Fragmentation of Cluster States and Alpha-Particle Correlations in Light Nuclei

K.A. Gridnev[1,3], M.W. Brenner[2], S.E. Belov[1], K.V. Ershov[1],
E. Indola[2], V.G. Kartavenko[3] and W. Greiner[3]

[1] St-Petersburg State University, Russia
[2]Åbo Akademi, Department of Physics, Turku, Finland
[3]Institut für Theoretische Physik, JWG Universität Frankfurt am Main, Germany

Abstract

The interaction of alpha particles above 5 MeV with a 2s-1d target is dominated by resonances. It can not be described only in terms of a mean field one-body potential. The analysis of the elastic scattering of alpha particles from ^{28}Si encourage the comprehension of the resonance states to be mainly fragments of a mixed parity band. The analysis of angular distributions of particles scattered from ^{32}S are discussed in the present article in terms of such bands. The analysis of new data from an experiment made at Florida State University reveals the existence of states that do not belong to the bands mentioned. This follows from a coupled channel analysis of the elastic and inelastic (2^+) cross-sections. A structure of alpha particles on the nuclear surface is suggested.

1 Resonances observed in the excitation function

The large backward yield of elastically scattered particles has been called Anomalous Large Angle Scattering, ALAS. Many explanations have been proposed for the understanding of this phenomenon [1]. The cross-section depends strongly on the energy and scattering angle. For the study of scattering of alpha-particles experimental data should preferably be taken in small energy steps from a few MeV up to about 20 MeV or more. Moreover, the energy and angular resolution should be 10 keV and 0.2 degree or better. Only a few experiments satisfy one of these needs but none of them satisfies all [2]–[12]. The energy dependence of elastic scattering from α+^{28}Si at 173 degrees has been measured between 3 and 28 MeV [6, 7, 13]–[15]. The energy resolution between 6.5 and 19.0 MeV was typically 15 keV. The diffraction pattern of the angular distributions has mostly been analysed in terms of scattering from a complex poptential. Mostly the real and imagianary parts of the potential were of the Woods-Saxons (W-S) or its squared form (W-S)^2. These approaches give good fits to the experimental angular distributions for bombarding energies above 22 MeV. Below that energy the W-S and (W-S)^2 fits are generally poor. Similarly, a global potential proposed by Malik has to be modified at e.g. 14.5 MeV [16]. The shortcomings of fits based only on potential scattering are demonstarted by the alpha scattering from ^{32}S [9]. We have improved the fits considerably by adding a complex resonance term to the amplitide of the (W-S)^2 potential scattering.

Different circumstances indicate that the peaks observed in the excitation function are single or overlapping resonances, which spins can be assigned uniquely [6, 7]. The influence of intermediate states or resonances in alpha scattering has been suggested by several investigators before (e.g. ref [3, 17]–[19]). Nevertheless the strong variation of the cross-section has sometimes been considered due to statistical fluctuations [20]. Recently, however, the analysis of α + ^{28}Si data in terms of contribution of resonances resulted in a sucessfull fit of the elastic and inelastic excitation function at many backward angles [21]. It excludes a claim that the peaks observed in the excitation function would be due to statistical fluctuations.

Two interfering mechanisms, the resonant scattering and the non-resonant potential scattering are thus considered. The effect of large angle scattering is mainly due to the former. It is propotional to the squared Legendre polynomial of the order L. Since the target and the projectile are spinless, the spins J of the resonances equal L . The contribution of the potential scattering to the cross-section can frequently be considered as a small "background". Especially high spin resonances contribute comparatively much more. The cross-section may increase by one or more orders of magnitude, when going from 165 degrees to the most backward experimental angles [22]. The scattering from silicon targets was in a preceding work compared to (^{6}Li,d) stripping measurements [23]. The excitation function of elastic scattering showed peaks at the same energy of excitation in ^{32}S as did the excitation function of the ^{28}Si(^{6}Li,d)^{28}Si

Table 1: Parameters of the angular distribution fits. The real and imaginary radius and diffuseness parameters were kept at the fixed values $r_V = 1.37$ fm, $a_V = 1.30$ fm, $r_W = 1.75$ fm and $a_W = 0.70$ fm

