Evidence of α correlation from binding energies in medium and heavy nuclei

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If the effect of α clustering due to the interaction of the excited correlated proton pair with correlated neutron pairs in medium and heavy nuclei were taken into consideration, quasiparticle energies would not be simply additive. The empirical values of the extra term $\delta(\alpha)$ indicate that α correlations exist to a certain extent in these nuclei.

Spontaneous α decay[1] and $(d,{}^6\mathrm{Li})$ α transfer reactions[2,3] can be viewed as direct evidence of α clustering in ground states of medium and heavy nuclei. Similar indications from analyses of empirical data of binding energies seem possible. However, the conclusion is yet uncertain.[4–6] Gambhir *et al.*[5] considered that α clustering effects are shown in the staggering of separation energies of proton and neutron pairs. While Leander[6] pointed out that those results could be obtained from the liquid drop model with shell corrections, there would be no room for additional staggering due to α correlations. It is worthwhile to study this problem further.

The pairing correlation and the corresponding superfluidity are mainly demonstrated by the following characteristics: (1) The quasiparticle number or equivalently the seniority number s is a conserved quantity; (2) quasiparticle energies are no less than the energy gap Δ. Hence,

$$\frac{dE}{ds} \approx \Delta \ . \tag{1}$$

For ground states of medium and heavy nuclei,

$$s = \begin{cases} 0 \text{ even-even nuclei} \\ 1 \text{ even-odd or odd-even nuclei} \\ 2 \text{ odd-odd nuclei ,} \end{cases} \tag{2}$$

we have therefore, an additional term in the binding energy,

TABLE I. Empirical values of $\delta(\alpha)$ in MeV from S_n (upper value) and S_p (lower value) for nuclei in the region $82 < Z < 126$, $126 < N < 184$.

Z \ N	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142
83	0.363	0.295	0.252													
	0.361	0.469	0.263	0.340												
84	0.468	0.437	0.351													
	0.271	0.427	0.255	0.331												
85	0.231	0.246	0.235	0.205												
	0.208	0.315	0.234	0.331												
86	0.292	0.303	0.330	0.309	0.245											
	0.147	0.273	0.215	0.310	0.283											
87		0.184	0.195	0.284	0.334	0.399	0.399									
	0.106	0.199	0.201	0.230	0.327	0.350	0.320									
88		0.218	0.246	0.280	0.341	0.267	0.145									
								0.142								
89									0.199	0.173	0.189					
								0.165	0.238	0.182						
90								0.201	0.221	0.231	0.275	0.199				
										0.216	0.270	0.345	0.169			
91												0.313	0.264	0.215	0.192	0.182
															0.139	0.132
92																0.127
																0.100

$$\delta B = \begin{cases} \Delta \text{ even-even nuclei} \\ 0 \text{ even-odd or odd-even nuclei} \\ -\Delta \text{ odd-odd nuclei} \end{cases} \quad (3)$$

due to short-range correlations.

In the case of α-particle superfluidity, there must be additional quantum numbers and corresponding energy terms. However, this is not the case for medium and heavy nuclei because valence protons and neutrons are located at different shells. In Ref. 7 we have pointed out that α clustering can only be realized through the interaction of the excited correlation proton pair with correlated neutron pairs. The α-transfer rate depends on the combined effects of proton and neutron pairings.

Such arguments have been supported by α preformation probability analyses from data on spontaneous α decay[1] and α spectroscopic factor analyses from $(d,{}^6\text{Li})$ reactions.[2] Their variation as a function of the mass number A has the same feature as that of the pairing effect. It can be seen even more clearly from the comparison between the relative cross section of (p,t) and $(d,{}^6\text{Li})$ reactions as a function of A from some tin isotopes.[3]

In view of such arguments, additional energy is required in removing a nucleon from the even-even nucleus in which α clustering is more probable. We have to generalize the expression (3) as

$$\delta B = \begin{cases} \Delta + \delta(\alpha) \text{ even-even nuclei} \\ 0 \text{ even-odd or odd-even nuclei} \\ -\Delta \text{ odd-odd nuclei} \end{cases} \quad (4)$$

and the relation

$$\delta(\alpha) > 0 \quad (5)$$

is regarded as an indication for the existence of α correlations in medium and heavy nuclei.

One should be very careful in extracting the quantity $\delta(\alpha)$ from empirical data of binding energies. The binding energy of the nucleus consists of contributions from both long- and short-range correlations of nucleons. If the contribution from the long-range correlation were eliminated, we could then exhibit the effect of the short-range correlation. Neglecting higher-order terms, we have

