PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 70, No. 5
May 2008
pp. 847–862

Resonance states in ^{16}O+^{16}O, ^{12}C+^{16}O, α+^{16}O and α+^{12}C with modified Morse potentials

B SAHU[1,*] and L SATPATHY[2]
[1]Department of Physics, North Orissa University, Takatpur, Baripada 757 003, India
[2]Institute of Physics, Sachivalaya Marg, Bhubaneswar 751 005, India
[*]Corresponding author. E-mail: bd_sahu@yahoo.com

MS received 19 November 2007; revised 9 January 2008; accepted 30 January 2008

Abstract. The resonance states in ^{16}O+^{16}O, ^{12}C+^{16}O, α+^{16}O and α+^{12}C are described using modified Morse potential proposed earlier whose success has already been demonstrated in the case of ^{12}C+^{12}C system. The general validity of such a potential with long range, shallow depth and repulsive soft core determined from the resonance data itself is being examined through the present study of the resonances in the above four systems. In each system, the experimental data of a large number of states have been successfully described with a modified Morse potential. The success points out a common mechanism of the origin of these states, and reaffirms authentically the diatomic-like rotational and vibrational picture of the nuclear molecular resonances proposed previously. The close resemblance between the physics of diatomic molecules and nuclear molecular resonances extending to the level of potential which is Morse type in both the cases – although belong to two different areas of physics – is further strengthened through the present study.

Keywords. Elastic and quasi-elastic scattering; resonances; low and intermediate energy heavy-ion reactions.

PACS Nos 25.70.Bc; 25.70.Ef; 25.70.-z

1. Introduction

The phenomenon of nuclear molecular resonances (NMR) discovered [1] as early as in 1960, has defied to date, a satisfactory understanding [2,3] at a fundamental level in terms of nuclear interaction and dynamics. Phenomenological description [4–7] has not been very successful either. The most studied system, both theoretically and experimentally [8,9], is the ^{12}C+^{12}C system which exhibits more than 40 such states. The proper description of this phenomenon is dynamical in nature, in which the potential between the two colliding pair of nuclei and their shapes are the evolving entities which should be determined in every step by the laws governing the collision process. Thus starting with two well-separated nuclei in their ground state, the microscopic description should predict the evolution of the collision process leading to the formation of NMR. This is too complex to be achievable in the near future. A pedagogical approach [9] developed earlier called dynamic potential model (DPM), treats this phenomenon fully quantum mechanically. It identifies the essential collective coordinate of the many-body dynamics to be the separation distance between the colliding nuclei, to govern the physics of NMR. Thus the system has been reduced to a two-body problem with an effective potential acting between them. The prominent rotational and vibrational features in the empirical resonance spectra of NMR quite akin to those seen in the case of diatomic molecules, had spurred us to propose the effective potential to be of Morse [10] type. So we had taken Morse potential plus a constant [11] to represent the effective potential

$$V_{\mathrm{eff}}(r) = A + B[\exp(-2\beta x) - 2\exp(-\beta x)], \tag{1}$$

where $x = (r - R_0)/R_0$, whose four parameters A, B, β and R_0 could be determined by fitting the resonance data of $^{12}C+^{12}C$ itself. The potential so determined has a shallow depth, long range of about 15 fm, and a soft repulsive core. Following the usual phase-shift method, the resonances were calculated and about 36 states could be described. Subsequently this approach was applied to $^{16}O+^{16}O$, $^{12}C+^{16}O$, $\alpha+^{12}C$ and $\alpha+^{16}O$ with equal success [9,12–14]. The mechanism of resonances that emerged from this study [9] is the following. The two nuclei in the entrance channel when they are far apart, are in general in their respective spherical ground state. If they approach each other they develop oblate deformation due to repulsive Coulomb force. At the distance of closest approach which they reach either by overcoming the Coulomb barrier or sub-barrier tunneling, they retain their identity attending the maximum of oblate deformation. In the exit channel they develop strong prolate configuration due to which they are caught behind a thick Coulomb barrier. In an effort to separate, they undergo rotation and vibration, thereby develop the NMR. Thus these states are produced in the final phase of the reaction in the exit channel. The long range of about 15 fm of the effective Morse potential determined in the case of $^{12}C+^{12}C$ system is a reflection of this feature. This mechanism is altogether different from other mechanisms [2,3] in which the resonances are produced in the early phase in the entrance channel before undergoing fusion and other absorption processes. The hypothesis of molecular window [15,16] of low level density is not necessary to rescue these states from being washed away in the sea of high level density of the corresponding compound nucleus, as NMR is being described here all along in the dinuclear picture.

Kato and Abe [17] re-examining our results, could reproduce all our states inside the pocket of the effective Morse potential, and also the low-lying ones at the top of the potential. However, they could not reproduce the high-lying ones. There upon we identified [18] the two discomfitures of our potential: (i) its shallow behavior at the outer edge, which to be realistic should be steeply rising like the Wood–Saxon potential and (ii) the inappropriate insertion of Coulomb potential in the tail region violating the continuity. To repair these two defects we constructed a potential retaining all its essential features like depth, range and the repulsive soft core, with the incorporation of the above two features, and termed it as modified Morse potential [18] given by

$$V_{\mathrm{eff}}(r) = \begin{cases} V_I \mathrm{e}^{-a_I r} + V_0[\xi_1 - (\xi_1 - \xi_2)\rho_1(r)], & \text{if } r \le R_m \\ V_0 \xi_2 \rho_2(r), & \text{if } r > R_m \end{cases} \tag{2}$$

where

$$\rho_n(r) = \left[\cosh^2 \frac{r - R_m}{d_n}\right]^{-1}, \quad n = 1, 2 \tag{3}$$

