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Study of the high-lying, high-spin $\alpha+^{28}\text{Si}$ resonance structure in ^{32}S

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Abstract

The structure of highly excited elastic α -scattering resonances in ^{32}S was studied with the reaction $^{28}\text{Si}(\alpha, \alpha_0)^{28}\text{Si}$ at beam energies between 22 and 30 MeV. The data were collected with a thick-target method giving continuous energies. The properties of 24 resonances in the spin range $\ell = 9 - 12 \hbar$, and up to 32 MeV excitation in ^{32}S , were determined. The strong drop-off in elastic cross section at about 27.5 MeV laboratory energy was studied, and a similar but less drastic effect is observed at 21.5 MeV. Some possible explanation for these behaviours are discussed. The present results complement previous high-resolution data at lower energies, and favours the interpretation of the resonances as α -cluster states. The implications on potential models from resonances with angular momenta as high as $12\hbar$ are discussed.

1 Introduction

During the last decade there has been a renewed interest in cluster states, called molecular states for heavier components. This has been spurred by the finding that high-lying states, that are still narrow, persist in light nuclei where a continuum has earlier been presumed [1]. In very light nuclei, with $A \sim 8-16$, α -cluster structures are the most conspicuous, see e.g. [2]. In heavier nuclei, also other cluster combinations like ^{12}C and ^{16}O have been observed. Indeed, these kinds of structures, both α -clusters and molecular clusters of heavier specimen, were discussed to some detail almost three decades ago [3]. Further, see reference [4] for a comprehensive presentation of nuclear molecules.

The appearance of α -cluster structures in medium-light nuclei, with $A \sim 20-44$, is not properly understood. Such structures have been studied in $^{20,22}\text{Ne}$ [5, 6] (band structures), in ^{36}Ar [7] (low-spin states) and in ^{40}Ca and ^{44}Ti (α -clusters) [8]. One of the most detailed studies of α -cluster structures in medium-light nuclei was reported in [9]. In that work the elastic $\alpha+^{28}\text{Si}$ channel in the energy range $E_{\text{Lab}} = 6.0 - 19.6$ MeV was studied. More than 80 α -cluster states were identified, having unambiguous angular momentum values in the excitation energy range 12 – 23 MeV, out of about 200 resonances totally observed. That study was preceded by another one [10] at low energies with $E_{\text{Lab}} = 4 - 7$ MeV. It has also been followed by a complete study

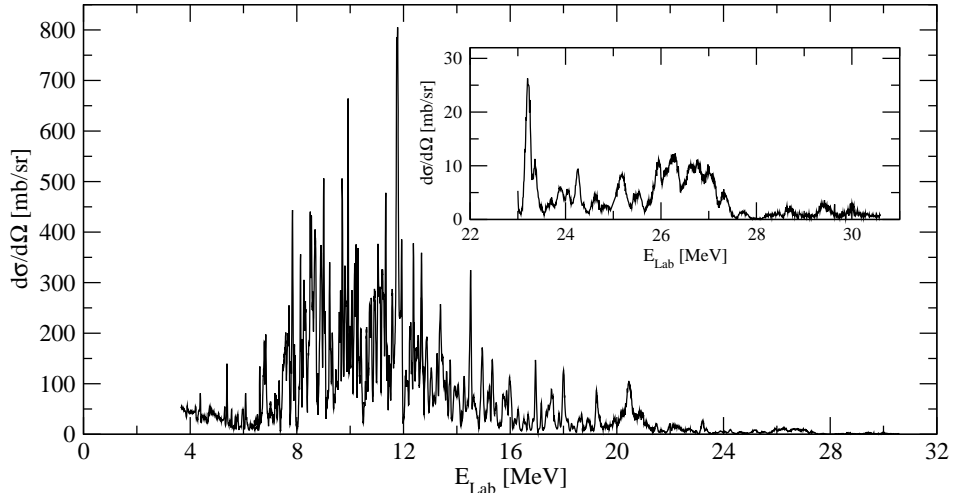


Figure 1: Excitation function of the elastic $\alpha+^{28}\text{Si}$ scattering over a large energy range. From the present work and [9, 10]. The inset is a magnification of the uppermost part at $E_{\text{Lab}} \sim 23 - 31$ MeV.

of the region [11]. There also exists an old work of $\alpha+^{28}\text{Si}$ scattering [12], albeit with low energy resolution.

