From ALAS to nuclear gas

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Abstract. Anomalous Large Angle Scattering and no inelastic scattering are apparent at peaks in the excitation function of elastic alpha-particle scattering from $^{28}\text{Si}$ and $^{32}\text{S}$. Mixed parity bands of intermediate states are observed in $^{32}\text{S}$ and $^{36}\text{Ar}$ and referred to in $^{28}\text{Si}$. Missing decay to the ground states of $^{28}\text{Si}$ and $^{24}\text{Mg}$ above the thresholds of “break-up” in oxygen + four and three alpha particles is considered a signature of an alpha-particle gas above these thresholds.

1. Introduction
Occasionally the fitting of experimental angular distributions of the elastic scattering of $\alpha$-particles from $N\alpha$ targets by the optical model alone is not successful. Frequently the measured backward yield is larger than the calculated. This effect has been named anomalous large angle scattering, ALAS. The ALAS occurs especially at energies where the excitation function of elastically scattered $\alpha$ particles displays pronounced peaks. In a large number of investigations of elastic scattering from $^{28}\text{Si}$, however, the fitting of the angular distributions by adding a resonance term has been successful. The resonances have then been considered intermediate states formed in $^{32}\text{S}$ by the capture of the incoming alpha particle. The spins J of the presumed states are the order one of the squared Legendre polynomials, P_l(\Theta), that give the best fits. A found linear dependence of the energy against J(J+1) furthermore indicates that we are dealing with states, that describe essential properties of the nucleus. Nevertheless more evidence seem to be required to defend this viewpoint instead of considering the pronounced peaks as fluctuations of a statistically varying yield. To this end the elastic and inelastic scattering measured in 5 keV energy steps at the Florida State University tandem, Tallahassee [1] (see figure 1) are recalled. The analysis of the experimental angular distributions of elastic and inelastic ($2^+$) scattering using a coupled channel (CC) code with the resonance amplitudes added coherently [2] is not as yet fully exploited. The yield of alpha particles scattered by the Coulomb-potential and the direct effect are the cause of a background that obscures the resonance scattering of interest. If, however, the intermediate state is formed by a transfer reaction instead of by the capture, this effect is avoided. Therefore the population of highly excited states in $^{32}\text{S}$ were investigated by the transfer of the alpha particle from $^6\text{Li}$ to $^{28}\text{Si}$ as well.

2. Pronounced peaks indicating cluster states
The ALAS is evident at the angles 173.4 and 167.6 degrees and energies 14.6, 15.0, and 15.4

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MeV. Angular distribution measurements result in the spin $8^+$ for these resonances. The excitation functions are fitted all over the energy range 14.3-15.4 MeV with $V=170$ MeV, $r_v=1.52$ fm and $a_v=0.48$ fm for the radius, depth and diffuseness of the real part and $W=8.0$ MeV, $r_w=1.55$ fm and $a_w=0.39$ fm for the imaginary. The Wigner shapes of the resonances, that give the best fit to the peaks are given by the parameters of table 1. The energy $E_r$ is in the centre of the peak. The other parameters are the spin-parity $J^\pi$, total width $\Gamma$, partial widths $\Gamma_{el}$ and $\Gamma_{inel}$ of the elastic and inelastic scattering and six parameters labelled -,0 and + of the three projections of the inelastic part.

The parities are assumed be natural, $\pi=(-1)^l$. It should be emphasized that the inelastic partial width of the pronounced peaks is zero or much smaller than the elastic. This is a striking fact as compared to the other resonances. It implies that the three states decay mainly to the ground states of $^{28}$Si and $^4$He, which thus are constituents of $^{32}$S before its decay. The states are therefore considered cluster states. There are, however, six or seven unpronounced $8^+$ resonance states. They may be considered states that result from the interference between the cluster states and a background of a more complicated structure. The phenomenon is called broadening [3], which implies that the decay strength is spread out to adjacent states.

Figure 1. In the elastic scattering (left) three pronounced $8^+$ peaks are seen at 14.6, 15.0 and 15.4 MeV at the scattering angles 173.4, 167.6 and 150.0 degree. The peaks do not appear in inelastic scattering (right).
Table 1. Energy (lab.syst. MeV), spin-parity, widths (keV) and phases (radians) of resonances