and $V_0 > 0$ with the eight parameters V_0, ξ_1, ξ_2, R_m, d_1, d_2, V_I and a_I. This potential is quite flexible in admitting varieties of shapes. We had recalculated the resonances of the ^{12}C+^{12}C system using this modified Morse potential in the more versatile S-matrix approach where the specifically developed [19] imaginary test potential (ITP) and imaginary phase shift (IPS) methods were applied for unambiguous and authentic identification of resonances. In this study, hereafter referred to as I, we showed that more than 25 resonances with $L = 0^+$–12^+ with well-defined spin and parity, lie in the same energy region where such states are observed in experiment, thus reaffirming the rotation–vibration picture of NMR proposed earlier. This close resemblance extending right up to the level of potential, between the physics of NMR and diatomic molecules belonging to two different areas was shown. In the present paper we extend this study to the four reactions ^{16}O+^{16}O, ^{12}C+^{16}O, α+^{16}O and α+^{12}C to see if the modified Morse potential can describe the resonances in all these systems, and the above conclusions are not ^{12}C+^{12}C specific, but are general features of the NMR phenomenon.

In I, we had described in detail the method of calculation of the resonances and their authentic identification in the case of ^{12}C+^{12}C. Here we have adopted exactly the same, and hence we have omitted its description in the present paper. The interested readers may refer to it. In §§2, 3, 4 and 5, we have presented the results of our study of resonances on ^{16}O+^{16}O, ^{12}C+^{16}O, α+^{16}O and α+^{12}C systems respectively. Section 6 contains the discussion and §7 the conclusions.

2. ^{16}O+^{16}O system

The parameters of the effective Morse potential (1) have been obtained [9,13] by fitting 25 observed resonance states with spin in the range $L = 2^+$ to $L = 24^+$ spread up to excitation energy of about 40 MeV. The values of the four parameters are

$$\begin{aligned} A &= 22.85 \text{ MeV}, \\ B &= 19.00 \text{ MeV}, \\ \beta &= 0.963, \\ R_0 &= 7.47 \text{ fm}. \end{aligned}$$

This effective potential comprising the Morse potential plus the Coulomb tail for $L = 0$ is shown in figure 1a as a dotted curve. The corresponding modified Morse potential obtained with the incorporation of the above two corrections is presented as a solid curve in the same figure, whose parameters are $R_{\rm m} = 12.06$ fm, $d_1 = 0.25$, $d_2 = 10.0$, $\xi_1 = 2.5$, $\xi_2 = 7.63$, $V_0 = 1$ MeV, $V_I = 53$ MeV and $a_I = 0.505$. The Coulomb potential commences from $r = 12.06$ fm. This potential has a depth of 5.13 MeV, a long range of 12 fm and a repulsive soft core of 53 MeV. In figure

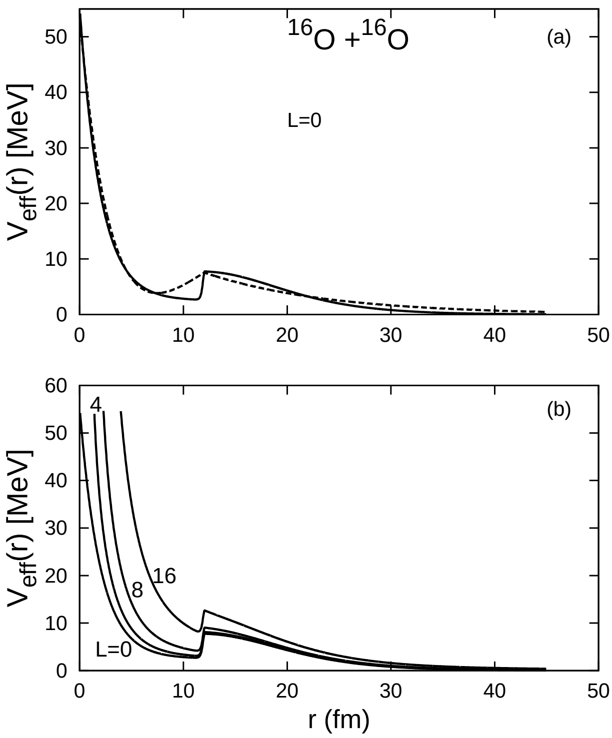

Figure 1. Plot of potential as a function of the radial position. (**a**) The Morse potential (dashed curve) expressed by (1) with Coulomb tail beyond $r = 10.3$ fm is compared with the newly constructed modified Morse potential (solid curve) expressed by (2) for $L = 0$. (**b**) The modified Morse potential (2) for $L = 0$, 4, 8, 16.

1b, this modified Morse potential plus the centrifugal potential for $L = 0$, 4, 8, 16 are presented to show the respective potential pockets and thereby its ability for sustenance of resonances.

Following the method elaborated in I, resonances were calculated for the above modified Morse potential, and 56 states spread up to 40 MeV of excitation with spin $L = 0$ to 24 were obtained. The TIP and IPS methods followed in the calculation using the test imaginary potential

$$V_{\mathrm{T}} = -iW_0[1 - \rho_I(r)], \quad \text{if } r < R_m \tag{4}$$

with ρ_I as defined in (3) and $W_0 = 0.1$ MeV ensured the genuineness of these resonances, which was further ascertained by plotting the respective wave function $|\psi|$ as a function of r. As representative examples, in figures 2a and 2b, the modulus of the wave function of the resonances at 8.98 MeV and 11.74 MeV with spin $L = 10$ are presented respectively. The concentration of the wave function with higher amplitude in the interior region of the potential shows the authenticity of the resonances. Our above modified Morse potential is entirely a real potential. The actual collision of the two nuclei is always associated with some absorptive

