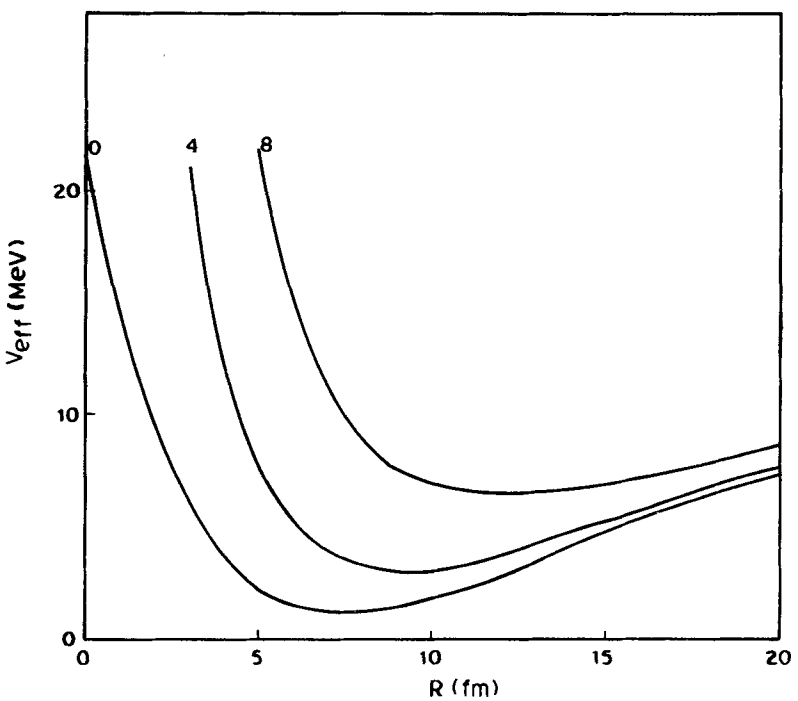

Figure 5. The effective potential equation (1) plus the centrifugal potential has been plotted for $L = 0$, 4, and 8 in $\alpha + ^{12}C$ system.

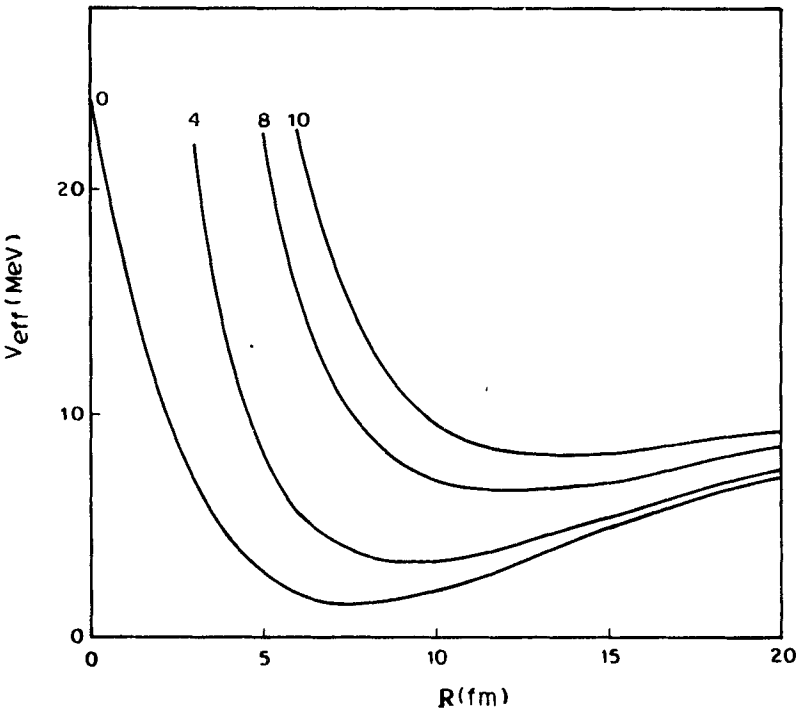

Figure 6. The effective potential equation (1) plus the centrifugal potential has been plotted for $L = 0, 4, 8, 10$ in $\alpha + {}^{16}O$ system.

the former case $L = 8$ has no pocket while $L = 6$ shows a shallow pocket which supports the observation of the higher angular momentum states of 6 experimentally. Similarly for the latter, the total potential for $L = 11$, does not show pocket while $L = 9$ shows a shallow pocket. Interestingly, such resonance with the angular momentum as high as 9 has been detected. This analysis strongly supports the goodness of the effective potential determined here from the resonances data for the two systems.