E_α	V	W	J	Γ_α/Γ	P_{res}	J,ref.f
(MeV)	(MeV)	(MeV)				
10.10	207.3	7.6	5	0.60	0.0	5
10.30	211.8	7.8	5	0.60	2.9	5
10.60	206.4	7.3	6	0.40	3.0	5
11.00	199.6	1.5	6	0.06	3.0	6
11.30				no fit		
11.80				no fit		7
12.00	198.9	3.0		no res		6
12.20	200.6	3.2		no res		7
12.50	212.9	4.3		no res		7
12.90	208.6	4.2	8	0.11	0.18	7
13.40	184.1	11.1	6	0.40	0.55	6
13.60	210.5	11.0	7	0.26	0.7	7
13.90	196.4	9.1	7	0.20	0.3	7
14.30	186.8	7.2	7	0.40	1.9	7
14.80	208.3	6.8	8	0.16	0.3	8
15.20	182.3	9.9	8	0.34	0.4	8
15.50	215.4	11.2	8	0.26	3.1	8
15.90	194.5	6.6		no res		8
16.10	209.5	7.1		no res		8

stripping reaction. The spins were obtained by a comparison of the angular distributions to squared Legendre polynomials $P_L^2(\cos\theta)$. The parities are natural; 0^+, 1^-, 2^+, 3^- and so on. In the scattering of 10 to 20 MeV alpha-particles from silicon, spins of resonances between 7 and 9 are observed. The 14.3 - 15.4 energy range was investigated in more detail using the Florida State University Pelletron. The current good energy resolution of this experiment led to an observation of about eight times more resonances than found before in that energy range. From correlation analysis the mean width 20 keV of the resonance was deduced. Safe for a couple of resonances all were assigned spin 8 [8]. The coupled channel analysis of the same energy region reveals ten J=5, one J=6, thirteen J=7, ten J=8 and three J=9 resonances [21] (see Table)

2 Rotational bands and surface structure

A linear dependence has been noted when energies of the resonance in α + ^{28}Si are plotted versus J(J+1) [5] (see Figure). A similar line describes the alpha-particle transfer to ^{24}Mg by (^6Li,d) stripping [24]. This has been understood to be an indication of the existence of a mixed parity bands [3, 25], the states of which are represented by many fragments of equal spin. Bands of even and odd parity states are not expected from fundamental theories based on the interaction between fermions. In terms of the Pauli principle there should be so-called Firsov splitting between bands of different parities [26]. The lack of splitting implies that the nuclear surface has a structure of bosons, that interact with the incoming alpha-particles [25]. The low density on the nuclear surface makes the existence of alpha matter probable there. Nuclear matter theories imply indeed that below the point of the matter being compressible there is no thermodynamical stable uniform state of it. Below this point the system breaks up into clusters [27, 28]. The variety of possible clusters may be illustrated by the Ikeda-diagram [29]. The bosonisation mentined here is considered to occur when the Broglie wavelength corresponding to the interacting alpha-particles is comparable to the distance between them [30].

The moment of inertia parameter C of the relation $E = CJ(J+1)+E_0$ is small in comparison to that