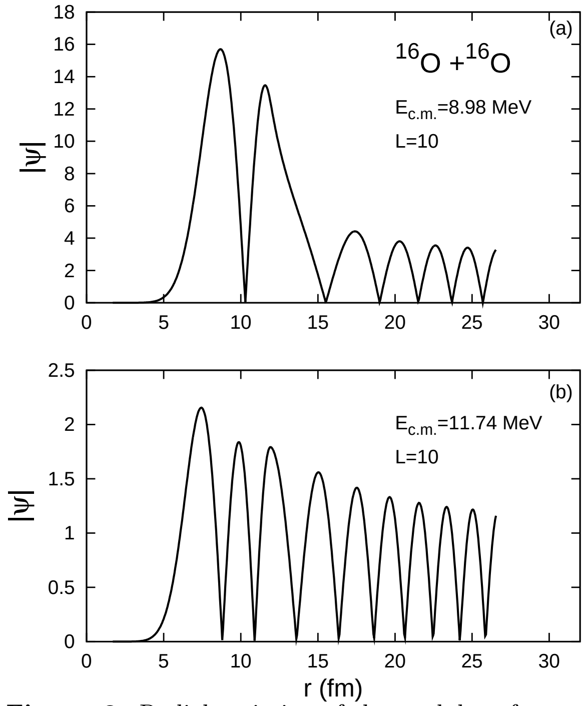

Figure 2. Radial variation of the modulus of wave function for $L = 10$ at resonance energies $E_{\text{c.m.}}$=8.98 MeV (**a**) and $E_{\text{c.m.}}$=11.74 MeV (**b**).

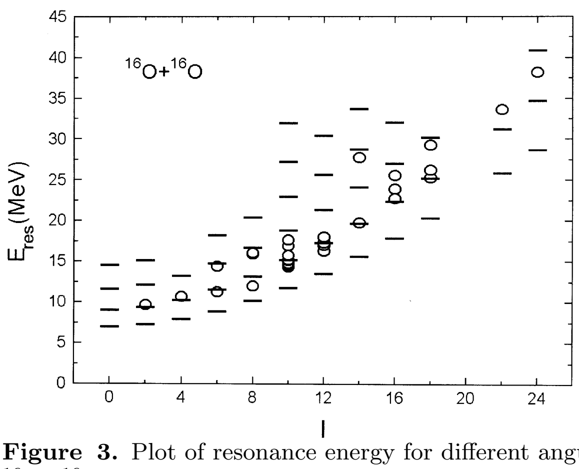

Figure 3. Plot of resonance energy for different angular momenta L for the ^{16}O+^{16}O system. Present calculated results are shown by solid lines (–) and the corresponding experimental results are represented by open circles (○).

processes however weak they may be. To simulate this physical feature we have added a weak imaginary potential $W = 0.5$ and recalculated the resonances. The results so obtained are shown as solid lines in figure 3, where the experimental data

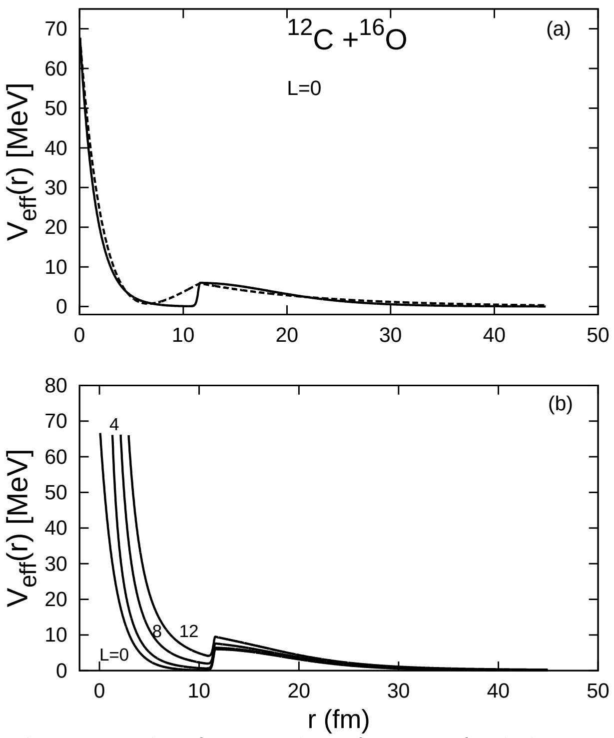

Figure 4. Plot of potential as a function of radial position. (**a**) The Morse potential (dashed curve) expressed by (1) with a Coulomb tail beyond $r = 11.62$ fm is compared with the newly constructed modified Morse potential (solid curve) expressed by (2) for $L = 0$. (**b**) The modified Morse potential for $L = 0$, 4, 8, 12.

are shown as open circles. It is pleasing to see that the calculated spectra for all the spin $L = 0^+$ to 24^+ lie close to the observed spectra in the relevant energy region. The modified Morse potential produces more than 25 states starting from ground state up to excitation energy as high as 40 MeV in accordance with experiment. It is desirable to have a comparison with the ^{12}C+^{12}C system [12] where the highest spin state observed was 12^+ at about 20 MeV of excitation. This feature is a reflection of the comparatively shallower modified Morse potential of about 3 MeV compared to that of ^{16}O+^{16}O which is about 5.13 MeV. Consistency of description of both the systems is quite satisfying.

3. ^{12}C+^{16}O

The parameters of the effective Morse potential determined before [9,13] by fitting the resonance data of about 35 states comprising of both odd and even states are

$A = 16.72$ MeV,
$B = 15.99$ MeV,
$\beta = 1.22$,
$R_0 = 6.65$ fm.