We have calculated the resonances using our effective potentials following the standard method of quantum mechanics. The details can be seen in Satpathy and Sarangi (1990). We calculate the phase shift and correspondingly the cross-section σ_L for various L values as a function of every E which is given by

$$\sigma_L(E) = \frac{4\pi}{k^2}(2L+1)\sin^2\delta_L(E) \tag{5}$$

where $k^2 = 2\mu E/\hbar^2$. Thus we plot $\sigma_L \sim E$ and identify the resonances. We have chosen a typical result of our calculation for the even angular momentum resonances in $\alpha + {}^{12}C$ system. Figure 7 shows the resonances for $L = 6$. In this, there are three clear resonances at 1·8, 3·8 and 8·2 MeV. As expected, the half width of the resonances increases with the rise of energy. It must be mentioned here that these states do not have any definite radial or vibrational quantum number n. So we have plotted them separately. For $\alpha + {}^{12}C$ system, the resonance energies thus calculated for both the odd and even L values are plotted against $L(L+1)$ in figure 8 as crosses. For $\alpha + {}^{16}O$

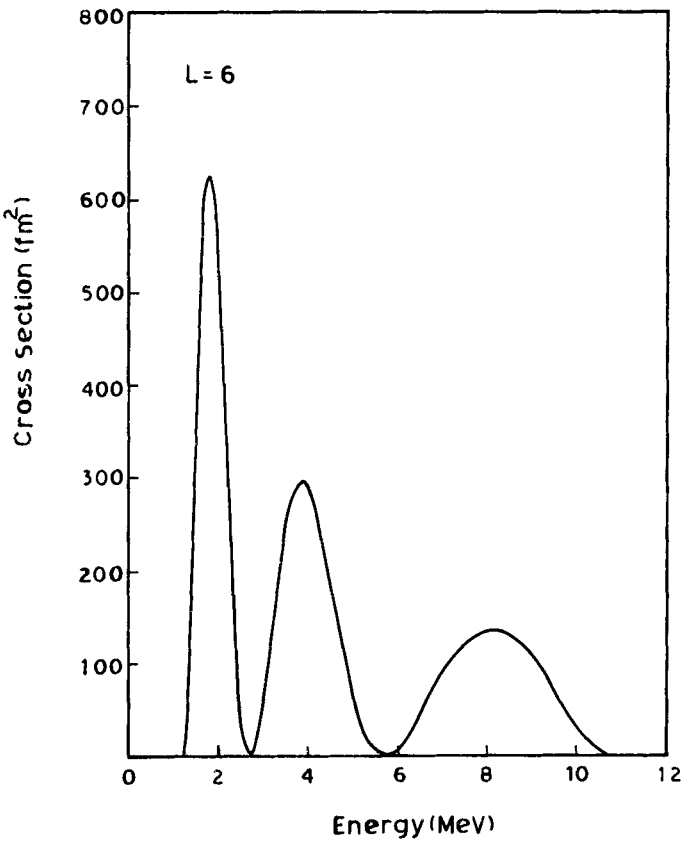

Figure 7. The variation of cross-section with energy for the orbital angular momentum $L = 6$ in $\alpha + {}^{12}C$ system. The figure shows the resonant structure in the cross-section.

system, the same are plotted as crosses in figure 9. In general we have included those states which have half width less than 2MeV. The experimental data are shown as solid dots in figures 8 and 9. It is indeed gratifying to find that in many cases, there are experimental data in the vicinity of our calculated resonances. In general, our calculation has predicted more states than detected so far. Experimentally several resonances in the relevant energy regions have been detected without assignment of their spins. Thus, we would conclude that those states lying above the top of the well which have been inadvertently described as boundstates, in § 2, (most of them) are really quasi-bound states i.e. resonances.

