Alpha-clustering in the fp-shell region*

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Abstract :

Recent development of α-particle cluster study in the fp-shell region around ^{40}Ca is reviewed including the observation of the parity-doublet α-cluster $K=0^-$ band in ^{40}Ca.

I. Introduction

Since we predicted in 1986 the existence of the $K=0^-$ band with the α-cluster structure in ^{44}Ti [1], much attention has been paid to the α-clustering aspects in the fp-shell region. The experimental observation of this band in ^{44}Ti [2] has dramatically evidenced that the α-cluster structure is essential in this region. ^{40}Ca is an analogue nucleus of ^{16}O. Although parity-doublet $K=0^+$ and $K=0^-$ bands with the α-cluster structure have been observed in ^{16}O, no corresponding parity-doublet $K=0^-$ band has been observed in ^{40}Ca. Ogawa et al. [3] investigated the structure of ^{40}Ca in the coupled-channel OCM (orthogonality condition model) of the $\alpha+{}^{36}$Ar cluster model assuming SU(3) (08) for the ^{36}Ar core and concluded that the situation of α-clustering in ^{40}Ca is quite different from ^{16}O : one of the most important conclusions of the OCM calculation was that the $K=0^-$ band with the $\alpha+{}^{36}$Ar cluster structure does not exist in ^{40}Ca in accordance with the experimental result.

On the other hand, a new theory has predicted an inevitable existence of the $K=0^-$ band with the $\alpha+{}^{36}$Ar cluster structure in ^{40}Ca. Whether this band will be observed in experiment has been a focus of the α-cluster structure study. In my talk I will speak about recent development of α-clustering in the fp-shell region around ^{40}Ca nucleus.

II. Alpha-particle clustering in ^{40}Ca

Unified description of bound and scattering states of the $\alpha+{}^{36}$Ar system inevitably predicts the existence of the $K=0^-$ band with the α-cluster structure just above the α-threshold [4] (Fig. 1). The most decisive test to know whether the α-cluster picture still persists in the ^{40}Ca nucleus is whether this band is really observed in experiment. The experiment of ^{36}Ar (^{6}Li, d) ^{40}Ca reaction was performed at the Research Center for Nuclear Physics, Osaka University [5]. The observed energy spectra are shown in Fig. 2. The angular distributions were analyzed in the finite range distorted wave Born approximation using the computer code TWOFNR. The

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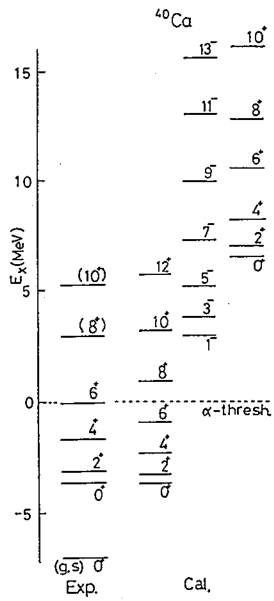

Fig. 1
The Pauli-allowed energy levels of ^{40}Ca calculated with the Woods-Saxon squared potential which was determined from the analysis of $\alpha+^{36}$Ar scattering are shown in comparison with the experimental data.

analysis was done by using a phenomenological Woods-Saxon potential to generate the form factor of ^{40}Ca. The members of the $K=0^-$ band were assigned as follows: 1^-(8.15 MeV), 3^-(9.36 MeV), 5^-(10.80 MeV), 7^-(12.65 MeV). This $K=0^-$ band is a counterpart of the $K=0^+$ band starting from the 0^+ state at 3.35 MeV. Thus it is found that the α-cluster picture persists in ^{40}Ca having parity-doublet bands with the α-cluster structure similar to ^{16}O. This also shows that the unified description of bound and scattering states is very instrumental for the α-cluster study.

III. Alpha-clustering in ^{42}Ca

The intruder states appear in the ^{44}Ti region widely. In Fig. 3, weak coupling feature of the intruder states is shown. In ^{42}Ca, which is an analogue nucleus of ^{18}O, the $K=0^+$ band starting from the 0^+ state at 1.84 MeV cannot be understood in the conventional shell model.

We have performed a unified description of bound and scattering states for the $\alpha+^{38}$Ar system. α-particle scattering from ^{38}Ar is