For $L = 0$, this is shown in figure 4a as a solid curve. The corresponding modified Morse potential which has the values of the parameters as $R_m = 11.62$ fm, $d_1 = 0.25$, $d_2 = 10$, $\xi_1 = 0.0$, $\xi_2 = 5.95$, $V_0 = 1$ MeV and $a_I = 0.65$ is presented as a dotted curve in the same figure. The Coulomb tail commences from $r=$ 11.62 fm. This potential has a depth of 5.95 MeV, range 11.62 fm and a repulsive soft core of 70 MeV. In figure 4b, this modified Morse potential together with the centrifugal potential for $L = 0$, 4, 8 and 12 are presented to show the structure of the respective potential pockets. This being an asymmetry system, both odd and even spin resonances are manifested. The calculation of these states were carried out as before. As representative examples, we have displayed the modulus of the wave function $|\psi|$ of the two calculated resonance states with $L = 9$ at 9.88 MeV and 13.55 MeV in figures 5a and 5b respectively to show their structure. The accumulation of wave function in the inner region of the potential with higher amplitude testifies the genuineness of these resonances.

Experimentally, about 35 states comprising both odd and even angular momenta in the range $L = 4$ to 16 are observed within about 30 MeV of excitation. The

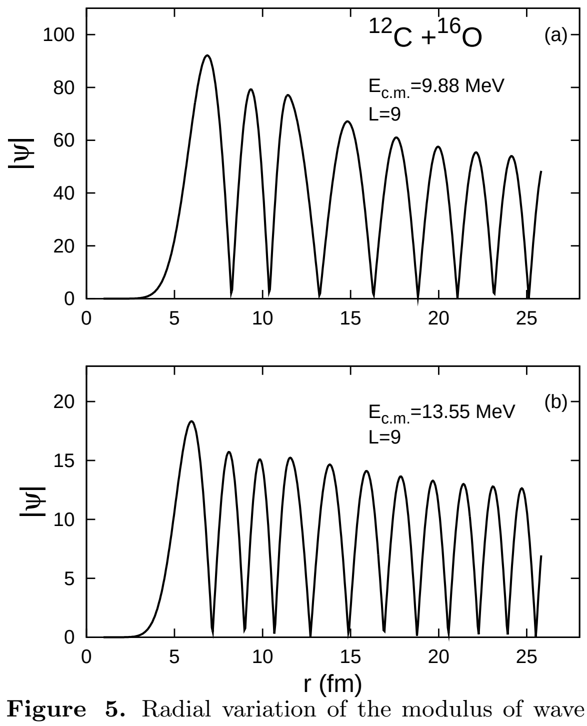

Figure 5. Radial variation of the modulus of wave function for $L = 9$ at resonance energies $E_{\mathrm{c.m.}} = 9.88$ MeV (**a**) and $E_{\mathrm{c.m.}} = 13.55$ MeV (**b**).

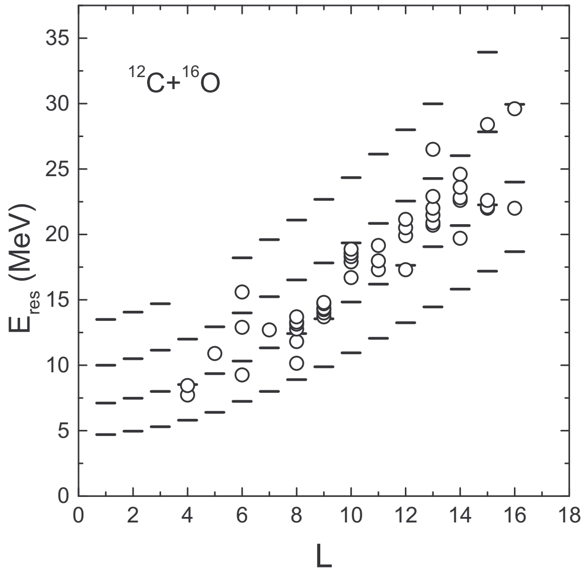

Figure 6. Plot of resonance energy for different angular momenta L for the $^{12}C+^{16}O$ system. Present calculated results are shown by solid lines (–) and the corresponding experimental results are represented by open circles (∘).

present calculation quite satisfactorily produces a large number of states with $L = 0$ to 16 in this energy range often quite close to the data. In figure 6, the calculated states and the experimental states are shown as solid lines and closed circles respectively. The agreement can be considered quite reasonable.

4. $\alpha+^{16}$O system

This system exhibits a large number of resonances of both odd and even spin out of which 65 states with well-defined spin and parity were selected for fitting with the Morse potential. The parameter so determined in refs [9,14] are

$$A = 11.02 \text{ MeV},$$
$$B = 9.48 \text{ MeV},$$
$$\beta = 0.945,$$
$$R_0 = 7.66 \text{ fm}.$$

For $L = 0$, this potential is shown as a solid curve in figure 7a. The corresponding modified Morse potential is shown as a dotted curve in the same figure the parameters of which are $R_m = 10.3$ fm, $d_1 = 0.15$, $d_2 = 10$, $\xi_1 = 1$, $\xi_2 = 2.1$, $V_0 = 1$ MeV, $V_I = 25$ MeV and $a_I = 0.50$. The Coulomb tail commences from $r = 10.3$ fm. This potential has a depth of 1.1 MeV, a long range of 10.3 fm and a repulsive core of 22 MeV. In figure 7b, this modified Morse potential plus the centrifugal potential for $L = 0$, 2, 4, 6 are displayed which show the potential pockets for all