4. Discussion and conclusions

We have been able to describe most of the states with well-defined spin in both the $\alpha + {}^{12}C$ and $\alpha + {}^{16}O$ systems in a fully quantum mechanical model. In the former system about 20 states and in the latter about 45 states observed in experiment have been well accounted for. It will be interesting to examine how well the rotation-vibration characteristics are manifested in these systems? For well-defined rotational and vibrational features in a spectrum, the characteristic vibrational energy must be much

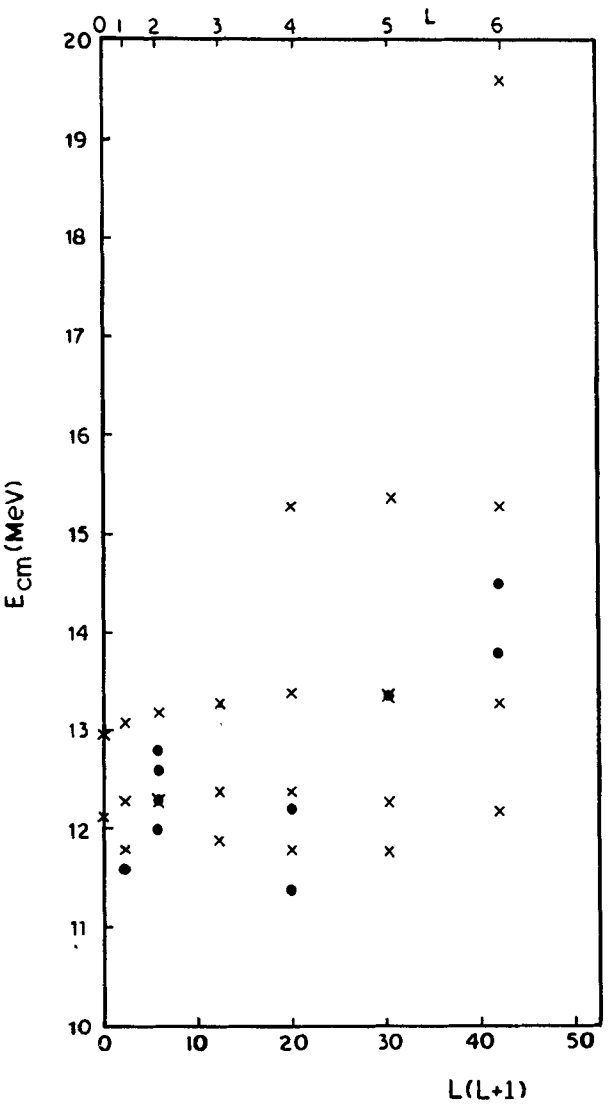

Figure 8. The calculated resonance states have been presented as (x) in the energy against $L(L+1)$ plot for both odd and even values of L of the $\alpha + {}^{12}C$ system. The solid dots are the experimental data.

larger than the rotational energy. In the present model, the ratio of the characteristic rotational to vibrational energy is given in terms of the parameters of the potential as

$$\frac{E_{\text{rot}}}{E_{\text{vib}}} = \frac{1}{2\beta\gamma},$$

where γ is defined by (4). For both the systems, the above ratio is 0·06 which is quite small and similar to that of ${}^{12}C + {}^{12}C$ system in which this ratio is 0·05. Thus the rotation-vibration features are quite well pronounced. This rotation-vibration must be contrasted with the usual rotation-vibration observed in low energy nuclear spectra.