All the above-mentioned studies (except [12]) rely on the so-called thick-target method, which allows continuous energy registration [13]. The present work aims at verifying the structures observed in the preliminary studies up to $E_{\text{Lab}} \sim 31$ MeV. Further, angular-momentum measurements give the spin values of these relatively narrow resonances.

2 Experimental procedure and excitation function

The $\alpha+^{28}\text{Si}$ elastic-scattering experiment was performed at the K=36 cyclotron of the Department of Physics of Oslo University (OCL), using a compact scattering chamber of 47 cm inner diameter. The OCL cyclotron is equipped with a 90° , 1 m radius analyzing magnet, and the overall accuracy of the energy determination has been measured to be some few tens of keV [14]. The excitation function was followed continuously from 19 MeV up to 31 MeV. The thick-target method of [13] was used for this purpose, since it allows recording the large energy range of about 12 MeV beam energy in a relatively short time, in steps of ~ 400 keV. Here, a very high-resolution experiment is not needed since the resonance widths are larger than about 60 keV.

The angular distributions were measured in nine angles between $\theta_{\text{lab}} = 173^\circ$ and 133° for the energy interval $E_{\text{Lab}} = 26 - 30$ MeV. The detectors were 1.5-5 mm thick and had resolutions between 17 and 25 keV. The large-angle detectors were shifted in steps of 3° since large angular-momentum values of $\ell = 10 - 12$ were anticipated. A detector at a fixed angle, $\theta_{\text{norm}} = -160^\circ$, was used for normalization. At the highest energies, where the elastic cross section is very low, one can separate out the inelastic contributions from both the 2_1^+ state at 1.78 MeV, and the 4_1^+ state at 4.62 MeV. This is done over an energy range of ~ 2.5 MeV. These excitation curves are in very good agreement with the previously measured data in references [12] and [15]–[18].

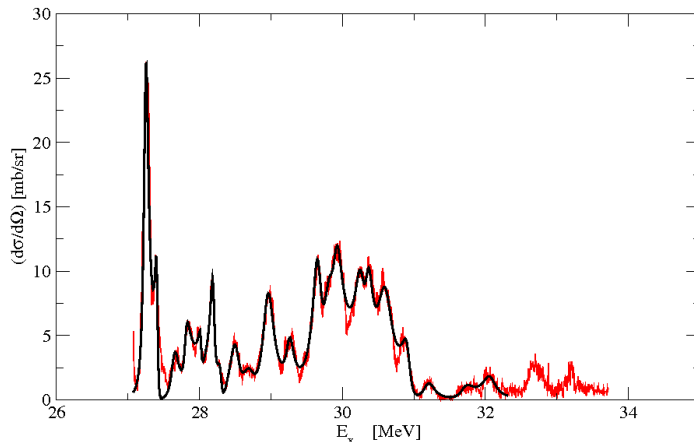


Figure 2: (color online) R-matrix fit (solid black line) to the elastic excitation function of $\alpha+^{28}\text{Si}$ (red) over the excitation energy range 27 – 32.5 MeV.

The total excitation function of the elastic $\alpha+^{28}\text{Si}$ reaction, including the present data, i.e. for an energy span of $E_{\text{Lab}} = 4 - 31$ MeV, is shown in Figure 1. In this figure one should especially note the enlarged high-energy part of the excitation function (inset panel). There are two noticeable features. First, there is a bump in the excitation function at $E_{\text{Lab}} \sim 24.5 - 27.5$ MeV, and within this bump one can clearly distinguish a rich resonance structure at these high energies, $E_x \geq 29.5$ MeV. Secondly, there is a strong drop-off at $E_{\text{Lab}} \sim 27.5$ MeV above the ~ 3 MeV wide bump. The intensity reduction is about a factor of 10 in comparison with energies around 26 MeV, and the cross section stays low at still higher energies. In this region the resonances seem almost to disappear.

This behaviour seems suspicious, however, a similar drop-off has been observed in several investigations before, see [12, 15, 16, 17, 18]. But the feature has gone unnoticed, and has not been discussed to any detail. One should also notice a similar behaviour of the cross section at and above 21 MeV of beam energy, see Figure 1. These two bumps will be one of the main issues of the present study, and they will be discussed later. The present investigation continues the study of the α -cluster states above about 20 MeV of excitation energy, and especially up to and beyond the drop-off at about $E_{\text{Lab}} = 27.5$ MeV, corresponding to an excitation energy of 33.4 MeV in ^{32}S . It may also be noted that the drop-off occurs over an energy span of only about 500 keV. This question will be addressed in subsection 4.2.