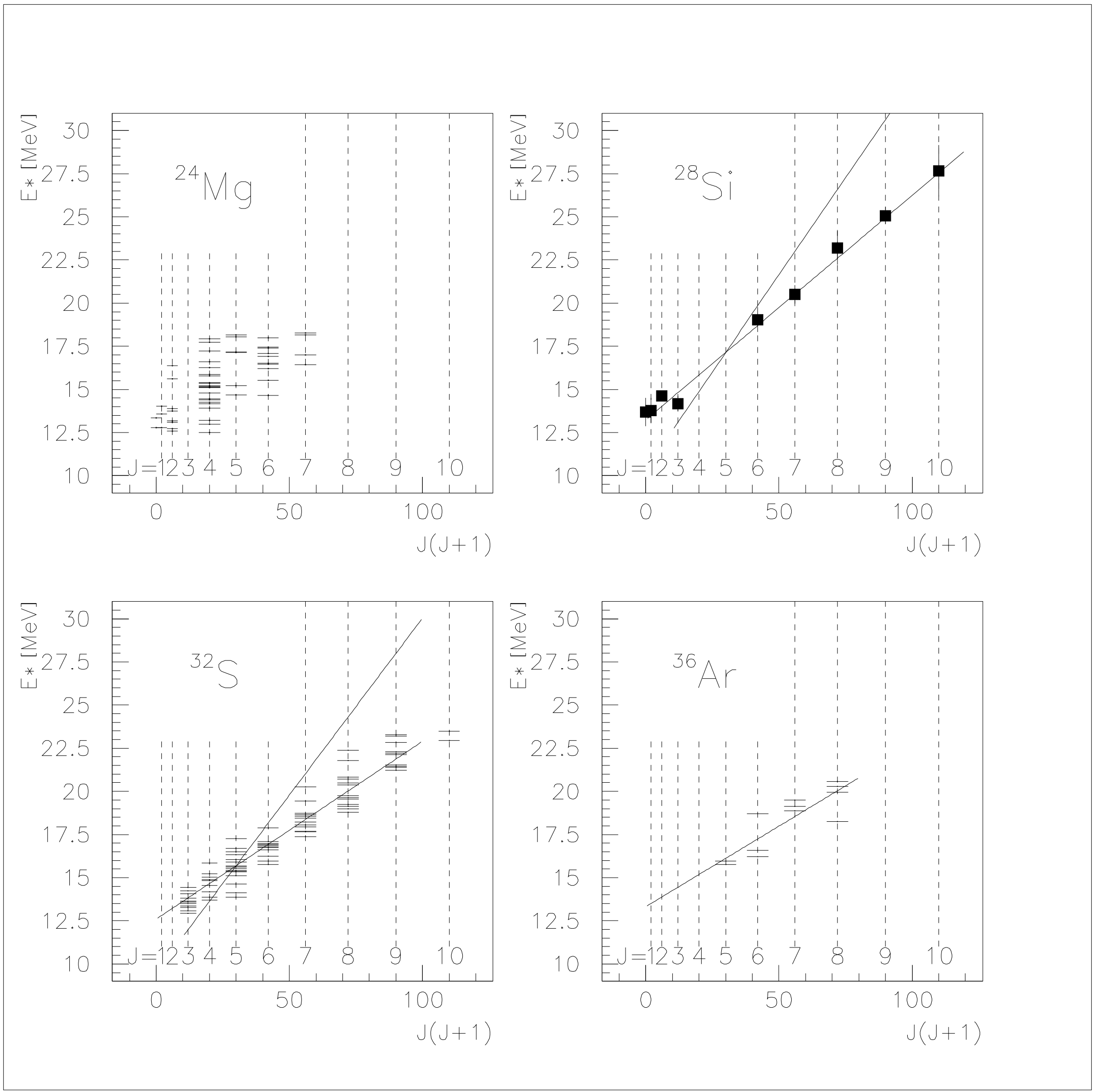

Figure 1: The energies of states formed in elastic scattering of α-particles from some alpha nuclei. Stright lines are fitted to the excitation energies of the compound system and plotted versus J(J+1). For silicon and sulfer steep lines correspond to moment of inertia parameters of one orbiting particle

expected for a single alpha-particle orbiting the target nucleus. If we assume that the orbit radius equals the sum of the target and alpha-particle radius, 1.25 $A^{1/3}$ + 1.60, we expect for A = 24, 28 the rotational constants C = 225, 205 keV (energy in c.m.). However, the experimental constants are C = 131, 103 keV. The radius parameter 1.25 gives e.g. a ^{28}Si radius of 3.8 fm. The Hofstadter rms radius for the target is 3.04 fm [13]. The latter would yield an even larger rotational constant, that would diverge more from experiment.

We conclude that the value of C can not be reproduced by assuming a single particle orbiting a non-rotating target. The agreement with experiment is, however, found if a part of the target nucleus is assumed to rotate jointly with the captured alpha particle [5]. The rotating mass of ^{28}Si and ^{32}S may be considered to consist of three and four alpha particles orbiting a ^{16}O core [31].
The formation of the alpha particles from the valence nucleons has been discussed by Lönnroth [32]. Microscopic shell model calculations have been mentioned as a mean to create the alpha-cluster correlations. One possibility would be to start from ^{16}O and to advance toward more complex cases of increasing number of nucleons. A sudden cut-off of the cross-section at 27 MeV hints at an upper limit of the spin near $12\hbar$ to 14 $\hbar$. It may be due to the "running out of valence particle spin". If so, it indicates the limitation in number of valence particles i.e. to particles within the skin at the nuclear surface mentioned above.

