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Research Article

A comprehensive study of $^{17}F + ^{12}C$ system at 60 MeV: cluster model, optical model and double folding model

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Abstract

In the present study, we analyze the quasi-elastic scattering data of $^{17}F + ^{12}C$ reaction at 60 MeV using the cluster model, the optical model and the double folding model. We compare the theoretical results obtained for all the models with the experimental data. These comparison provide information about the similarities and differences of the models used in calculations.

Keywords: Cluster model, optical model, double folding model.

1. Introduction

Exotic nucleus interactions with the technological development of the radioactive ion beam (RIM) facilities have been intensively examined as both theoretically and experimentally. Various approaches have been used to obtain agreement results with the experimental data. The cluster model has become one of well-known models for analysing exotic nucleus interactions (Majka et al. 1982; Oertzen et al. 2006; Freer 2007; Kanada et al. 2008; Dufour & Descouvemont 2011; Ghamdi et al. 2012; Suhara & Kanada-En'yo 2013). In this context, the exotic nuclei are assumed as core plus valence proton(s) or neutron(s). ^{17}F nucleus, a weakly bounded proton halo nucleus, is one of these nuclei; thought to be core and valence proton bounded by 0.6 MeV. ^{17}F has a rms radius of 3.7 fm (Liang et al. 2002) due to a weakly bound structure and is also important owing to its features (Lewis & Hayes 1999; Guang-Peng et al. 2008).

- it is very interesting due to its effect in the hot CNO cycle of nuclear
- ^{17}F has two bound states (ground state and one excited bound state)
- the first excited state of ^{17}F has a halo structure
- the first excited state of ^{17}F is $J^{\pi}=(1/2)^{+}$ and E_x=0.5 MeV

Many theoretical and experimental studies have been carried out on the ^{17}F nucleus (Liang et al. 2000; Liang et al. 2003; Romoli et al. 2004; Blackmon et al. 2005; Mazzocco et al. 2010; Signorini et al. 2010; Kucuk & Moro 2012). Recently, Zhang et al. (2012) have measured the quasi-elastic scattering data of ^{17}F scattered from ^{12}C at 60 MeV. They have fitted the experimental data by using an optical model and continuum discretized coupled channels, and have reported that the breakup effect does not play a very important role for weakly bound projectiles on light targets. However, for the $^{17}F + ^{12}C$ reaction, optical model and double folding model calculations with and without the cluster structure of the ^{17}F nucleus have not been performed. The aim of the present paper is to investigate the quasi-elastic scattering data of ^{17}F scattered from ^{12}C at 60 MeV by using different models such as the cluster model, the optical model and the double folding model. From the theoretical results obtained, the similarities and differences of the models used in calculations will be clearly seen. Also, the parameters used in the cluster model, the optical model and the double folding model analysis of $^{17}F + ^{12}C$ reaction will be given. These parameters will be useful in examining the nuclear interactions (e.g. the elastic scattering, inelastic scattering, transfer reactions) with ^{17}F.

In the next section, we present the theoretical models used in our calculations. Then we give the results and discussions of the calculations in Section 3. Finally, section 4 is devoted to our summary and conclusions.

2.Theoretical Analysis

2. 1. The optical model analysis without cluster structure of ^{17}F

We investigate the scattering data without cluster structure of ^{17}F nucleus on the ^{12}C target nucleus within the framework of the optical model. The nuclear potential has two parts as the real and imaginary potential. In our calculations, both the real and the imaginary potential have been taken as the Woods-Saxon (WS) type in the following form

$$V_{Nuclear}(r) = -V_0 f(r,R_i,a_i) - iW_0 f(r,R_i,a_i) \quad (1)$$

$$f(r,R_i,a_i) = \frac{1}{1+\exp\dfrac{r-R_i}{a_i}} \quad (2)$$

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where $R_i=r_i(A_P^{1/3}+A_T^{1/3})$ (i= V or W). A_P and A_T are devoted to the masses of projectile and target nuclei. In determining the parameters of the nuclear potential we have started with the values given by Blackmon et al. (2005). Then, we have changed the parameters of the Woods-Saxon potential in order to obtain good agreement results with the experimental data. All the parameters used in calculations are shown in Table 1. The code FRESCO (Thompson 1988) has been used for all calculations.

Table 1. The optical model and double folding model parameters obtained without cluster structure of ^{17}F nucleus.