3 Data analysis and results

The excitation functions were analyzed in the framework of the R-matrix approach [20]. The method was developed in [21] and previously applied e.g. in [22]. Following the procedure outlined in [23], the method was used with success by the Wisconsin group, see e.g. [24, 25] and references therein. The scattering amplitude, $f(\theta)$, is separated into a nonresonant term and a sum of resonant partial waves. For spinless

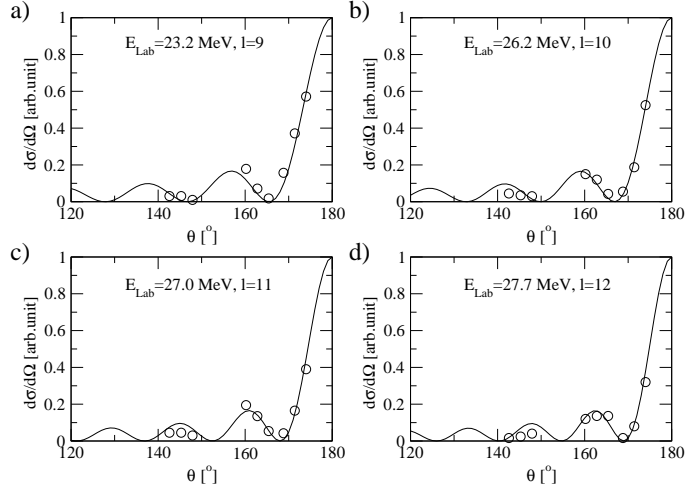


Figure 3: Experimental angular distributions (circles) for some strong resonances in the energy range 23.2–27.7 MeV and curves of $P_\ell^2(\cos \theta)$. The superposition clearly gives the angular-momentum values from $\ell = 9$ to $\ell = 12$, cf. Table 1.

particles the total scattering amplitude can be written as

$$f(\theta) = \rho(\theta) \times \exp(i\chi) - \frac{i}{2k} \sum_m (2l_m + 1) \frac{\Gamma_{l_m}}{\Gamma} [\exp(2i\beta_{l_m}) - 1] \exp(2i\phi_{l_m}) P_{l_m}(\cos \theta), \quad (1)$$

where ρ and χ are the background amplitude and the phase shift, θ is the center-of-mass angle, k is the wave number, β_ℓ is a resonant phase shift, and ϕ_ℓ is a relative background phase shift. The resonant phase shift is given by

$$\beta_{l_m} = \arctan \left(\frac{\Gamma}{2(E_{\text{res}} - E_{\text{Lab}})} \right), \quad (2)$$

where E_{res} and E_{Lab} are the resonance and particle energies, respectively. The relation between the excitation energy E_x and the laboratory energy E_{Lab} is

$$E_x = 0.875 E_{\text{Lab}} + Q, \quad (3)$$

where Q is the reaction Q -value, equal to 6.95 MeV for the present reaction. The background amplitude ρ was assumed to be a function that is smoothly depending on energy, and was interpolated by lines connecting five points for the 5 MeV energy interval. The phase shifts ϕ_{l_m} are fixed for each resonance and are not varied with energy and angle. With the above premises the cross section is given by the standard expression

$$\frac{d\sigma}{d\Omega} = |f(\theta)|^2. \quad (4)$$

The result of the R-matrix fit to the data of the present experiment is shown in Figure 2. The structure of the data confirms the previous findings in refs. [12, 15, 16, 17, 18]. The present data reaches beyond the intensity drop by more than 3 MeV. The fit is very good, and thereby unambiguous resonance quantum characteristics, i.e

Table 1: Properties of strong resonances in ^{32}S from the elastic scattering $\alpha+^{28}\text{Si}$.