The occurrence of even and odd spins in the same band implies also that the rotating object has not more than one symmety axis. We may think of a rotating pear or of an asymmetric disc, having the symmety axis in the plane of the disc. Such shapes would occur if an alpha particle is captured on spherical target. As mentioned above only a part of the target will start to rotate jointly. We may expect various shapes of that jointly rotating part and consider its thickness to depend on the azimuthal and polar angle.

3 Fragmentation of cluster states in light nuclei

The last experiments on the scattering of alpha-particles on light nuclei demonstrated the appearance of the bands belonging to the same momenta [2]. The energy range of these bands was in average about 2 MeV. We have the bands in the rotational band consisting of even and odd states showing the moment of inertia of a few alpha-particles rotating around a core.There were many attempts to explain this phenomena (rotational-vibrational model, solitons, Bose-Einstein condensate). But none of these attempts were satisfactory.The situation reminds the situation which took place with the stripping reactions.The experimentalists observed the fragmented single particle states belonging to the same momenta.The theory explained this phenomena with the help of the model of paring correlation. The anology between fragmentation (here the term fragmentation has another meaning to respect upper text) of nuclei and buckyballs leds us to the idea of the consideration of light nuclei as quasicrystals [33]. We established that quasicrystalline structure can be formed when the distance between alpha-particles is comparable with the length of De Broglia wave of alpha-particle. The dying behavior of microscopic wave functions of alpha particles in the intrinsic region of nucleus says us about the existanse of clusters in the surface region of nucleus. Relying on the experiment [1] we suppose the quasicristalline structure of nucleus ^{32}S. (In the vertexes there are alpha-particles or solitons, describing by Bloch functions [34]. The phonon exitation of quasicrystal leads to the appearance of bands inside of rotational band.The number of the states in the band is determined by the shape of nucleus.The microscopic calculation of the momenta of inertia for such systems is in progress now.Applying this model to the scattering of alpha partcles we obtained that the formfactor of clusterized nucleus can be factorirized on formfactor of cluster and the dencity of clusters in nucleus. It gives us the possibility to study the distribution of clusters in nuclei. By the way this solution allowes us to distingwish what kind of distribution we have: volume or surface one. Similar situation takes place at the scattering of electrons on metal cluster and fullerenes [35]

One can consider the cross section of the elastic scattering at large angles as an exchange process which can be factorized as

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{el}} = |F\left(\vec{Q}\right)|^2 \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{p}}, \tag{1}$$

where $(d\sigma/d\Omega)_{\mathrm{p}}$ is the cross section for a point projectile with mass m, scattering by the core-target interaction, $F\left(\vec{Q}\right)$ - the form factor of the projectile (in our case it is the formfactor of ^{28}Si because in the experiment which we analysed the inverse geometery was used:

$$F\left(\vec{Q}\right) = \int d^3r|\phi_0(\vec{r})|^2 \exp\left(i\vec{Q}\vec{r}\right), \tag{2}$$

where $\vec{Q} = \vec{k} - \vec{k}'$ is transfered momentum [36] We shall consider the structure of the system ^{28}Si+^{4}He as a configuration of alpha-particles located preferably in the surface layer of compound nucleus. In correspondence with Ikeda diagramm [29] evidentely at high exitation energies of nucleus the role of cluster structure incereases but the role of shell structure decreases. Supposing the quasicrystalline structure of nucleus we factorized the formfactor of the projectile in the following way:

$$F^{\mathrm{N}}(\vec{q}) = F^{\alpha}_{\mathrm{A}}(\vec{q}) \sum_i u_{\mathrm{j}}(\vec{r}) \exp\left(i\vec{Q}\vec{r}\right) = F^{\alpha}_{\mathrm{A}} n^{\mathrm{N}}(\vec{q}), \tag{3}$$