^{17}F + ^{12}C	N_R	V	r_v	a_v	W	r_w	a_w
		MeV	*fm*	*fm*	*MeV*	*fm*	*fm*
Optical Model	-	140.66	0.959	0.717	15.50	0.959	0.46
Double Folding Model	0.805	-	-	-	11.66	0.925	0.55

2. 2. The Optical Model Analysis with Cluster Structure of ^{17}F

Here we have assumed cluster case of ^{17}F in the analysis of the quasi-elastic scattering data of ^{17}F scattered from ^{12}C. With this goal, ^{17}F projectile has been taken as core (^{16}O) + valence (p). Then, ^{17}F + ^{12}C system has been thought as ^{16}O + ^{12}C, p + ^{12}C and p + ^{16}O interactions in calculations and these cases have been illuminated in Figure 1.

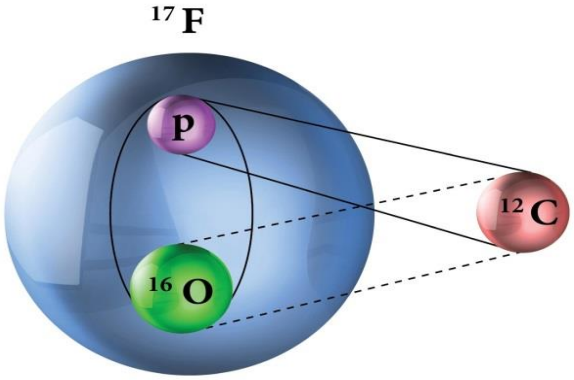

Figure 1. The representation of core + target, valence + target and valence + core interactions for cluster case of ^{17}F projectile.

Both the real and the imaginary parts of the interaction potentials of ^{16}O + ^{12}C (core + target), p + ^{12}C (valence + target) and p + ^{16}O (valence + core) in the calculations have been taken as Woods-Saxon type in the following form

$$V_{Nuclear}(r) = -\frac{V_0}{1+\exp(\frac{r-R_i}{a_i})} - i\frac{W_0}{1+\exp(\frac{r-R_i}{a_i})}. \quad (3)$$

To define the optical model parameters of all the interactions, we have first used the optical model values given for ^{16}O + ^{12}C and p + ^{12}C systems in previous studies (Menet et al. 1971; Nicoli et al. 2000). To obtain good consistent theoretical results with the experimental data, we have changed these parameters. The achieved optical model parameters of ^{16}O + ^{12}C and p + ^{12}C systems have been given in Tables 2 and 3, respectively.

Table 2. The optical model and double folding model parameters obtained for p+ ^{12}C system in cluster structure of ^{17}F.

p+ ^{12}C	V *MeV*	r_v *fm*	a_v *fm*	W *MeV*	r_w *fm*	a_w *fm*
Optical Model	51.2	0.96	0.69	14.7	1.296	0.699
Double Folding Model	38.2	1.25	0.52	19.9	1.250	0.520

Table 3. The optical model and double folding model parameters obtained for ^{16}O + ^{12}C system in cluster structure of ^{17}F.

^{16}O + ^{12}C	N_R	V	r_v	a_v	W	r_w	a_w
		MeV	*fm*	*fm*	*MeV*	*fm*	*fm*
Optical Model	-	330.0	1.112	0.5	14.06	1.122	0.500
Double Folding Model	1.1	-	-	-	7.300	1.110	0.731

Finally, for the values of depth, radius and diffuseness of p + ^{16}O potential we have used 50 MeV, 1.250 fm and 0.650 fm, respectively.

2. 3. The Double Folding Model Analysis without Cluster Structure of ^{17}F

In this section of the study we consider the structure without cluster of ^{17}F nucleus. We determine the real part of the $V_{Nuclear}(r)$ potential by using the double folding model. In this context, the double folding potential is presented as following form

$$V_{DF}(r) = \int dr_1 \int dr_2 \rho_P(r_1)\rho_T(r_2)v_{NN}(r_{12}) \quad (4)$$

where $\rho_P(r_1)$ and $\rho_T(r_2)$ are the nuclear matter density of projectile and target nuclei, respectively. In our calculations, the density distribution of ^{17}F has been taken from the Hartree-Fock-Bogolubov (HFB) method based on the BSk2 Skyrme force (RIPL-3). The density distribution of ^{12}C has been chosen as following form