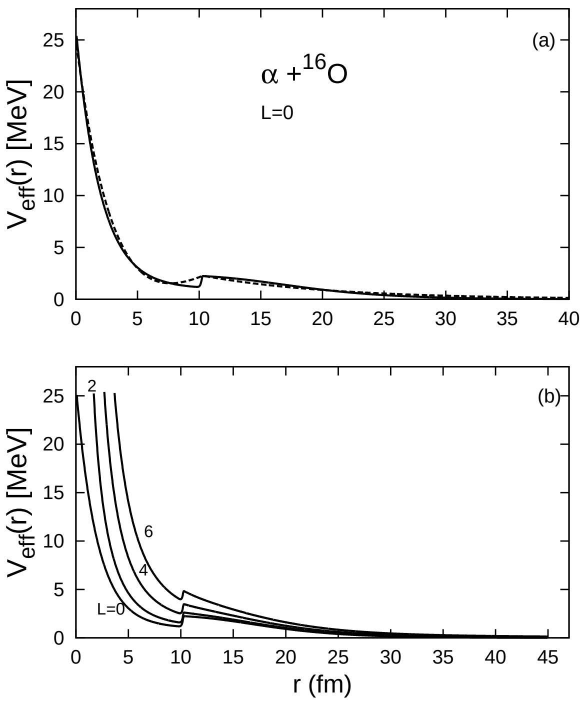

Figure 7. Plot of potential as a function of radial position. (**a**) The Morse potential (dashed curve) expressed by (1) with a Coulomb tail beyond $r = 10.3$ fm is compared with the newly constructed modified Morse potential (solid curve) expressed by (2) for $L = 0$. (**b**) The modified Morse potential for $L = 0$, 2, 4, 6.

these angular momentum states. The calculation of resonances with both the odd and even angular momenta were carried out following the same method as above. The highest angular momentum state $L = 9$ observed in this system is at 19.1 MeV. Our calculation produces 18 resonances with $L = 0$ to 9 spread over an excitation of 18 MeV most of which are close to experimental values of resonances. In figures 8a and 8b, the modulus of wave function $|\psi|$ for the two calculated resonances with $L = 2$ at excitation energies of 2.90 MeV and 5.96 MeV are shown as representatives. The accumulation of wave function with higher amplitude in the interior region, a characteristic feature of resonance formation, is evident in the figure. The calculated spectra along with the experimental states are shown in figure 9 as solid lines and open circles respectively. Experimentally, a large number of resonances are observed many of which are overlapping.

5. α+^{12}C system

This system exhibits more than 20 resonances with well-defined spin and parity with angular momentum range 0 to 6^+ within an excitation energy of about 15 MeV.

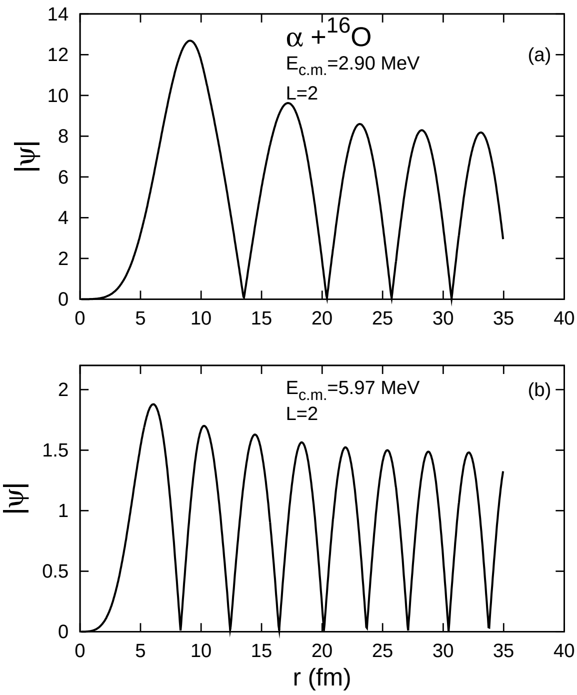

Figure 8. Radial variation of the modulus of wave function for $L = 2$ at resonance energies $E_{\rm c.m.}$=2.90 MeV (**a**) and $E_{\rm c.m.}$=5.97 MeV (**b**).

Being an asymmetry system, it has both odd and even angular momentum states. In refs [9,14], the parameters of the effective Morse potential were determined by fitting 35 states with well-established spin. The parameters so determined are

$$A = 11.51 \text{ MeV},$$
$$B = 10.35 \text{ MeV},$$
$$\beta = 0.885,$$
$$R_0 = 7.53 \text{ fm}.$$

For $L = 0$, this potential is plotted in figure 10a as a solid line. The parameters of the corresponding modified Morse potential are determined as $R_m = 9.86$ fm, $d_1 = 0.15$, $d_2 = 10$, $\xi_1 = 0.75$, $\xi_2 = 1.65$, $V_0 = 1$ MeV, V_I=24 MeV and $a_I = 0.55$. This modified Morse potential is shown in figure 10a as a dotted curve. The Coulomb potential commences from $r = 9.86$ fm. The potential has a depth of 0.9 MeV, a long range of 9.86 fm and a soft core of 25 MeV. In figure 10b, this potential plus the centrifugal potential for $L = 0$, 2, 4, 6 are presented to show the pocket profile of the potential to find if resonances could be sustained. The calculation of the resonances for this potential were done following the same method as above. To see if the resonances are genuine, the mod of the wave function $|\psi|$ were plotted as function of r in each case. For two representative cases of resonances with $L = 2$ at energies 2.67 MeV and 5.89 MeV, $|\psi|$ is depicted in figures 11a and 11b