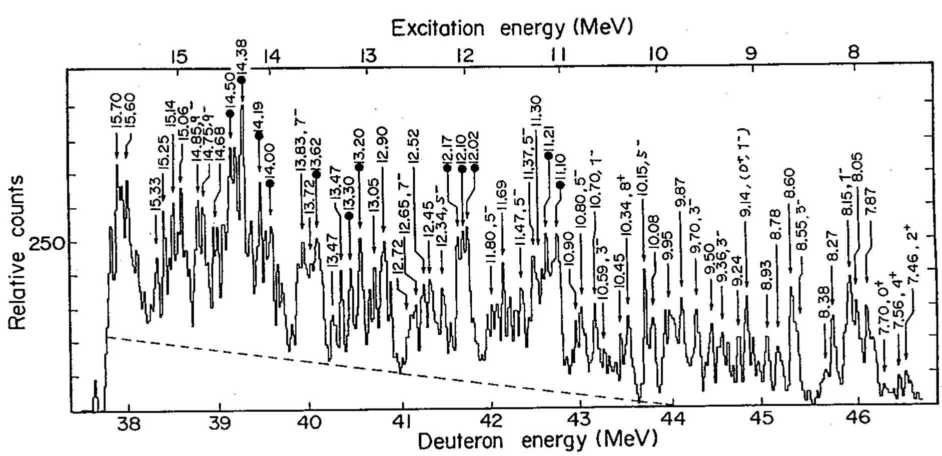

Fig. 2
Observed energy levels of ^{40}Ca in the ^{36}Ar (^{6}Li, d) ^{40}Ca reaction.

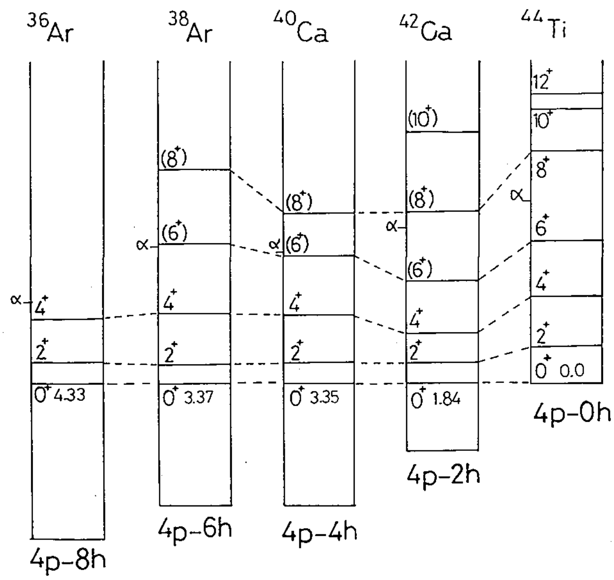

Fig. 3
Weak coupling feature for the experimental intruder states which are considered as the candidates for the α-cluster states is shown extending to the ^{36}Ar nucleus.

available only at $E_\alpha=24$ MeV [6] and we have analyzed this angular distribution by employing a Woods-Saxon squared potential for real and imaginary part of the optical potential. The potential parameters to fit the data are $V=187$ MeV, $r=1.36$ fm, $a=1.29$ fm, $W=22$ MeV, $r_i=1.4$ fm, $a_i=1.0$ fm and $r_{coul}=1.4$ fm. In Fig. 4 calculated angular distributions are shown in comparison with the experimental data. We see that the characteristic feature of the angular distributions is reproduced by the calculation. In Fig. 4, also shown are the angular distributions divided into internal and barrier wave component in the semi-classical picture [7]. We notice that the backward angular distribution is dominated by the internal wave, which means that internal part of the real potential is responsible for the backward angular distribution.

By using this potential we have calculated the energy levels of ^{42}Ca. As shown in Fig. 5, the calculated $K=0^+$ energy levels correspond with the experimental $K=0^+$ band very well. The calculated B(E2) values between the states of this band are enhanced very much, however, to reproduce the experimental values, still additional effective charges are needed; the origin of which may be related to the coupling to the giant quadrupole resonance as suggested by Bando in ^{20}Ne [8]. The $K=0^-$ band with the α-cluster structure which is a parity-doublet counterpart of the $K=0^+$ inevitably appears above the α-threshold. This has not been observed in experiment up to now. What is interesting is that there is no analogue band in ^{18}O. Therefore it is very interesting to know wheteher this band exists. If the $K=0^-$ band would be really observed in experiment, a fruitful α-cluster picture in ^{42}Ca and fp-shell region will be reconfirmed. We have calculated the r. m. s. radii and B(E2) values for the $K=0^-$ and $K=0^+$ bands (Table I) as

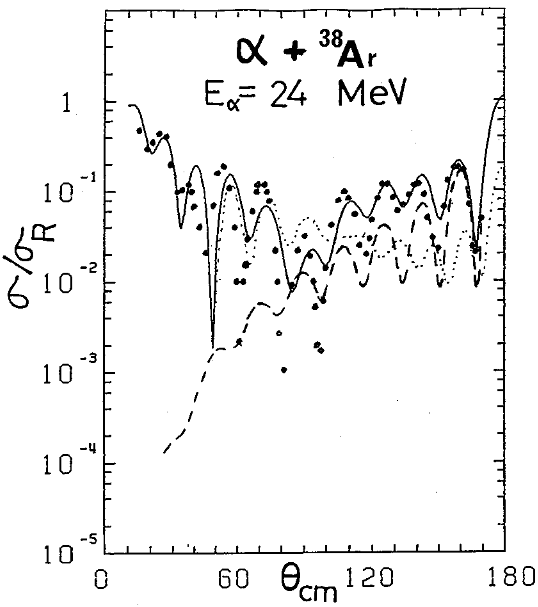

Fig. 4
Calculated angular distributions for $\alpha+{}^{38}$Ar scattering are compared with the experiment. The dashed and dotted lines represent the angular distributions due to the internal and barrier wave, respectively.