$$\rho_P(r_1) = \rho_0(1+wr_1^2)\exp(-\beta r_1^2) \quad (5)$$

where ρ_0=0.1644 fm^{-3}, w=0.4988 fm^{-2}, and β=0.3741 fm^{-2} (Farid & Hassanain 2000; Karakoc & Boztosun 2006). The effective nucleon-nucleon interaction, v_{NN}, is integrated over both density distributions. We have chosen the most common one, the M3Y nucleon-nucleon (Michigan 3 Yukawa) realistic interaction, which is given as

$$v_{NN}(r) = 7999\frac{\exp(-4r)}{4r} - 2134\frac{\exp(-2.5r)}{2.5r} + J_{00}(E)\delta(r) \quad (6)$$

where $J_{00}(E)$ represents the exchange term, since nucleon exchange is possible between the projectile and the target. $J_{00}(E)$ has a linear energy-dependence and can be expressed as

$$J_{00}(E) = 276\,[1-0.005\,E/A_p] \quad (7)$$

where A_P and E are devoted to the mass and the laboratory energy of the projectile, respectively.

However, the imaginary potential has been produced with Woods-Saxon potential. We have carried out test calculations in order to see the variation of the parameters which are the depth (W_0), the radius (r_w) and the diffusion parameter (a_w). Then we have used 0.925 fm value for r_w. In a similar manner, a_w has been kept constant at 0.55 fm. We have investigated the W_0 value so as to obtain a good agreement between the theoretical results and the experimental data. All the parameters of the imaginary potential used in calculations have been shown in Table 1.

2. 4. The Double Folding Model Analysis with Cluster Structure of ^{17}F

Finally, we examine the role of cluster case of ^{17}F projectile on the theoretical results within the framework of the double folding model. While ^{17}F projectile is assumed as core (^{16}O) + valence (p), it is thought that ^{17}F + ^{12}C system consists of ^{16}O + ^{12}C, p + ^{12}C and p + ^{16}O interactions. We determine the real part of the interaction potential of ^{16}O + ^{12}C system with the aid of the double folding model. For the imaginary potential of this system, Woods-Saxon potential is used. The potentials of p + ^{12}C and p + ^{16}O interacting systems are given as

$$V_{Nuclear}(r) = -\frac{V_0}{1+\exp(\frac{r-R_i}{a_i})} - i\frac{W_0}{1+\exp(\frac{r-R_i}{a_i})}. \quad (8)$$

The density distribution of ^{16}O has been taken from RIPL-3 (RIPL-3). For the density distribution of ^{12}C target nucleus, we have chosen the gaussian type as the following form

$$\rho_P(r_1) = \rho_0(1+wr_1^2)\exp(-\beta r_1^2) \quad (9)$$

where ρ_0=0.1644 fm^{-3}, w=0.4988 fm^{-2}, and β=0.3741 fm^{-2} (Farid & Hassanain 2000; Karakoc & Boztosun 2006). To obtain convenient theoretical results with the experimental data, we have changed the optical model parameters of ^{16}O + ^{12}C and p + ^{12}C systems. The obtained parameters are shown in Tables 2 and 3. The potential parameters of p + ^{16}O system has been taken 50 MeV depth, 1.250 fm radius and 0.520 fm diffuseness.

3. Results and Discussions

In the present study we have reanalyzed the quasi-elastic scattering data of ^{17}F + ^{12}C system at 60 MeV. We have divided the analysis of the data into four parts. In the first part we have performed the phenomenological calculations without cluster case of ^{17}F based on the optical model. We have used Woods-Saxon type potential for both the real and the imaginary potential. The optical model parameters used in the calculations are given in Table 1 and the theoretical results are shown in Figure 2. We have observed that the optical model results are in agreement with the data but not perfect. If one compares our results with the results of Zhang et al. (2012), one can see that the agreement between the our results and the results of Zhang et al. (2012) on the definition of the experimental data are similar. However, Zhang et al. (2012) have used square Woods-Saxon form for the real part and square Woods-Saxon plus surface term for the imaginary part in theoretical calculations of the optical model. On the other hand, we have used a Woods-Saxon type potential for both the real part and the imaginary part in theoretical calculations of the optical model. In this case we reduce the number of the parameters and the ambiguities in determining the optical model parameters. To make a comparative analysis, we have performed the optical model calculations for cluster structure of ^{17}F. The system has been assumed as three different interactions that consist of ^{16}O + ^{12}C, p + ^{12}C and p + ^{16}O. In order to fit the experimental data, we have changed the optical model parameters of the system. The obtained parameters have been presented in Tables 2 and 3. Also, the results for the cluster case have been plotted in Figure 2.