| E_r  | J^π | Γ  | Γ_el | Γ_inel | Φ' | Γ_inel | Φ' | Γ_inel+ | Φ' |
|------|-----|----|------|--------|----|--------|----|---------|----|
| 14.386 | 7^- | 20 | 14 | 3 | 3.6 | 1.6 | 0 | 0 |
| 14.427 | 5^- | 40 | 26 | 14 | 6 | 1.01 | 7 | 0.1 | 0 |
| 14.457 | 7^- | 20 | 13 | 3 | 1 | -1.3 | 1 | -2.3 | 1 | 0.7 |
| 14.470 | 7^- | 20 | 6 | 13.5 | 2.5 | -3.1 | 0 | 11 | -1.5 |
| 14.471 | 5^- | 40 | 26 | 7 | 0 | 0 | 7 | -3.7 |
| 14.491 | 7^- | 30 | 23 | 6.5 | 0 | 0.5 | -2.6 | 6 | -3.3 |
| **14.564** | **8^-** | **30** | **22** | **3** | **-1.6** | **1** | **-2.2** | **1** | **-2.5** |
| 14.580 | 5^- | 40 | 29 | 11 | 9 | 1.1 | 0 | 2 | -0.7 |
| 14.640 | 8^- | 10 | 3 | 0.5 | 0 | 0.5 | 2.5 | 0 |
| 14.657 | 7^- | 25 | 4 | 21 | 7 | -0.5 | 14 | -1.1 | 0 |
| 14.675 | 8^- | 17 | 10 | 0.5 | 0 | 0 | 0.5 | 4 |
| 14.725 | 5^- | 40 | 25 | 7 | 3 | 1.8 | 4 | -2.1 | 0 |
| 14.755 | 7^- | 30 | 5 | 24 | 23 | -0.5 | 0 | 1 | -1.3 |
| 14.770 | 8^- | 20 | 6.5 | 5.5 | 4.5 | -1.4 | 1 | -1.9 | 0 |
| 14.831 | 5^- | 40 | 22 | 17 | 15 | 1.1 | 1 | -1.7 | 1 | 0.9 |
| 14.846 | 9^- | 20 | 4 | 13 | 13 | 0.5 | 0 | 0 |
| 14.860 | 7^- | 25 | 10 | 12 | 12 | -0.4 | 0 | 0 |
| 14.889 | 7^- | 25 | 6 | 3 | 0 | 1.5 | -0.8 | 1.5 | -0.7 |
| 14.923 | 9^- | 25 | 11 | 10 | 4 | -1.2 | 2 | -4.4 | 4 | -5.4 |
| 14.926 | 8^- | 20 | 6 | 12 | 0 | 6 | -3.5 | 6 | -4.6 |
| 14.940 | 7^- | 25 | 6 | 11 | 7 | -3.6 | 3 | -2.1 | 1 | -2.7 |
| 14.959 | 5^- | 40 | 26 | 13 | 7 | -1.1 | 0 | 6 | 0.26 |
| 14.983 | 7^- | 20 | 13 | 5 | 0 | 1 | -0.4 | 4 | -0.5 |
| **14.992** | **8^-** | **20** | **18** | **1** | | | | | |
| 15.002 | 5^- | 40 | 35 | 4 | 3 | -0.5 | 1 | -2.9 | 0 |
| 15.056 | 5^- | 40 | 17 | 5 | 1 | -0.6 | 4 | -2.1 | 0 |
| 15.078 | 6^- | 50 | 12 | 37 | 25 | -0.4 | 12 | 2.2 | 0 |
| 15.080 | 7^- | 30 | 2 | 16 | 0 | 0 | 16 | -1.3 |
| 15.127 | 9^- | 30 | 9 | 4 | 4 | -0.5 | 0 | 0 |
| 15.158 | 5^- | 40 | 18 | 21 | 16 | 1.1 | 5 | -2.6 | 0 |
| 15.164 | 7^- | 30 | 15 | 4 | 2 | -0.4 | 0 | 2 | 1.7 |
| 15.208 | 8^- | 35 | 17 | 4 | 0 | 1 | -1.2 | 3 | -1.6 |
| 15.270 | 8^- | 35 | 12 | 7 | 1 | -0.32 | 6 | -0.67 | 0 |
| 15.312 | 7^- | 30 | 17 | 4 | 0 | 4 | 0.7 | 0 |
| 15.318 | 5^- | 60 | 40 | 18 | 4 | -1.7 | 11 | -2.5 | 3 | -0.3 |
| 15.376 | 8^- | 23 | 9 | 4 | 2.5 | 1.3 | 1.5 | 0.3 | 0 |
| **15.383** | **8^-** | **23** | **14** | **1** | **0** | | | | |