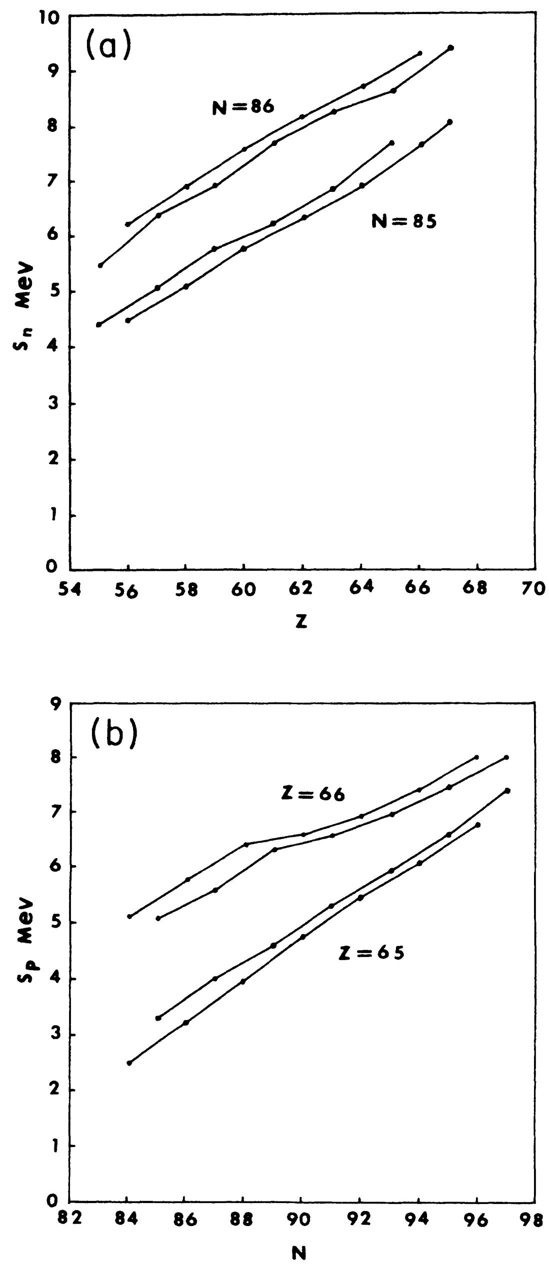

FIG. 1. (a) Neutron separation energies for nuclei with fixed N; (b) proton separation energies for nuclei with fixed Z.

$$\begin{aligned}\delta(\alpha) &\approx (-)^{Z+N+1}\tfrac{1}{2}[S_n(Z-1,N) - 2S_n(Z,N) + S_n(Z+1,N)] \\ &\approx (-)^{Z+N+1}\tfrac{1}{2}[S_p(Z,N-1) - 2S_p(Z,N) + S_p(Z,N+1)] \;,\end{aligned} \quad (6)$$

where

$$\begin{aligned} S_n(Z,N) &= B(Z,N) - B(Z,N-1) \\ S_p(Z,N) &= B(Z,N) - B(Z-1,N) \;. \end{aligned} \quad (7)$$

The quantities inside the square brackets in Eq. (6) behave as

$$\frac{\partial^3 B(Z,N)}{\partial Z^2 \partial N} \text{ and } \frac{\partial^3 B(Z,N)}{\partial N^2 \partial Z} \;,$$

respectively. Therefore, contributions from long-range correlations, including the symmetry energy, have been essentially eliminated. Now the quantity given by Eq. (6) mainly gives the nonlinearity of quasiparticle energies due to α correlation and is regarded as an indication for α clustering effects.

Using empirical data given in Ref. 8 we obtain typical curves for neutron (proton) separation energies with fixed $N(Z)$ inside the region $50<Z<82$, $82<N<126$ as shown in Fig. 1. The distance between the two lines with fixed $N(Z)$ represents the quantity defined in Eq. (6). The values $\delta(\alpha)$ for nuclei inside the region $82<Z<126$, $126<N<184$ are given in Table I. Both values obtained from S_n and S_p are shown in Table I. They are comparable with each other and in right order of magnitude. On the whole, we conclude that the quantities given above can be reasonably regarded as evidence for α correlation in medium and heavy nuclei to a certain extent.

It should be noted that a similar even-odd term

$$\delta B = \begin{cases} \Delta \\ 0 \\ -0.776\Delta \end{cases} \tag{8}$$

$$\Delta = 13.3 A^{-1/2}\ \text{MeV}$$

has been used by Zheng *et al.*[9] in their mass formula, but no theoretical explanation was given.

[1] R. Bonetti and L. Milazzo-Colli, Phys. Lett. **49B**, 17 (1974).

[2] F. D. Becchetti, L. T. Chua, and J. Jäncke, Phys. Rev. Lett. **34**, 225 (1975).

[3] F. D. Becchetti and J. Jäncke, Phys. Rev. Lett. **35**, 268 (1975).

[4] A. S. Jensen, P. G. Hansen, and B. Jonson, Nucl. Phys. **A431**, 393 (1984).

[5] Y. K. Gambhir, P. Ring, and P. Schuck, Phys. Rev. Lett. **51**, 1235 (1983).

[6] G. A. Leander, Phys. Rev. Lett. **52**, 311 (1984).

[7] Ren Zhong-zhou and Xu Gong-ou, Phys. Rev. C **36**, 456 (1987).

[8] A. H. Wapstra and G. Audi, Nucl. Phys. **A432**, 1 (1985).

[9] C. Y. Zheng, T. S. Cheng, and F. C. Yang, Nucl. Phys. **A334**, 470 (1980).