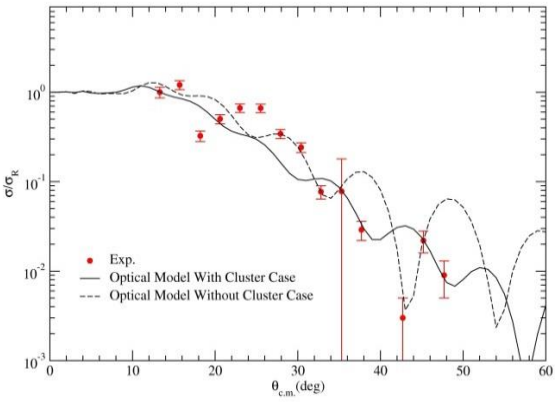

Figure 2. The elastic scattering angular distributions obtained with and without cluster case of ^{17}F by using the optical model. The experimental data have been taken from Zhang et al. (2012).

The theoretical results obtained with and without the cluster structure of ^{17}F have been compared with the experimental data in Figure 2. We have observed that the theoretical results with the cluster case of ^{17}F are slightly better than the results without the cluster structure of ^{17}F.

As the other model used in our analysis, we have discussed the double folding model with and without the cluster structure of ^{17}F projectile. We have divided the calculations into two parts. Firstly, we have performed the double folding model calculations for the structure without the cluster of the ^{17}F projectile. For this purpose, while the real potential has been acquired by the double folding model, the imaginary potential has been taken as Woods-Saxon potential.

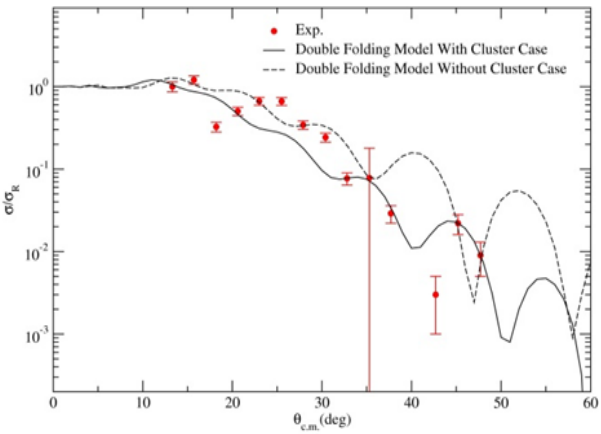

Figure 3. The elastic scattering angular distributions obtained with and without cluster case of ^{17}F by using the double folding model. The experimental data have been taken from Zhang et al. (2012).

Density distribution of ^{17}F has been obtained from RIPL-3 (RIPL-3) and the density distribution of ^{12}C target nucleus has been accepted in the gaussian form as given in Eq. (9). We have searched for convenient values of the imaginary potential parameters in order to obtain a good fit for the experimental data. The parameters used in calculations have been given in Table 1 and the results have been plotted in Figure 3.

The sensitivity on the normalization constant (N_R) of the theoretical results has been investigated and N_R has been found as 0.805. The results are in agreement with the experimental data, but are not a perfect fit. Finally, we have examined the cluster structure of the ^{17}F nucleus. We have assumed that the ^{17}F + ^{12}C system consists of ^{16}O + ^{12}C, p + ^{12}C and p + ^{16}O interactions. The real part of the ^{16}O + ^{12}C system has been obtained by using double folding calculations and the imaginary part has been taken as Woods-Saxon potential. Although the real and imaginary potentials of p + ^{12}C and p + ^{16}O interactions are the same with the optical model calculations for the cluster case of ^{17}F, we have changed the parameters of the potentials to fit the data. The obtained values are given in Tables 2 and 3. Also, in Figure 3, we have given comparative results with and without the cluster structure of ^{17}F. We have observed that the theoretical results obtained for the cluster case of ^{17}F are better than the results without the cluster structure of ^{17}F.