3. Bands of rotational states

The yield of elastic alpha-particle scattering has been investigated in larger energy steps and with a poorer energy resolution than that presented in figure 1. In this experiment the pronounced states, i.e. the states considered cluster states, clearly appear, whereas the week states of complicated structure are smaller or obscured (c.f. [1] figure 2). The excitation function was measured by a thick target technique at the Abo Akademi cyclotron [4]. That of figure 1 was obtained with a tandem, which explains its much better resolution of it. The peaks of the cluster states gather along a line when the energy is plotted against J(J+1). The lines of figure 2 indicate the existence of rotational bands, the head of which in all cases lie near 12.5 MeV [5]. The plots make possible the deduction of the...
moments of inertia of the intermediate nuclei. The steep solid line corresponds to the moment of inertia of one alpha particle bound to the surface of the target nucleus. The lines fitting the points of $^{28}\text{Si}$ and $^{32}\text{S}$ are for 3 and 4 alpha particles bound to a core of $^{16}\text{O}$. It is seen that $^{36}\text{Ar}$ does not follow the systematic of alpha particles on an oxygen core. There are no data on high lying states of the cluster character in $^{24}\text{Mg}$ to indicate a structure of two alpha particles on that core. The above facts bring about the idea that the 3 and 4 alpha particles and a $^{16}\text{O}$ ground state make the structure of the silicon and sulphur intermediates that decay to the ground state of the target nucleus.

Figure 2. Excitation energies against $J(J+1)$. Steep lines: One $\alpha$-particle on the target nucleus. Fitted lines: Several $\alpha$-particles on an oxygen core (see text)

4. Fragmentation and sudden loss of two boson decay.
The multitude of states of the same spin, e.g. thirteen spin 8 states, can be considered a fragmentation of one cluster state. A theory to explain this phenomenon has been proposed by Gridnev [6]. A system of bosons can be described by the Gross-Pitaevsky equation. When applied to the above system of four alpha particles we can determine the value of the parameters of the energy expression; $E=A+BJ(J+1)+C'N+F_n$, where $B$ is related to the moment of inertia, $N$ is the main quantum number and “$n$” indicates the number of particles described. We chose the possible values 0,1,2,3 for $n$ to indicate the fourfold nature of the particle number. The energy expression can be fitted when $E$ is plotted in a periodic system of four members in each period numbered by $N$. For the parameters we get $A=12.10$ MeV, $B=98.0$ keV, $C'=1.33$ MeV and $F=0.382$ MeV. This results in one line of every $J$ value, because roughly $C' \approx 4*F=1.52$MeV.

It is interesting to learn whether the systematic of states continues at high excitation or if there is an upper limit. Energy regions of higher excitation in $^{32}\text{S}$ were reached by the transfer reaction $^{28}\text{Si}(^6\text{Li},d)^{32}\text{S}$. It was exploited in an experiment using the tandem and CT2000 scattering chamber of LNS in Catania [7]. The reaction was interfered by reactions in carbon and oxygen present in the target and scattering from hydrogen. It was therefore necessary to discriminate the interfering reaction.
by measuring the simultaneous emission of the deuterons and the alpha particles emitted from $^{32}\text{S}$. This enabled, indeed, the extraction of the yield of sulphur decaying to the $^{28}\text{Si}$ ground state, the yield of which corresponds to the elastic scattering of alpha particles from $^{28}\text{Si}$ (c.f. section 2). At 31 MeV a sudden loss of decay into the two $0^+$ bosons, $\alpha$ and $^{28}\text{Si}_{\text{g.s.}}$ was observed. The same has been observed in alpha-particle scattering as well \[7,8\]. The energy threshold above which the nuclear forces are too small to keep four alpha particles and oxygen bound together appears to lie at the same energy \[7\]. There is no sign of any similar break-even threshold, up to this level. We conclude that the constitution of $^{32}\text{S}$ of the five parts, $^{16}\text{O}_{\text{g.s.}}$ and four alpha particles, is unique in the investigated energy region. It represents one structure of the high excited sulfur nucleus that may be formed in the alpha-particle scattering and the alpha-particle transfer reaction.

According to the systematic of figure 2, a similar structure of oxygen and three alpha particles is expected in $^{28}\text{Si}$. Indeed the excitation function of elastic scattering hints at a loss of yield near the break-even threshold at 24 MeV \[9\].

5. Conclusions
We expect the energy against $J(J+1)$ to follow the fits of figure 2 up to high energies. The spin of the $^{32}\text{S}$ states at 31 MeV is therefore expected to be high ($\approx 15h$). Moreover, we expect the nucleus to decay into five parts above this threshold, since the nuclear forces do not prevent it. Energy, however, would be required for the disintegration, because it implies a transport of energy away from the break-up centre. The required amount is bound in the rotation of the excited sulphur nucleus. At the break-even threshold and up till a level, which depends on the radii at break-up, there is not enough energy available for the fragments to depart. The lack of binding forces does not, however, hinder the movement of fragments out from the centre of rotation. They may remain at larger distances than in nuclei below the threshold, so as to make a matter of low density i.e. a gas. This may be similar to what recently has been described in terms of a multi-$\alpha$-structure \[10\] and a dilute Bose gas \[11\].

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6. References
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