Alpha energy E_{Lab} [MeV]	Excitation energy E_x [MeV]	Spin ℓ [\hbar]	Width Γ_{CM} [MeV]
19.33	23.86	7	~ 0.1
20.55	24.93	8	~ 0.1
22.80	26.90	11	~ 0.2
23.20	27.25	9	0.08
23.38	27.44	8	0.04
23.65	27.69	9	0.15
23.84	27.82	9	0.11
24.08	28.04	10	0.04
24.28	28.17	10	0.07
24.40	28.30	8	0.08
24.64	28.48	10	0.17
24.85	28.67	10	0.22
25.15	28.97	10	0.19
25.50	29.25	9	0.13
25.95	29.66	10	0.16
26.12	29.88	10	0.20
26.24	29.91	10	0.16
26.64	30.26	9	0.17
26.76	30.37	10	0.13
27.03	30.61	11	0.25
27.39	30.89	12	0.14
27.72	31.19	12	0.20
28.30	31.71	9	0.22
28.60	31.98	12	0.22
29.43	32.7	–	~ 0.3
30.34	33.5	–	~ 0.2

excitation energy E_x , angular momentum ℓ -value and α -width Γ_α , can be extracted for all resonances. Examples of angular distributions are shown in Figure 3, together with best-fitting squared Legendre polynomials $P_\ell^2(\cos\theta)$, and they indeed indicate unambiguous angular momentum values. The values determined are collected in Table 1.

One should here note the fact that *all* the structure revealed in Figure 2 can be attributed to resonances, and that the continuous background contribution is insignificant. Indeed, the cross section for Rutherford scattering at 173° is only ~ 1 mb at these energies. Further, the cross section goes to almost zero at about 27.5 MeV, but there still remain some scattered elastic resonances at higher energies, even up to an excitation of almost 34 MeV. The angular momenta at these excitation energies are surprisingly high, up to $\ell \sim 12\hbar$, which will be discussed in section 4.

The general reduction in cross section of more than an order of magnitude above $E_x \sim 31$ MeV is still better demonstrated in Figure 4, showing the total excitation function from ~ 10 MeV up to ~ 34 MeV excitation. The continuous line is the result of smoothing the experimental data with a Gaussian of width 1.0 MeV FWHM. What especially should be noted is, that the reduction in fact is preceded by a bump

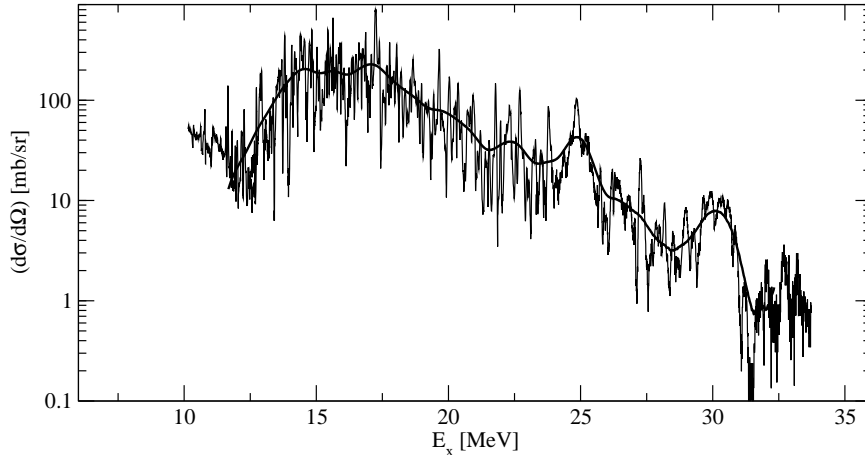


Figure 4: The $\alpha+^{28}\text{Si}$ excitation function for $E_{\text{Lab}} \sim 3 - 31$ MeV. The low-energy data are from [10], the intermediate data up to 19.6 MeV from [9], and the highest from the present work. Note especially the bumps at $E_x \sim 25$ and ~ 30 MeV.

with a centroid at $E_x \sim 30$ MeV and a width $\Gamma_{30} \sim 2$ MeV. But more than that, there is clearly another similar bump at $E_{\text{Lab}} \sim 25$ MeV, having an apparent width of $\Gamma_{25} \sim 1.5$ MeV. The smoothed data clearly illustrate these gross features, which will be discussed in the next section.

4 Discussion

The discussion is divided into three subsections addressing the structure and properties of the elastic α -particle resonances, the reduction of the elastic α -scattering cross section at high energy, and the implications of the existence of states with $\ell \sim 12\hbar$ on an $\alpha+^{28}\text{Si}$ potential model.