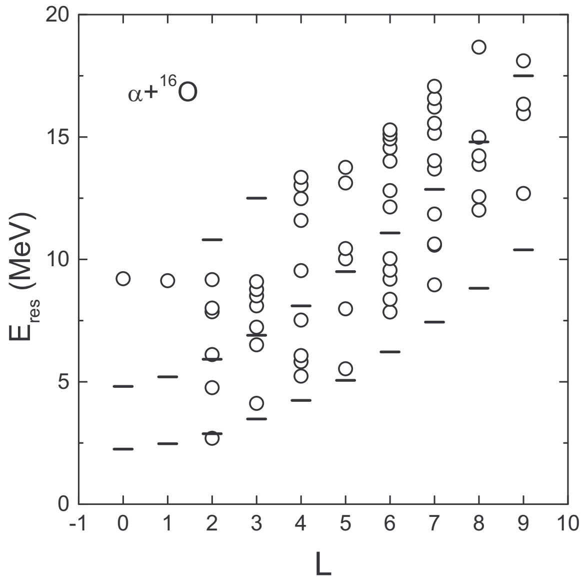

Figure 9. Plot of resonance energy for different angular momenta L for the α+^{16}O system. Present calculated results are shown by solid lines (–) and the corresponding experimental results are represented by open circles (○).

respectively. Concentration of the wave function in the form of larger amplitude at the interior region, a typical characteristic of resonances can be seen in both the figures. The predicted 14 resonances are presented as solid lines in figure 12 where the experimental ones are shown as open circles. It is nice to see that this potential produces states with angular momentum $L = 6$ at excitation energies 6.46 MeV and 13 MeV in the close proximity of the experiment. Many other states with lower angular momentum lie closer to experiment also. There are several high-lying states with $L = 1$, 2, +4 which the present model cannot describe. These states may be produced by some other mechanism.

6. Discussions

The NMR in all the four systems ^{16}O+^{16}O, ^{12}C+^{16}O, α+^{16}O and α+^{12}C have been described in a common approach using modified Morse potential whose success has been demonstrated earlier in the case of ^{12}C+^{12}C system. The number of resonances described are about 25, 35, 20 and 14 respectively which span the observed energy and spin distributions in each case. Considering the present study to be microscopic in nature, the success can be termed as quite reasonable. The modified Morse potential in each case has been derived from the corresponding effective Morse potential whose parameters have been determined by fitting the resonance data itself. The characteristics of the potentials show a systematic trend having long range, shallow depth and repulsive soft core. For a holistic view, the ranges and depths of these four potentials together with those of ^{12}C+^{12}C studied earlier

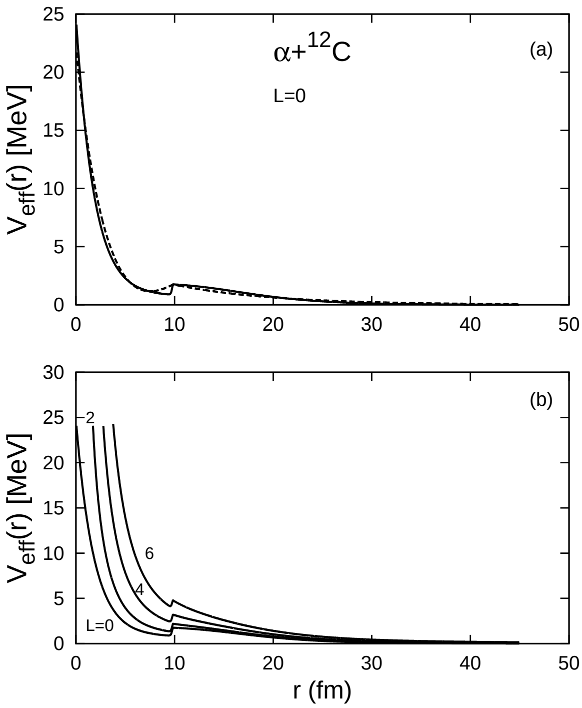

Figure 10. Plot of potential as a function of radial position. (**a**) The Morse potential (dashed curve) expressed by (1) with a Coulomb tail beyond $r = 9.86$ fm is compared with the newly constructed modified Morse potential (solid curve) expressed by (2) for $L = 0$. (**b**) The modified Morse potential for $L = 0$, 2, 4, 6.

have been displayed in figures 13a and 13b respectively. The ^{12}C+^{12}C system has a comparatively longer range of about 15 fm which has been shown in [9] to be due to the preponderance of the linear chain of 3α clusters 0^+ at 7.65 MeV excitation in ^{12}C. This is the famous Hoyle state which plays a key role in the synthesis of carbon nucleus in the stellar evolution. It is indeed satisfying that in figure 13a this feature is manifested as a peak. On the other hand in ^{16}O+^{16}O, the bonding potential will be predominantly determined by the first collective excited state at 6.06 MeV in ^{16}O nucleus. Unlike in the ^{12}C case, this state is not a linear chain of 4α clusters but a prolate deformed state of 4p–4h nature. So the range of the potential is substantially smaller for ^{16}O+^{16}O compared to ^{12}C+^{12}C system. There is indeed a linear chain of 4α clusters 0^+ state at 16.75 MeV excitation [20] in ^{16}O which is a 8p–8h state. But unlike ^{12}C it is at a very high excitation level to play a serious role in the formation of resonances. Hence, although ^{16}O+^{16}O system is a larger system than ^{12}C+^{12}C, the range of the bonding potential is lower in the former compared to that in the latter. For the ^{12}C+^{16}O system, the range is 11.62 fm which is lowest amongest the three systems ^{16}O+^{16}O, ^{12}C+^{12}C and ^{12}C+^{16}O. This is a smaller system compared to ^{16}O+^{16}O system. More importantly, the 6.06 MeV 0^+ state in ^{16}O being at a relatively lower excitation compared to the