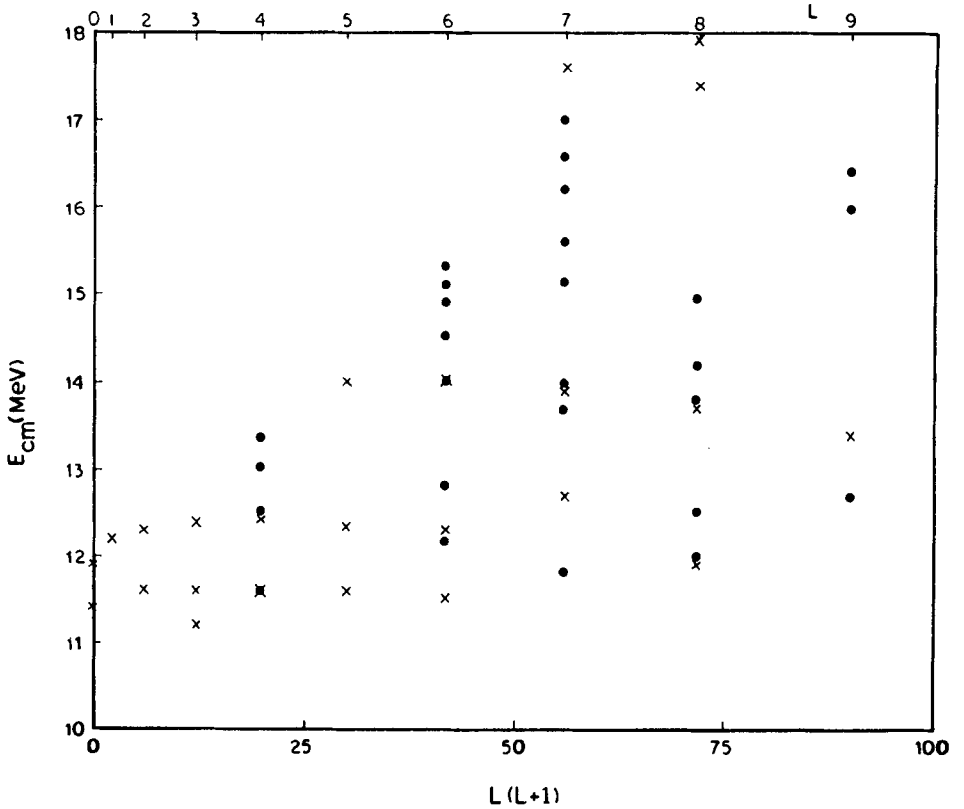

Figure 9. Same as figure 8 but for the $\alpha + {}^{16}O$ system.

Here the rotation takes place around the common centre of mass of the two nuclei, and vibration occurs by the vibration of the internuclear separation distance. Thus in the present model, they are of dipole origin. The usual rotation vibration seen in low lying nuclear spectra are of quadrupole origin where the shape of the nucleus undergoes rotation and vibration. The characteristic E_{rot}/E_{vib} for such quadrupole degree of freedom in the typical examples of ^{188}Os and ^{190}Os are 0·04 and 0·05 (Eisenberg 1970) respectively which are quite similar to the values in the present case.

From the effective potentials determined here, both the systems show similar behaviour. The depths of the potentials are similar being about 11 MeV. The highest angular momentum states observed in $\alpha + {}^{12}C$ and $\alpha + {}^{16}O$ systems are 6 and 9 respectively. The somewhat higher angular momentum states in the latter system may be understood in terms of its effective potential which will have pocket for higher L values because of lower centrifugal potential arising out of its higher effective mass. This is quite clear from the effective potential shown in figures 2 and 4 respectively, for $\alpha + {}^{12}C$ and $\alpha + {}^{16}O$. The larger number of states observed in the latter system are mainly due to these extra partial waves. Thus these experimental facts are in conformity with the prediction of the model. It must be emphasized that, at the heart of the present successful description is the effective potential whose bound and resonance states describe most of the states. The general features of these potentials determined here can be understood and reconciled with our knowledge from other areas of nuclear physics like nuclear structure and heavy ion reactions. The depth of