where F^{α}_{A} is the form factor of alpha-particle, $u_{\mathrm{j}}(\vec{r}) \exp\left(i\vec{Q}\vec{r}\right)$ are the Bloch wave functions, which are the eigenfunctions of the wave equation for a periodic potential which is the product of a plane wave $\exp\left(i\vec{Q}\vec{r}\right)$ and a function $u_{\mathrm{j}}(\vec{r})$ with the periodicity of the crystal lattice. We considered the case when the transfered momentum coincides with the lattice momentum. Using Wigner-Seitz approach we immideately obtain the energy band for each momentum:

$$\epsilon_{\mathrm{m}} = \left(\epsilon^2_{\mathrm{bot}} + m^2\right)^{1/2} \tag{4}$$

where $m = 0, \pm\pi/R, \pm 2\pi/R, \cdots \pm N\pi/R$, R is the radius of Wigner-Seitz cell. For different momenta we found the number of states in the band from 8 to 12. It does not contradict the Talmi-Moshinsky rule:

$$2(N-1) + L = \sum_i^j 2(n_{\mathrm{i}} - l) + l_{\mathrm{i}} \tag{5}$$

where N-main quantum number of a cluster, L-orbital momentum of a cluster, n,l-shell model quantum numbers. It will be possible to get very close results in the framework of unitary representations of certain groups [37]. It is necessary to say that the idea of crystalline soliton matter was exploited in the work of N.Glendenning and B.Banerjee [38]. In another work M.Danos and A.B.Johnson [39] considered the collective excitations in the crystalline nucleus model for the explanation of the giant dipole resonances. They obtained the following formula for the energy of dipole resonances in the frame of model of cubic cristalline lattice with alpha-particle vertexes:

$$E = E_0 + 6V \cos\left(\frac{\pi}{N+1}\right) \tag{6}$$

where $N = (A/4)^{1/3}$, A is mass number,$V = -3.3MeV, E_0 = 29.6MeV$ In the frame of the nonlinear approach it is possible to obtain the appearance of the energy bands. It can be reached by the balance of two-body and three body forces in the Skyrme model [40]. To understand the appearance of the energy bands it is very easy to take into acount the D.Robson's work [41]. He paid an attention to the evidence of the tetrahedral nature of ^{16}O. Considering the ^{16}O nucleus as semirigid system he factorized the wave function as a product of the rotational part consisting of the linear combination of D-matrix elements for each momentum J and the vibrational part:

$$\Psi^{\mathrm{J}}_{\mathrm{RV}} = \Psi^{\mathrm{J}}_{\mathrm{R}} \Psi^{\mathrm{J}}_{\mathrm{V}} \tag{7}$$

and respectively, matrix elements (in the case of electron scattering):

$$\begin{aligned} M(0 \to J) &= (M_{\mathrm{R}}(0 \to J))\, M_{\mathrm{V}}, && (8)\\ M_{\mathrm{V}} &= <\Psi^0_{\mathrm{R}}|\exp(i\vec{q}\Delta\vec{r}_{\alpha_{\mathrm{i}}})|\Psi^0_{\mathrm{R}}>, && (9)\\ M^{\mathrm{J}}_{\mathrm{R}} &\sim <\Psi^{\mathrm{J}}_{\mathrm{R}}|\exp(i\vec{q}\vec{R}_i)|\Psi^{\mathrm{J}}_{\mathrm{R}}> = g_{\mathrm{J}} j_{\mathrm{J}}(qR) Y^*_{\mathrm{JM}}(\vec{q}) && (10) \end{aligned}$$

The constant g_{J} is determined by the tetrahedral geometry. Now we return to the formula (3). The same result was obtained in the case of the diffraction of fast electrons on the fullerene C_{60} [42] molecule. In the formula (3) the module $u_{\mathrm{j}}(\vec{r})$ which has the periodicity we took equal to 1. The summation is going through the coordinates of all clusters. If we take instead of the sum the integral, in this case we shall have two possibilities: volume and surface integration. Taking into account the surface distribution of clusters we got the following result:

$$n(q) = N J_0(qR) \tag{11}$$

where N-the number of clusters, $J_0(qR)$- the spherical Bessel function. This result is very suprising because the anamalous large angular scattering (ALAS) can be described by the module of zero order the Bessel function squared. There is another interesting result. Keeping in mind the rotational invariance the correlation function of two alpha-particles described by Bloch functions can be expressed through

$$K(\vec{\chi}) = \int d^2x \; u^{\mathrm{rand}}(\vec{x}) \; u^{\mathrm{rand}}(\vec{x}+\vec{\chi}) = const \; J_0(k_0|\vec{\chi}|), \tag{12}$$

where J_0 is the spherical Bessel function, k_0 - the module of wave vector, χ - the argument of correlation function. It is necessary to note that we used the gaussian distribution of amplitudes.