4.1 Elastic resonances

The elastic resonances as observed in [9, 10] and this work are collected in Figure 5. The excitation energies of the resonances are plotted as a function of $\ell(\ell + 1)$. (In the lower left corner there would be other spectroscopic states with known spin and parity J^π , see [26]; they are omitted here.) The band-like structure starting at $E_x \sim 12$ MeV consists of the previously studied resonances at low energy [10], at intermediate energies [9], and of states up to the right established in the present study. The band closely follows the expression

$$E_\ell = \frac{\hbar^2}{2\mathcal{J}} [\ell(\ell + 1)], \quad (5)$$

and therefore it is quite suggestive that the set of states with natural spin and parity, i.e. $1^- - 9^-$ and $0^+ - 10^+$, group according to increasing energies as expected from a rotational behavior. This structure was thus interpreted as a rotating ^{32}S nucleus described by an $\alpha+^{28}\text{Si}$ nuclear molecule configuration, and studied using the procedure of [27]. The moment of inertia for the two constituents at touching distance (using $r_0 = 1.3$ fm) is $\mathcal{J}_{\text{mol}} = 7.6 \hbar^2/\text{MeV}$, whereas for a spherical mass with $A = 32$ it is $\mathcal{J}_{\text{spher}} = 2.6 \hbar^2/\text{MeV}$. The experimental value, extracted from the

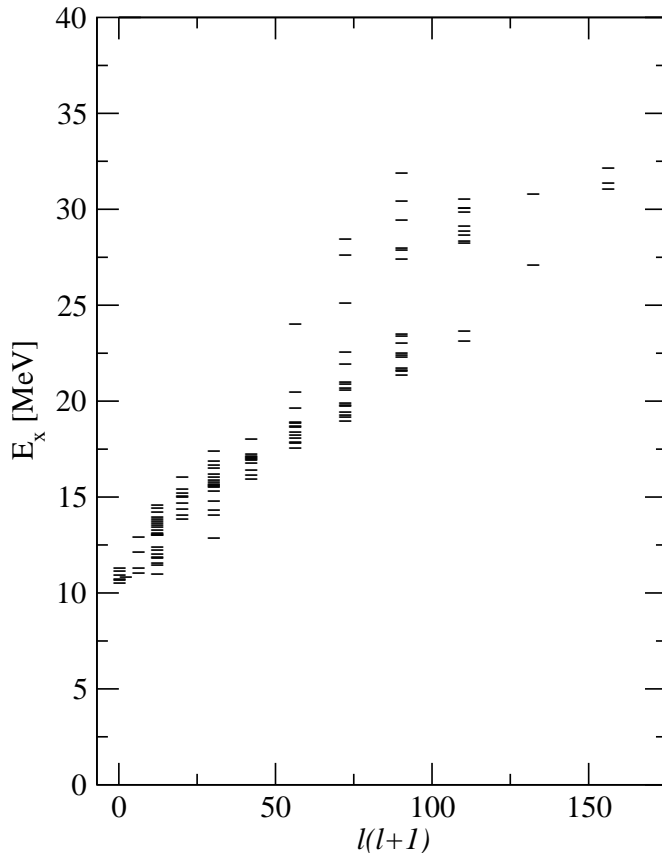


Figure 5: The topmost α -cluster levels in ^{32}S are from the present work. The levels in the middle, forming a band-like structure, are taken from [9, 10].

$\ell(\ell + 1)$ behavior of the weighted averages of the individual states with spin ℓ , is $\mathcal{J}_{\text{exp}} \sim 4.0 \hbar^2/\text{MeV}$ for the data reported in [9, 11]. This effective moment of inertia corresponds to an elongated object, but is less than that of two osculating spheres, in accordance with the intuitive picture of an α -particle located at or in the nuclear surface.

However, one notices a peculiar effect when the data from the present work, shown topmost in Figure 5, is compared to the previously observed band-like structure. The states with $J^\pi = 8^+ - 12^+$ seem to follow another trajectory on this plot than do the lower-lying $1^- - 9^-$ and $0^+ - 10^+$ states of the band described above. The slope represents a larger effective moment of inertia, close to that of two osculating spheres, $\mathcal{J}_{\text{mol}} \sim 8 \hbar^2/\text{MeV}$. The band seems to intercept the axis at about $E_x \sim 22$ MeV, as compared to ~ 12.2 MeV for the band reported in [9].