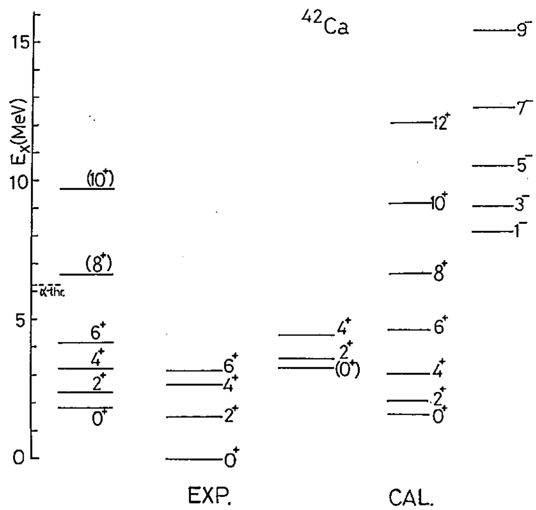

Fig. 5
Energy levels of ^{42}Ca calculated in the $\alpha+{}^{38}$Ar cluster model with the Woods-Saxon squard potential which fits $\alpha+{}^{38}$Ar scattering are compared with the experiment.

Table I.
The r. m. s. radii and intra-band B(E2) values of the K=0$^-$ and K=0$^+$ bands in ^{42}Ca calculated with the Woods-Saxon squared potential which fits $\alpha+{}^{38}$Ar scattering are shown.

J^π	$\langle R^2\rangle^{1/2}$ (fm)	B(E2) (J ⟶ J−2) (e^2fm^4) Exp.		J^π	$\langle R^2\rangle^{1/2}$ (fm)	B(E2) (J ⟶ J−2) (e^2fm^4)
0^+	4.53			1^-	5.27	
2^+	4.51	<594	107	3^-	5.21	246
4^+	4.44	356±106 $332\pm^{18}_{49}$ 498±21	141	5^- 7^-	5.10 4.92	263 235
6^+	4.34	$433\pm^{303}_{139}$	134	9^-	4.68	180
8^+	4.20	$546\pm^{407}_{147}$	109	11^-	4.40	116
10^+	4.03		75	13^-	4.01	54
12^+	3.83		37			

well as the α-reduced widths (Table II). The reduced α-widths of ^{42}Ca are between those of ^{44}Ti [9] and ^{40}Ca [4], for both of which the K=0$^-$ band with the α-cluster structure has been observed in experiment. Although the coupling with the shell-model-like states may cause distribution of the α-widths, it is expected that this band could be still observed in experiment. Since ^{38}Ar is a stable nucleus, it is highly desirable to perform the α-transfer reaction such as ^{38}Ar (^{6}Li, d) ^{42}Ca.

Table II

Resonance energies and widths of the members of the ^{42}Ca $K=0^-$ band, together with the corresponding dimensionless reduced widths θ_α^2 calculated with the channel redius a=7.4 fm. θ_α^2 calculated for ^{40}Ca and ^{44}Ti in the α-cluster model [4, 9] are also shown for comparison.

J^π	$E_{c.m.}$ (MeV)	E_X (MeV)	$\Gamma_{c.m.}$ (keV)	θ_α^2 (%)	θ_α^2 (^{40}Ca) (%)	θ_α^2 (^{44}Ti) (%)
1^-	2.06	8.31	$<<0.001$	>16	25	16
3^-	2.89	9.14	4.8×10^{-3}	16	22	14
5^-	4.37	10.62	0.184	12	19	10
7^-	6.48	12.73	1.12	7.8	10	6.4
9^-	9.23	15.48	1.81	3.7	4.3	2.8
11^-	12.60	18.85	1.10	1.1	1.2	0.8
13^-	16.52	22.77	0.22	0.16	0.13	0.1

IV. Concluding remarks

There are many intruder states in the ^{40}Ca region. As shown in Fig. 3, we see that weak coupling feature holds not only in the $^{40}Ca\sim^{44}Ti$ region but also $^{36}Ar\sim^{40}Ca$ region. In the upper half of the sd-shell region, α-cluster structure theory has not been successful and typical α-cluster states have not been observed near the α-threshold. Fig. 3 suggests that unified description of bound and scattering states in this region may be also useful for the α-cluster structure study. Therefore it is highly desirable to perform systematic α-particle scattering as well as α-transfer reactions such as (^6Li, d). This may open a fruitful way to the α-cluster study in the upper half part of the sd-shell region as well as in the fp-shell region. In the fp-shell region, as a next step $\alpha+^{48}Ca$ cluster structure study of ^{52}Ti is also very interesting [10], since this nucleus has a core which is $N\neq Z$ closed shell: this may be a prototype of α-cluster study of heavy nucleus such as ^{212}Po.

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