4 Discussions and conclusions

In the present article the existence of resonanses in the scattering of alpha-particles from 2s-1d targets is placed without dispute by experimental evidences. The bands of resonance states at the excitation energies over 13 MeV in ^{28}Si and ^{32}S are explained in terms of a model of three and four alpha-particles orbiting a ^{16}O core. This model is deduced from the systematics of resonances of highest spins. The dynamic properties of these particles have been discussed referring to published theoretical models. A vibrational degree of freedom [31, 43] and solitonic or bosonic quantum numbers [30, 44] have been mentioned as exciting issues. They hint at the occurrence of new kinds of nuclear dynamics [6]. New measurements of the elastic and inelastic scattering which cover large energy ranges scanned in small energy and angular steps are needed to promote the understanding of the current experimental results. Here we have the confirmation that the investigation of scattering of alpha-particles at large angles gives us some feeling of the quasicrystalline structure of light nuclei. The energy band structure of the rotational bands is some signature of the crystalline structure.

We would like to express our sincere gratitude to Prof. A.V. Solovi'ev for helpful discussions. Partial support of Deutsche Forchungsgemeinchaft and Russian Foundation of Basic Research is gratefully acknowledged.

References

[1] K.A. Gridnev, A.A. Ogloblin, Fiz. Elem. Chastits At. Yadra 6 (1975) 393

[2] A.E. Antropov, M. Brenner, V.Z. Goldberg, W. Greiner, K.-M. Källman, T. Lönnroth, A. Ludu, P. Manngård, A.E. Pahkomov, V.V. Pankratov, *in Proceedings of 7th Int. Conf. on Nuclear Rection Mechanisms*, Varenna, Italy (Milano University, 1994, p.430

[3] R. Stock, G. Gaul, R. Santo, M. Bernas, B. Harvey, D. Henrie, J. Mahoney, J. Sherman, J. Steyaert, M. Zisman, Phys.Rev. C6 (1972) 1226

[4] R. Abegg, C.A. Davies, Phys. Rev. C 43 (1991) 2523

[5] M. Brenner, Z. Phys. A349 64 (1994) 64

[6] M. Brenner, *Proc. Int. Workshop on Fission Dynamics*, Luso, Portugal, 2000 (in press).

[7] K.-M. Källman, Doct. Diss. in Physics (Åbo Akademi, Turku, Finland, 1998).

[8] M. Brenner, N.R. Fletcher, J.A. Liendo, S.E. Belov, D.D. Caussyn, T. Kurtukian Nieto, S.H. Myers, *Clustering Phenomena in Nuclear Physics, Proc. Int. Conf.*, June, 2000, St.-Petersburg, Russia

[9] J.P. Aldridge, G.E. Crawford, R.H. Davis, Phys. Rev. 167 (1968) 1053

[10] V.Z. Goldberg, G.V. Rogachev, M. Brenner, K.-M. Källman, T. Lönnroth, M.V. Rozhkov, S. Torilov, W.H. Trzaska, R. Wolski, Phys. of Atomic Nuclei, 63 (2000) 1518

[11] C.P. Robinson, J.P. Aldridge, J. John, R.H. Davies, Phys. Rev. 171 (1968) 1241

[12] D. Frekers, R. Santo, K. Langanke, Nucl. Phys. A394 (1983) 189

[13] K.-M. Källman, Z. Phys. A356 (1996) 278

[14] L. Jarczyk, Inst. Phys., Silesian University, Katowice, 7-1979

[15] E. Indola, Masters Thesis in Physics (Åbo Akademi, Turku, 1999)

[16] P. Manngård, M. Brenner, M.M. Alam, I. Reichstein, F.B. Malik, Nucl. Phys. A504 (1989) 130