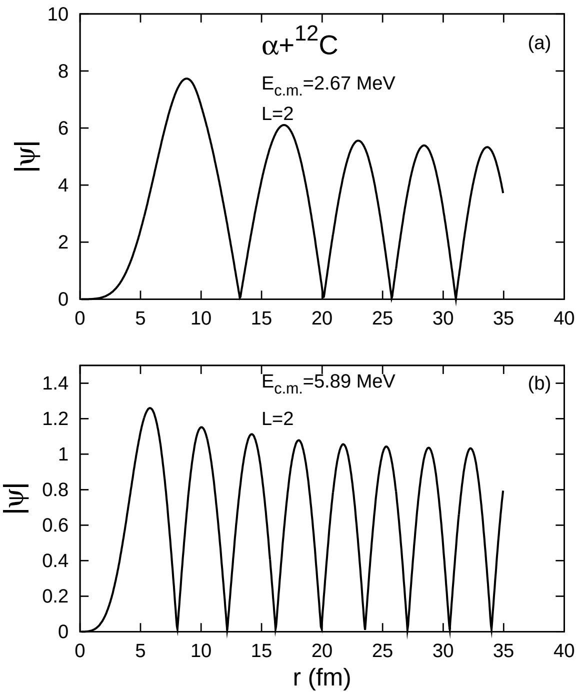

Figure 11. Radial variation of the modulus of wave function for $L = 2$ at resonance energies $E_{\text{c.m.}}$=2.67 MeV (**a**) and $E_{\text{c.m.}}$=5.89 MeV (**b**).

7.65 MeV 0^+ state (3α chain) in ^{12}C, is likely to play a dominant role in the determination of the bonding potential. Hence the range of the potential is the lowest amongest the three systems. In the case of the finite square well potential, the product of the strength and square of the range determines the number of bound states. The resonance states being quasibound states, for the modified Morse potential such a relation may be qualitatively valid which seems to be the case for the two symmetric systems ^{12}C+^{12}C and ^{16}O+^{16}O. In each of the two cases 25 states have been described. The lower ranges of 10.3 fm and 9.86 fm in α+^{16}O and α+ ^{12}C systems respectively are determined by the heavier partner. These potentials do not resemble the sudden and adiabatic potentials normally used in various calculations. They represent the potential in the final phase of the reaction in the exit channel where the colliding nuclei are strongly prolate deformed undergoing rotation and vibration before separation. This mechanism of NMR which emerged in our earlier extensive study, is being reaffirmed here through more authentically correct calculation.

It is worth pointing out here, how the accumulation of wave function occurs in the interior of the potential giving rise to resonance formation particularly at high excitation energy. Our previous effective Morse potential with its shallow behavior at the outer edge cannot produce resonance at high excitation energy. Here we repaired it by making it steeply rising which is realistic, and thereby the resonances at higher energy could be produced by the reflection of the wave function at this

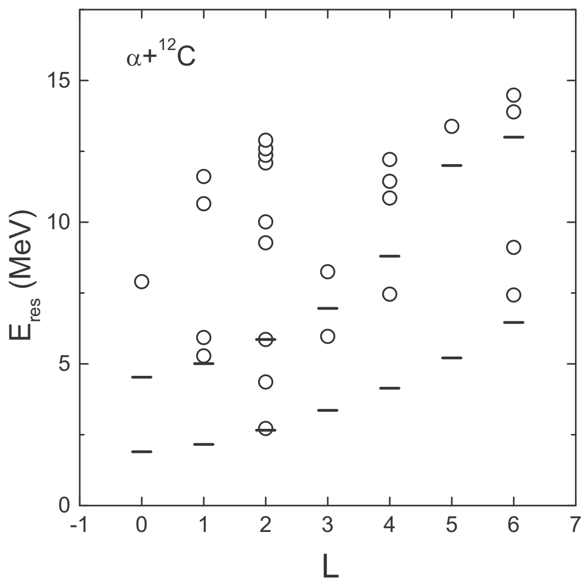

Figure 12. Plot of resonance energy for different angular momenta L for the $\alpha+^{12}$C system. Present calculated results are shown by solid lines (–) and the corresponding experimental results are represented by open circles (∘).

edge leading to accumulation. Thus our modified Morse potential is endowed with the ability to produce resonances at both high and low excitations. Although the depth of the potential is generally shallow, a large number of resonances are supported because of the long range.

Finally the rotation–vibration features of the resonance spectra empirically observed in all systems have been well-reproduced in our calculated spectra, which at fundamental level, originate from the Morse-like nature of the bonding potential. The members of the resonance spectra must result from a common substratum to exhibit this feature. It is indeed satisfying that the common substratum is the potential itself which is the most basic attribute of the system.

7. Conclusions

In summary, a reasonable description of the resonance spectra of ^{16}O+^{16}O, ^{12}C+^{16}O, $\alpha+^{16}$O and $\alpha+^{12}$C has been possible using modified Morse potential which was shown earlier in I to be successful in the case of ^{12}C+^{12}C. The modified Morse potential has been constructed by repairing the deficiencies, namely, the shallow behavior at the outer edge and the ad hoc insertion of the Coulomb tail in the effective Morse potential determined previously from the resonance data. Thus it retains all the main features of the effective Morse potential like long range, shallow depth and the repulsive soft core, and in addition to the new features of the steep outer edge and a smoothly continued Coulomb tail. Calculation of resonances in S-matrix approach using our TIP and IPS methods for authentic and

