Alpha-particle resonances and clusters in $^{32}$S, $^{34}$S, $^{36}$Ar and $^{40}$Ca

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Abstract. Recently the nuclei $^{32}$S, $^{34}$S and $^{40}$Ca have been examined in detail from an alpha-cluster point of view, adding to previous knowledge on cluster structures in medium light nuclei. But as often in science, new results give rise to more new questions than old ones they answer. In the text below some of these open questions and suggestions for future work are stated.

1. Introduction
In the last decade or so there has been a clear shift in the nuclear physics community. Many smaller laboratories have been closed down and the focus has shifted to a few large-scale facilities around the world. This concentration of experimental resources has opened many new and very interesting fields of exploration through exotic beams and reactions, and highly advanced detector set-ups.

At the same time, as the community has invested heavily in these specialized facilities, it has become increasingly difficult for smaller research groups to compete for beam-time for experiments examining less exotic nuclei. Still there is clearly a lot of work to be done among stable nuclei and nuclei close to stability. The medium-light nuclei (roughly between oxygen and titanium in the nuclide chart) are in a region of special interest. They represent the transition from light nuclei, where various ab-initio methods can make increasingly precise theoretical predictions, and the heavy nuclei where collective models can be used with relatively good precision. In the gap between these very different models it can be expected that descriptions based on cluster models are important.

2. Open questions and suggestions for future work
The Åbo Akademi University nuclear structure group has been working with alpha-cluster structures in medium light nuclei for more than 25 years [1], beginning as a study of the very old problem of Anomalous Large-Angle Scattering (ALAS) [2]. A lot of results have been published over the years, see e.g. [3, 4, 5] and the references therein. As the focus of the department has shifted to other areas of interest, this endeavor in nuclear structure physics is now coming to an end at Åbo Akademi University. But there are still many mysteries and open questions to be explored among these nuclei. In the following some suggestions are made where the work could be continued.
2.1. A systematic examination of alpha-particle resonances among medium light nuclei

The last few years have shown a great increase in interest for resonance scattering, especially in inverse kinematics. The Tick-Target Inverse Kinematics technique (TTIK) [6] has made it possible to measure excitation functions in large energy intervals in a relatively short time. Still, the analysis of such data, usually based on R-matrix theory [7], is very time consuming. It has been shown, though, that the combination of TTIK with a simplified R-matrix analysis can be a time efficient and relatively reliable method for mapping large numbers of resonances [3, 8].

Only a few of the alpha-conjugate nuclei in the region have been examined thoroughly ($^{32}$S, $^{36}$Ar and $^{40}$Ca) in this way and it would clearly be of interest to carry out similar work on $^{20}$Ne, $^{24}$Mg, $^{28}$Si and $^{44}$Ti. The measurements also need to be extended at least to the neutron rich side as the report on $^{34}$S [4] shows many interesting features. Especially the nuclei $^{40}$Ar and $^{44}$Ca should be easily accessible with stable beams and have an interesting conjugate plus four neutrons configuration possibility.

2.2. Verification of the nature of the observed resonances

The large amount of strong and narrow resonances found in these nuclei cannot yet be explained by theory. While it can be shown that the probability is low that the observed resonances are mainly caused by statistical effects (either so called Ericsson fluctuations or Porter-Thomas fluctuations), their contributions are not insignificant and the interplay with real quantum mechanical states is not well understood [9]. More experiments with high resolution and detailed analysis similar to [10] are needed to independently verify the resonances and their fine structure. New theory needs to be developed, perhaps along the promising lines of [11, 12].

2.3. Verification of and explanation for the proposed rotational model

The spin distributions of the observed resonances have been interpreted as an indication of a quantum mechanical rotation with the rotational levels split into many close-lying states with the same spin (see figure 1). If the proposed model is valid, the mechanisms behind the splitting need to be explained. The extracted moments of inertia point to a rotation involving a few alpha-particles orbiting an inert core. This strange type of dynamical structure needs to be verified experimentally and explained theoretically.

Figure 1. Comparison of resonances in $^{32}$S, $^{34}$S, $^{36}$Ar and $^{40}$Ca. The diamonds represent average energies of resonances with the same spin, weighted with the reduced widths of the resonances [5].
Closely connected to the rotational interpretation are the large reduced widths that are observed. Due to experimental limitations the values given in e.g. [3, 4, 5] have a large uncertainty and the measurements need to be improved in order to verify the cluster structure in these nuclei.

2.4. Explanation of the general structure of the observed spectra

Many of the excitation functions for medium light alpha-conjugate nuclei show interesting average features beside the resonances. For example, the spectrum of the nucleus $^{32}\text{S}$ shows a number of bumps followed by sharp decreases in cross section [13, 14]. At very high excitation energy the elastic cross section disappears completely. These features seem to coincide in energy with various alpha particle break-up thresholds, but due to the very high angular momenta involved such a process is difficult to imagine. It would, however, be an interesting experimental challenge to do detailed multichannel particle spectroscopy at these thresholds in order to understand their structure.

3. Summary

In the text above some challenges for both experimentalists and theorists have been expressed. Many more potentially interesting routes of exploration exist for resonances and clusters in medium light nuclei, like the connection to nuclear astrophysics and the importance of cluster resonances for nucleosynthesis in massive stars. Hopefully many of these questions can be settled through new experiments and new developments in theory in the near future. And hopefully experiments of this relatively straightforward type will not drown in the concentrated efforts to push the limits of rare beams and exotic reactions.

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References

[1] Manngard P, Brenner M, Alam M, Reichstein I and Malik F 1989 Nucl. Phys. A 504 130–142
[2] Corelli J C, Bieuler E and TenDam D J 1959 Phys. Rev. 116 1184–1193
[3] Lönnroth T et al 2010 Eur. Phys. J. A 46 5–16
[4] Norrby M et al 2011 Eur. Phys. J. A 47 73
[5] Norrby M et al 2011 Eur. Phys. J. A 47 1–7
[6] Goldberg V Z and Pakhomov A E 1993 Phys. At. Nucl. 56 1167
[7] Lane A M and Thomas R G 1958 Rev. Mod. Phys. 30 257–353
[8] Goldberg V Z, Rogachev G V, Brenner M, Källman K M, Lönnroth T, Rozhkov M V, Torilov S, Trzaska W H and Wolski R 2000 Phys. At. Nucl. 63 1518–1526
[9] Brenner M and Gridnev K A 2010 Cluster Structure of Atomic Nuclei (Kerala: Research Signpost) p 43
[10] Brenner M, Fletcher N R, Liendo J A, Belov S E, Causyn D D, Nieto T K and Myers S H 2000 Acta Phys. Hung. N.S. 11 221
[11] Gridnev K A, Torilov S, Kartavenko V G and Greiner W 2007 Int. J. Mod. Phys. E 16 1059–1063
[12] Gnilozub I A, Kurgalin S D and Tchuvil’sky Y M 2011 AIP Conf. Proc. 1377 441–443
[13] Brenner M, Lattuada M, Gulino M, Khlebnikov S V, Chengbo L, Prete G, Trzaska W H, Zadro M and Belov S E 2006 Phys. Scr. 74 692–696
[14] Norrby M, Brenner M, Lönnroth T and Kallman K M 2008 Int. J. Mod. Phys. E 17 2019