We further note that the analysis of [9] showed that the energy span of a certain ℓ -value only was about 3-5 MeV, see also [11], as indicated in the lower band members, with $\ell = 1 - 7 \hbar$, of Figure 5. When states of the next ℓ -value begin to occur, only few

further members of the previous spin occurred. That is, there is only little overlap between the different ℓ -groups. Thus, if e.g. all the $J^\pi = 9^-$ states displayed in Figure 5 belonged to one and the same ℓ -group, the energy span of the resonances with this particular ℓ -value would be more than 10 MeV, which is not compatible with the statement above. Consequently, it would be a natural interpretation that the upper states with $\ell = 8 - 12 \hbar$ belong to a band with the α -particle excited to one higher oscillator quantum number N , cf. [19].

Further, it is of interest to study the systematic properties of the resonances, i.e. their spin-parities and their widths, as function of excitation energy. The previously observed resonances have widths ranging from 10-30 keV in the low-energy region, $E_x \sim 12 - 15$ MeV in [10], and the widths increase to ~ 50 -150 keV in the intermediate-energy region $E_x \sim 15 - 25$ MeV [9, 11]. The resonances observed in this work follow this pattern and have widths increasing from ~ 50 to ≥ 200 keV, cf. Table 1.

Finally we compare the mean lifetimes of these levels with the α -particle transit times at the corresponding energies. A width of $\Gamma_\alpha = 40$ keV corresponds to a lifetime of about $\tau = 1.6 \cdot 10^{-20}$ s, and an α -particle energy of 15 MeV gives a transit time of $t_{\text{tr}} \sim 2.9 \cdot 10^{-22}$ s, whereas $\Gamma_\alpha = 150$ keV represents $\tau = 4.4 \cdot 10^{-21}$ s and 30 MeV gives $t_{\text{tr}} \sim 2.1 \cdot 10^{-22}$ s. Thus these lifetimes are longer than the transit times by factors $\sim 20 - 60$, and these estimates show that even at these excitation energies the system is somehow quasi-bound. Or, as it is often expressed, that the doorway states are coupled to more complicated structures.

4.2 Reduction of cross section at high energies

It is difficult to understand the rapid decrease of the elastic cross section above $E_x \sim 30$ MeV, see Figures 2 and 4. There are two physically feasible possibilities:

1. Two strong resonances interfere destructively at large angles. This would explain the strong reduction of cross section in backward angles.
2. The potential cannot sustain the increasing ℓ -values, and the cross section is dispersed over other reaction channels.

Regarding the first point we note that if there is destructive interference in backward angles, then in the angle plane there must also be positions, at specific angles, where there are constructive interference, and also intermediate situations, as required by the conservation of current density. In our angular distributions we find no trace of intensity anywhere, and therefore we must conclude that a two-resonance destructive interference cannot be the explanation.

With respect to the question of reaction channels we notice that the cross sections of fusion-like reactions, like (α, n) , (α, p) , $(\alpha, pn/d)$, $(\alpha, 2\alpha)$, etc., are smooth, and the change in the (α, α) channel would not be drastic. The threshold values for the mentioned reactions 9.25, 2.19, 16.26/13.72 and 11.41 MeV. As a consequence a smooth decrease starting above 10 MeV is therefore expected. Indeed, this is observed in the elastic cross section starting from about 10 MeV beam energy, as is clearly seen in Figures 1 and 4.

The energies for the break-up of ^{32}S into various multiple-fragment configurations are presented in Table 2. These configurations can be compared to configurations reported in the classical Ikeda diagrams, see e.g. ref. [28, 29]. The cluster-break-up Q-value for $^{32}\text{S} \rightarrow ^{16}\text{O} + 4 \cdot \alpha$ is 30.96 MeV, and this is almost exactly where the cross-section drop at the higher energy is situated, see Figure 4. The possibility of this break-up was first noticed in ref. [30]. Also another break-up, namely $^{32}\text{S} \rightarrow$

Table 2: Threshold energies for all possible break-ups of ^{32}S into configurations $\text{X}(+\text{Y})+n \cdot \alpha$, that is, one or two heavy multiple-alpha fragments $\text{X}(+\text{Y})$, e.g. ^{12}C , ^{16}O , ..., and n additional α -particles.