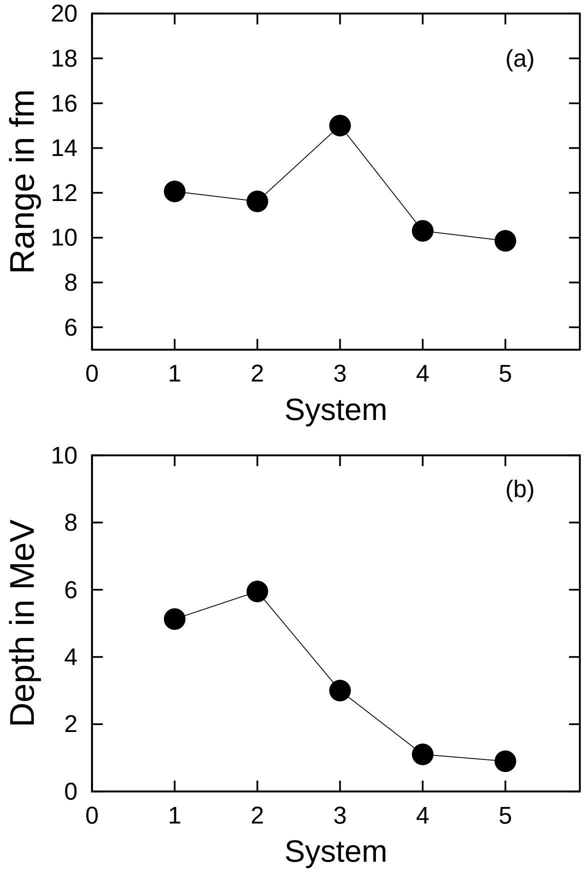

Figure 13. (**a**) Plot of ranges of the modified Morse potential for different systems. (**b**) Plot of depths of the same for different systems. In figures, 1: ^{16}O+^{16}O, 2: ^{12}C+^{16}O, 3: ^{12}C+^{12}C, 4: α+^{16}O and 5: α+^{12}C.

unambiguous identification of resonances, has been done as in I, with success in all the four systems. Our calculation has predicated 25, 35, 20 and 14 states in ^{16}O+^{16}O, ^{12}C+^{16}O, α+^{16}O and α+^{12}C covering the highest spin and excitation energy observed in experiment in each case. The ranges and the depths of these potentials show some systematic trend. The rotation–vibration feature of the spectra is reproduced. The long range nature of the potential reaffirms the mechanism of resonances arrived at earlier. That is, the two nuclei in the entrance channel being in their nearly spherical ground state approach each other; as they come closer by overcoming the Coulomb barrier or by sub-barrier tunneling, they develop oblate deformation mostly due to Coulomb interaction which reaches a maximum at the distance of closest approach. In the exit channel they develop strong prolate deformation giving rise to a thick Coulomb barrier behind which they are caught. In the effort to re-separate, they undergo rotation–vibration generating NMR. Finally they separate with the restoration of original shape. This mechanism is distinctly different from all other mechanisms proposed so far where NMR is produced in the entrance channel when the two nuclei come closer before undergoing fusion and other absorption processes. In the present mechanism, the necessity of the hypothesis of a low level – density window at the high excitation energy in the corresponding compound nucleus, is not necessary as the collision process takes place in the dinuclear regime. This mechanism is supported by extensive studies on deep inelastic and fusion phenomena in surface friction model by Gross and Satpathy [21] and also is in accordance with nuclear structure calculations [22,23].

The present study puts on a firm footing the close similarity of physics between the diatomic molecules and NMR at a fundamental level, most conspicuously manifested in the rotation–vibration feature of their respective spectra although they belong to two different areas of physics governed by totally different interactions, namely, electromagnetic and nuclear interactions respectively. It is all the more interesting to see that their similarity extends right up to the level of bonding potential which is Morse-like in both the cases.

Thus a consistent description of the resonances in the five systems including the $^{12}C+^{12}C$ presented earlier, has been possible with the potential derived from the resonance data itself, which show the general validity of the dynamic potential model proposed earlier. The present model may be applied to the study of heavier systems.

References

[1] D A Bromley, J A Kuehner and E Almquist, *Phys. Rev. Lett.* **4**, 365 (1960)
[2] B Imanish, *Phys. Lett.* **B27**, 267 (1968)
[3] W Scheid, W Greiner and R Lemmer, *Phys. Rev. Lett.* **25**, 1043 (1971)
[4] N Cindro, *J. Phys.* **G4**, L23 (1978)
[5] N Cindro and W Greiner, *J. Phys.* **G9**, L175 (1983)
[6] F Iachello, *Phys. Rev.* **C23**, 2778 (1981)
[7] K A Erb and D A Bromley, *Phys. Rev.* **C23**, R2781 (1981)
[8] N Cindro, *Riv. Nuovo Cimento* **4**, 1 (1981)
[9] L Satpathy, *Prog. Part. Nucl. Phys.* **29**, 327 (1992)
[10] P M Morse, *Phys. Rev.* **34**, 57 (1929)
[11] L Satpathy, P Sarangi and A Faessler, *J. Phys.* **G12**, 204 (1986)
[12] L Satpathy and P Sarangi, *J. Phys.* **G16**, 469 (1990)
[13] L Satpathy, P K Sahu and P Sarangi, *J. Phys.* **G18**, 1703 (1992)
[14] P Sarangi and L Satpathy, *Pramana – J. Phys.* **39**, 279 (1992)
[15] W Greiner and W Scheid, *Suppl. J. de Phys.* **32**, C6 91 (1971)
[16] A Arima, V McVoy and G Scharff-Goldhaber, *Phys. Lett.* **B40**, 7 (1972)
[17] K Kato and Y Abe, *Phys. Rev.* **C55**, 1928 (1997)
[18] L Satpathy, *J. Phys.* **G31**, 1233 (2005)
[19] B Sahu, L Satpathy and C S Shastry, *Phys. Lett.* **A303**, 105 (2002)
[20] F Ajenberg-Selove, *Nucl. Phys.* **A166**, 1 (1971)
[21] D H E Gross and L Satpathy, *Nuclear physics* edited by C H Dasso, R A Broglia and A Winther (North Holland Publishing Company, 1982) p. 691; *Phys. Lett.* **B110**, 31 (1982)
[22] A Faessler, A W Wadia, M Rashdan and M Ismail, *J. Phys.* **G10**, L135 (1985)
[23] P Sarangi, S Ali and L Satpathy, *Pramana – J. Phys.* **34**, 111 (1990)