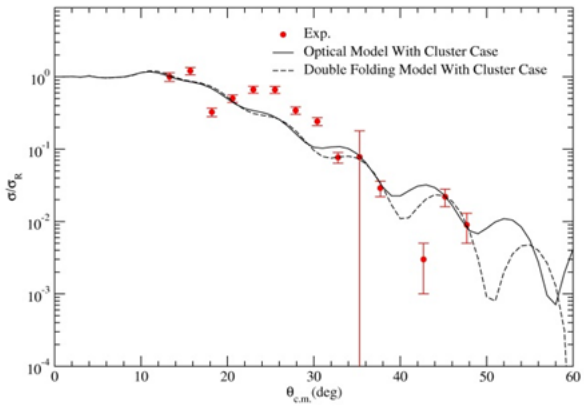

Figure 4. The elastic scattering angular distributions obtained for cluster case of ^{17}F by using both the optical model and the double folding model.

Additionally, in Figure 4, we have given as comparative the theoretical results obtained by using both the optical model and double folding model for the cluster structure of the ^{17}F nucleus. We have noticed that the the double folding model results are little better than the optical model results. Also, we have observed that the results of both the optical model and the double folding model are almost the same at smaller angles, whereas the phase shifts between the cross-sections appear at forward angles.

4. Conclusions

In this work we have reexamined the quasi-elastic scattering of the ^{17}F + ^{12}C system. We have performed the optical model and the double folding model calculations both without cluster structure and with a cluster structure of ^{17}F. We have noticed from the compared theoretical results of the optical and folding model as well as the experimental data that the cluster model, the phenomenological model and the double folding model results are in agreement with the data. However, the results could be improved for a more convenient set of results due to missing of some experimental data. The cluster model has an effect on the theoretical results in the fitting of the experimental data, but this effect is not very crucial. We can deduce that the effect of the cluster model in the analysis of this quasi-elastic scattering angular distribution is small for a light system with low Z target nucleus.

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References

Al-Ghamdi AH, Ibraheem AA, Farid M El-Azab (2012). An Investigation of ^{4}He + ^{12}C and ^{4}He + ^{16}O Reactions using the cluster model. Commun Theor Phys 58, 135140.

Blackmon JC, Carstoiu F, Trache L, Bardayan DW, Brune CR, Gagliardi CA, Greife U, Gross CJ, Jewett CC, Kozub RL, Lewis TA, Liang JF, Moazen BH, Mukhamedzhanov AM, Nesaraja CD, Nunes FM, Parker PD, Sahin L, Scott JP, Shapira D, Smith MS, Thomas JS, Tribble RE (2005). Elastic scattering of the proton drip-line nucleus ^{17}F. Phys Rev C 72, 034606.

Dufour M, Descouvemont P (2011). Microscopic cluster models. Int J Mod Phys E 20, 2.

Farid M El-Azab, Hassanain MA (2000). Density-independent folding analysis of the $^{6,7}Li$ elastic scattering at intermediate energies. Nucl Phys A 678, 39.

Freer M (2007). The clustered nucleus-cluster structures in stable and unstable nuclei. Rep Prog Phys 70, 2149-2210.

Guang-Peng A, Cheng-Jian L, Huan-Qiao Z, Zu-Hua L, Feng Y, Gao-Long Z, Chun-Lei Z, Zhen-Dong W, Fei J, Hui-Ming J, Xin-Xing X, Chun-Lin B, Ning Y (2008). Optical potential parameters of weakly bound nuclear system ^{17}F + ^{13}C. Chin Phys Lett 25, 12.

Kanada-En'yo Y, Kimura M, Taniguchi Y, Suhara T (2008). Cluster Structure of unstable nuclei studied with amd. Int J Mod Phys E 17, 10.

Karakoc M, Boztosun I (2006). α-α double folding cluster potential description of the ^{12}C + ^{24}Mg system. Phys Rev C 73, 047601.

Kucuk Y, Moro AM (2012). Exclusive breakup of ^{17}F on ^{58}Ni and ^{208}Pb within the continuum-discretized coupled-channels method. Phys Rev C 86, 034601.

Lewis R, Hayes AC (1999). Deuteron stripping as a probe of the proton halo in ^{17}F. Phys Rev C 59, 2.