[17] C.R. Gruhn, N.S. Wall, Nucl. Phys. 81 (1966) 161

[18] P.P. Singh, B.A. Watson, J.J. Kroepfl, T.P. Marvin, Phys. Rev. Lett. 17 (1966) 968

[19] C. Bergman, R.K. Hobbie, Phys. Rev. C 3 (1971) 1729

[20] T. Ericson, Ann. Phys. 23 (1963) 390

[21] V.V. Lazarev, *Clustering Phenomena in Nuclear Physics, Proc. Int. Conf.*, June, 2000, St.-Petersburg, Russia (in press)

[22] J.S. Eck, W.J. Thompson, K.A. Eberhard, J. Schele, W. Trombik, Nucl. Phys. A255 (1975) 157

[23] K.P. Artemov, M. Brenner, M.S. Golovkov, V.Z. Goldberg, K.-M. Källman, T. Lönnroth, P. Manngård, V.V. Pankratov, V.P. Rudakov, Sov. J. Nucl. Phys. 55 (1992) 492

[24] K.P. Artemov, M.S. Golovkov, V.I. Dukhanov, I.B. Mazurov, V.V. Pankratov, V.V. Paramonov, V.P. Rudakov, I.N. Serikov, V.A. Solovyev, V.A. Timofeev, Yad. Fiz. 51 (1990) 1220

[25] M. Brenner, In *Clustering Phenomena in Atoms and Nuclei*, Springer Series in Nucl. and Part. Physics, Heidelberg, 1991, p.327.

[26] K.A. Gridnev, in *Clustering Phenomena in Atoms and Nuclei*, Springer Series in Nucl. and Part. Physics, Heidelberg, 1999,. p. 153.

[27] J.W. Clark, Ann. Phys. 40 (1966) 127

[28] M.T. Johnson, J.W. Clark, Kinam, 2 (1980) 3

[29] H. Horiuchi, K. Ikeda, Y. Suzuki, Prog. Theor. Phys. Suppl. No. 52 (1972).

[30] K.A. Gridnev, S.E. Belov, K.V. Ershov, M. Brenner, D.K. Gridnev, J.S. Vaagen, *in Proc. Int. Conf. on Perspectives in Nucl. Phys.* Crete, Greece, Inst. Nucl. Phys. N.C.S.R. Demokritos, Athens, 1999

[31] M. Brenner, E. Indola, K.-M. Källman, T. Lönnroth, P. Manngård, M. Halldorsdottir, Th. Karlsson, Z. Máté, L. Zolnai, V.Z. Goldberg, G.V. Rogatchev, M.V. Rojkov, I.N. Serikov, W. Trzaska, R. Wolski, Heavy Ion Phys. 7 (1998) 355

[32] T. Lönnroth, Il. Nuovo Cimento 110A (1997) 961

[33] W. Bauer, Proc 1st Catania Relativistic Ion Studies, Asicastello, Italy, 1996, p.23.

[34] G. Kittel, Introduction in to Solid State Physics, (6th ed.,Ch. 7, Wiley-Sons,1986)

[35] L.G. Gerchikov, A.V. Solov'yov, J.-P. Connerade, W. Greiner, J. Phys. B: At. Mol. Opt. Phys. 30 (1997) 4133

[36] R.C. Johnson, J.S. Al-Khalili, J.A. Tostevin, Phys. Rev. Lett., 79 (1997) 2771

[37] Y. Alhassid, F. Guersey, F. Iachello, Phys. Rev. Lett. 50 (1983) 873

[38] N.K. Glendenning, B. Banerjee, Phys. Rev, C34 (1986) 1072

[39] M. Danos, B. Johnson, Europhys. Lett. 2 (1986) 205

[40] P. Burt, Phys. Lett. 71A (1979) 1

[41] D. Robson, Phys. Rev. Lett. 42 (1979) 876

[42] L.G. Gerchikov, P.V. Efimov, V.M. Mikoushkin, A.V. Solov'yov, Phys. Rev. Lett. 81 (1998) 2707

[43] U. Abbondano, N. Cindro, P.M. Milazzo, Nuov. Chim. A110 (1997) 955

[44] A. Ludu, A. Sandulescu, W. Greiner, K.-M. Källman, M. Brenner, T. Lönnroth, P. Manngard, J. Phys. G: Nucl. Part. Phys. 21 (1995) L41