Fragments $\text{X}(+\text{Y})$	$n \cdot \alpha$	Threshold energy [MeV]
^4He	7	45.41
^{12}C	5	38.14
^{16}O	4	30.96
^{20}Ne	3	25.93
^{24}Mg	2	16.92
^{28}Si	1	6.95
$^{12}\text{C} + ^{12}\text{C}$	2	30.86
$^{12}\text{C} + ^{16}\text{O}$	1	23.70
$^{16}\text{O} + ^{16}\text{O}$	0	16.54
$^{20}\text{Ne} + ^{12}\text{C}$	0	18.97

$^{12}\text{C} + ^{12}\text{C} + 2 \cdot \alpha$, would be possible. The second bump at $E_x \sim 25$ MeV is also followed by a strong reduction of the elastic cross section. Turning to Table 2 one sees that the cluster-break-up Q-value for $^{32}\text{S} \rightarrow ^{20}\text{Ne} + 3 \cdot \alpha$ is 25.93 MeV. It is therefore tempting to describe this feature as the same kind of collective effect as for the $^{32}\text{S} \rightarrow ^{16}\text{O} + 4 \cdot \alpha$ break-up.

The physics behind break-up phenomena has been suggested to be that the α -particles form a kind of Bose gas on the nuclear surface of ^{16}O , that is, a kind of α -particle matter on a core nucleus, as discussed in [31]. However, the α -particles must carry away about $12\hbar$ of angular momentum, so there remains (at least) the problem of an angular-momentum barrier. The possibility of this kind of structures was in fact discussed already long ago, see [32, 33], but not further elucidated, probably because of a total lack of experimental data at that time.

No quantitative calculations of α -particle bosonization on the nuclear surface have been performed. There exist, though, calculations for a phase transition to a Bose condensate of α -particles for light nuclei. This feature is discussed for mainly ^{12}C and ^{16}O . The first work of this kind is in [34], where differences in the ground-state and the threshold-state properties were discussed, in low-density nuclear matter. In [35] explicit α -cluster wave functions were constructed, based on the interactions derived in [36]. Threshold states for $2\alpha - 5\alpha$ nuclei were discussed in [37, 38]. But, as pointed out above, this concerned the bosonization of the nucleus as a whole. Further, a recent work discusses multiple α -particles on a ^{40}Ca core, [39]. For a very recent discussion of these effects, see [40] and other articles therein.

Finally, we shall shortly comment on the results from the inelastic α -particle scattering. Our data, as well as the previous results from the same region, [12, 15, 16, 17, 18], show no trace of a change in cross section as the Q-value for the 4α -emission is reached or surpassed. Therefore it seems unlikely that at a specific energy, just above the corresponding Q-value, all the elastic cross section would concentrate in a single reaction channel. A natural choice would be to leave the core in an excited state, irrespective of the opening of this exotic emission channel. This is indeed what the inelastic data show. There is presently no final answer on this question, and, in fact, this last objection is also in contradiction to the bosonization picture above.

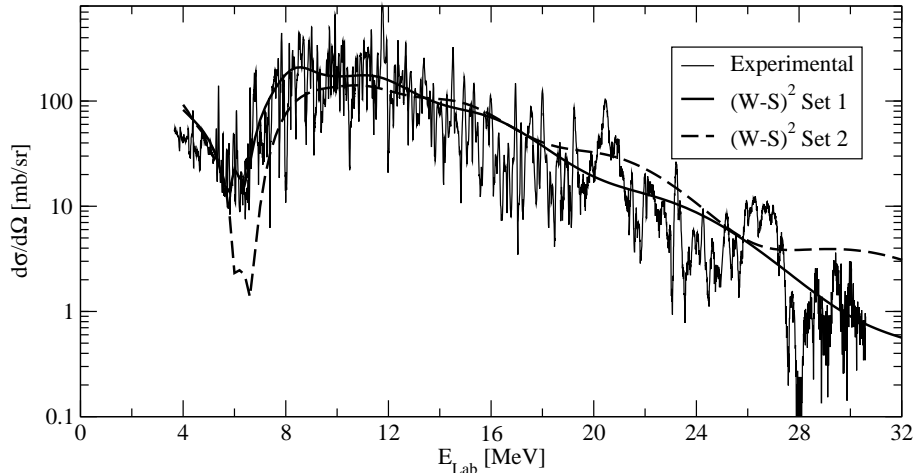


Figure 6: Calculated cross section as compared to the experimental data. The description and the parameter values of the two sets are given in the text.