Liang JF, Beene JR, Esbensen H, Galindo-Uribarri A, Gomez del Campo J, Gross CJ, Halbert ML, Mueller PE, Shapira D, Stracener DW, Varner RL (2000). Breakup of weakly bound ^{17}F well above the Coulomb barrier. Phys Lett B 491, 23-28.

Liang JF, Beene JR, Esbensen H, Galindo-Uribarri A, Gomez del Campo J, Gross CJ, Halbert ML, Mueller PE, Shapira D, Stracener DW, Thompson IJ, Varner RL (2002). Elastic scattering and breakup of ^{17}F at 10 MeV/nucleon. Phys Rev C 65, 051603.

Liang JF, Beene JR, Galindo-Uribarri A, Gomez del Campo J, Gross CJ, Hausladen PA, Mueller PE, Shapira D, Stracener DW, Varner RL, Bierman JD, Esbensen H, Larochelle Y (2003). Breakup of ^{17}F on ^{208}Pb near the Coulomb barrier. Phys Rev C 67, 044603.

Majka Z, Gils HJ, Rebel H (1982). Cluster folding model for $^{12}C(^{6}Li, ^{6}Li)$ scattering at 156 MeV. Phys Rev C 25, 6.

Mazzocco M, Signorini C, Pierroutsakou D, Glodariu T, Boiano A, Boiano C, Farinon F, Figuera P, Filipescu D, Fortunato L, Guglielmetti A, Inglima G, La Commara M, Lattuada M, Lotti P, Mazzocchi C, Molini P, Musumarra A, Pakou A, Parascandolo C, Patronis N, Romoli M, Sandoli M, Scuderi V, Soramel F, Stroe L, Torresi D, Vardaci E, Vitturi A (2010). Reaction dynamics for the system $^{17}F + ^{58}Ni$ at near-barrier energies. Phys Rev C 82, 054604.

Menet JJH, Gross EE, Malanify JJ, Zucker A (1971). Total reaction cross-section measurements for 30-60-MeV protons and the imaginary optical potential. Phys Rev C4, 4.

Nicoli MP, Haas F, Freeman RM, Szilner S, Basrak Z, Morsad A, Satchler GR, Brandan ME (2000). Detailed study and mean field interpretation of $^{16}O + ^{12}C$ elastic scattering at seven medium energies. Phys Rev C 61, 034609.

Reference Input Parameter Library (RIPL-3), http://www-nds.iaea.org/RIPL-3/

Romoli M, Vardaci E, Di Pietro M, De Francesco A, De Rosa A, Inglima G, La Commara M, Martin B, Pierroutsakou D, Sandoli M, Mazzocco M, Glodariu T, Scopel P, Signorini C, Bonetti R, Guglielmetti A, Soramel F, Stroe L, Greene J, Heinz A, Henderson D, Jiang CL, Moore EF, Pardo RC, Rehm KE, Wuosmaa A, Liang JF (2004). Measurements of ^{17}F scattering by ^{208}Pb with a new type of large solid angle detector array. Phys Rev C 69, 064614.

Signorini C, Pierroutsakou D, Martin B, Mazzocco M, Glodariu T, Bonetti R, Guglielmetti A, La Commara M, Romoli M, Sandoli M, Vardaci E, Esbensen H, Farinon F, Molini P, Parascandolo C, Soramel F, Sidortchuk S, Stroe L (2010). Interaction of ^{17}F with a ^{208}Pb target below the Coulomb barrier. Eur Phys J A 44, 63-69.

Suhara T, Kanada-En'yo Y (2013). $2\alpha + t$ cluster structure in ^{11}B. Few Body Syst 54, 1377-1380.

Thompson IJ (1988). Coupled reaction channels calculations ın nuclear-physics. Comp Phys Rep 7, 167.

Von Oertzen W, Freer M, Kanada-En'yo Y (2006). Nuclear clusters and nuclear molecules. Rep Prog Phys 432, 43-113.

Zhang GL, Zhang CL, Zhang HQ, Lin CJ, Pang DY, Wu XK, Jia HM, An GP, Wu ZD, Xu XX, Yang F, Liu ZH, Kubono S, Yamaguchi H, Hayakawa S, Binh DN, Kwon Y K, Iwasa N, Mazzocco M, La Commara M, Romoli M, Signorini C (2012). Quasi-elastic scattering of the proton drip line nucleus ^{17}F on ^{12}C at 60 MeV. Eur Phys J A 48, 65.