11 MeV may be accounted for in the following way. As has been pointed out (Satpathy *et al* 1986 and Sarangi *et al* 1990) on many occasions, the second 0^+ state at 7·65 MeV in ^{12}C is expected to play an important role in the mechanism of nuclear molecular resonances. This state being a linear chain of three α-cluster has a length of about 11 fm. This strongly prolate deformed state could support a rotational band with even angular momentum states. Thus in the collision of α on ^{12}C, if these states are excited, the system will find itself in a potential well of around 10 MeV. Because of the highly elongated shape of the state a range of 15 fm for $\alpha + ^{12}C$ system in this configuration is quite possible. Similarly in the case of $\alpha + ^{16}O$ system, the depth of 11 MeV can be accounted for as follows. In ^{16}O, there are two highly deformed 0^+ states at 6 and 11 MeV. The excitation of these states during the course of collision can transfer energy from the relative motion to the intrinsic excitation, leading to the trapping of the two ions in a potential well of around 10 MeV. Thus the effective potentials determined here can be understood from the point of veiw of nuclear structure. From the standpoint of the dynamics of heavy-ion collisions, these features can also be accounted for. It has been shown by Gross and Satpathy (1982a,b) in their extensive studies of fusion and deep inelastic collision phenomena in the frame work of their surface friction model, that the colliding nuclei develop oblate deformation in the entrance channel and very strong prolate deformation with symmetry axis collinear, in the exit channel. This feature of nuclear dynamics has been established in numerous calculations. Thus the effective potential determined here is the one seen by the two nuclei at the final phase of the reaction in the exit channel. Further, microscopic studies (Kruppa *et al* 1991) in the frame work of coupled channel formalism has also shown that the system develops strong prolate deformation when large number of channels are taken into account in the relevant region of energies. Thus a long range of 15 fm and depth of about 11 MeV are very much compatible with the known features of nuclear dynamics.

It must be emphasized here that the rotation-vibration features emerge naturally in this present model. We have only put in our model the general features of the heavy-ion potential known from the numerous calculations carried out in the past two decades. It has been supposed that the combination of a Morse potential and a constant can be a good representation of the effective potential between the two ions. Thus rotation-vibration feature is not an input in the model. The model has not been tailored towards the goal by putting a rotation-vibration Hamiltonian, as has been done in anharmonic rotation-vibration model of Cindro and Greiner (1981). Thus in the present model, the rotation-vibration feature of NMR naturally emerges in a more or less predictive manner. It must be noted here that, the effective potentials (figures 2 and 4) are positive for all values of r, i.e. they lie above the abscissa. Thus, the states inside the potential well will not be permanently stable. They will decay by tunnelling and as such will be quasi-stable. Therefore, the entire group of states in the present model has the characteristics of resonance states, which is in conformity with their nature observed in experiment. Thus, all these states in the present model are really resonance states. This is indeed very satisfying.

In view of the above, the mechanism of the quasi-molecular states observed in $\alpha + ^{12}C$ and $\alpha + ^{16}O$ systems is quite similar to that in $^{12}C + ^{12}C$ system as proposed earlier (Satpathy *et al* 1986, 1990). The mechanism of NMR that emerges from the series of studies is the following. The two spherical nuclei in their ground state, approach each other in the entrance channel. After the two nuclei come closer by

over-coming the Coulomb barrier, they form a composite system. In the exit channel, strong prolate deformation is developed. The stretched our configuration of the prolate deformation produces a thick Coulomb barrier which inhibits separations. While separating they undergo rotation and vibration like diatomic molecule and generate characteristic molecular type resonance states. Finally they separate out with the restoration of the original shape in the exit channel. It must be mentioned here that the effective potential determined here is the one seen by the two ions in the exit channel. This mechanism seems to be quite different from those of Imanishi *et al* (1969) and others in which the quasi-molecular states are supposed to be produced in the early phase of the collision in the entrance channel, before undergoing fusion and other absorptive process.

It is gratifying to find that the above mechanism which had emerged from our earlier study of $^{12}C + {}^{12}C$, $^{12}C + {}^{16}O$ and $^{16}O + {}^{16}O$ systems, now seems to be quite general to be able to describe the $\alpha + {}^{12}C$ and $\alpha + {}^{16}O$ systems equally well.

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