4.3 A potential model for the $\alpha+^{28}\text{Si}$ elastic cross section

The interaction between a (composite) particle and a nucleus is usually described by a local central complex optical potential $U(r)$. The potential is often parametrized with a squared Woods-Saxon form factor for both the real and the imaginary parts. In the present work the potential is parametrized according to the prescription of [41, 42], where a universal potential was obtained by fitting to data of $\alpha+^{16}\text{O}$ and $\alpha+^{40}\text{Ca}$. The present potential,

$$U(r) = -V f(r, R_V, a_V) - iW f(r, R_W, a_W), \quad (6)$$

has form factors given by $f(r, R_i, a_i) = 1/[1 + \exp(r - R_i/a_i)]^2$, where the indices are $i = V, W$ for the real and imaginary parts, respectively. The two best parameter values for the present elastic $\alpha+^{28}\text{Si}$ data, obtained from fits to angular distributions, were determined to be:

Set 1 $V = 189.4(1 - 0.00173E_{\text{Lab}})$, $W = -3.00(1 - 0.15E_{\text{Lab}})$, $R_V = 1.30$, $R_W = 1.95$, $a_V = 1.3$ and $a_W = 1.0$,

Set 2 $V = 192.4(1 - 0.00173E_{\text{Lab}})$, $W = -3.35(1 - 0.20E_{\text{Lab}})$, $R_V = 1.45$, $R_W = 1.65$, $a_V = 1.2$ and $a_W = 1.0$,

in units of MeV and fm. Note the energy dependences of the potential depths.

Figure 6 shows the excitation functions calculated with the above potentials in the backward angle 173° , superimposed on the measured data. As can be seen, there is generally good agreement for both potentials for the overall behavior. Further, one should notice the parameters in the expression above: the diffuseness parameters have the value $a_V = 1.2/1.3$ and $a_W = 1.0$, and these values are relatively large in comparison with standard values. In order to globally fit the present elastic cross section the corresponding potential has an extended surface. It is not clear whether this feature may be related to the proposed break-up of the ^{32}S intermediate nucleus.

There is one fairly clear difference between the two sets. For laboratory energies of 8 – 20 MeV the fits are quite comparable, although Set 2 underestimates for energies below 8 MeV. However, Set 2 (dashed in Figure 6) fits the region around 20 MeV partly better, but has an overshoot around 20–24 MeV. On the other hand, Set 1 (full line) fits the region where the cross section disappear much better, when Set 2

has an overshoot of almost an order of magnitude. This is also the case for energies below 10 MeV. The potential of Set 1 is the more diffuse one of the two. However, it turns out that the potential is unable to sustain angular momentum values in excess of about $8\hbar$. Thus the experimental values up to $12\hbar$ are in disagreement with the potential picture. This observation is presently not understood.

5 Summary and conclusions

The results from the present work confirm the existence of narrow resonances, $\Gamma_\alpha \sim 50 - 200$ keV, in the elastic α -particle scattering channel. These structures persist even to excitation energies in excess of 30 MeV, see figure 5. The resonances group into a band-like structure with an effective moment of inertia corresponding to an $\alpha+^{28}\text{Si}$ configuration of a touching molecular shape, and with a band-head energy of ~ 12 MeV. The topmost resonances may form a second band with a higher band-head energy and a larger moment of inertia.

The intensities of the resonance structures in the elastic-scattering cross section, slowly decrease up to about 25 MeV excitation, where rapid decreases in strength occur at excitation energies close to the Q-values of the $^{32}\text{S} \rightarrow ^{20}\text{Ne} + 3 \cdot \alpha$, $^{32}\text{S} \rightarrow ^{16}\text{O} + 4 \cdot \alpha$ and/or $^{32}\text{S} \rightarrow ^{12}\text{C} + ^{12}\text{C} + 2 \cdot \alpha$ break-ups in the elastic channels. The effect is not observed in the inelastic channel. Whether it is a collective multiple- α break-up effect cannot be decided by the data of the present study.

The highest-lying resonances have spin values of $\ell = 12\hbar$, and this is difficult to reconcile with a standard potential. However, in order to reproduce the experimental cross section, the diffuseness parameters of the potential have to be chosen substantially larger than the standard values. This corresponds to an extended surface diffuseness.

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