28Si + α as an Example of Novel Methods for Elastic Scattering Experiments

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Abstract. Elastic scattering of α-particles on heavier targets is a powerful tool to search for α-cluster states in various nuclei, especially in “light” nuclei (mass ~ 20–40). But performing such experiments with traditional methods is tedious work. Therefore novel methods for this type of experiment have been developed, namely the “Thick-Target” stepping method and the method of “Reverse Geometry”. The inelastic reaction $\alpha + 28Si \rightarrow ^{32}S* \rightarrow 28Si + \alpha$ as an example, since it is the most examined reaction in this mass area.

1. Introduction
The α-particle is notoriously strange. With its extremely high binding energy, no excited stated and 0+ spin and parity it seems to behave like a single particle without internal structure in most low-energy nuclear physics situations.

That some nuclei would behave like clusters of α-particles is an old concept and something easy to envision, like in the famous Ikeda diagram [1]. And for the very heavy elements α-decay is seen as a quantum mechanical effect, where an α-particle spontaneously forms in the nucleus and with a very small probability tunnels out trough the barrier. At any given time the nucleus of an α-decaying atom will contain a number of α-particles and some free neutrons and protons.

But between the lightest and the heaviest elements there is a large uncharted mass region where the effects of α-clustering have not been examined, neither experimentally nor theoretically to any greater extent. The aim of the Turku Alpha Clusters at High Excitation-project (TACHE) [2] is to gather experimental data in the mass region between 16O and 44Ti, to look for the effects of α-clustering, both in $n \cdot \alpha$ nuclei and in nuclei with “extra” neutrons or protons.

2. Elastic Scattering
One way of studying α-cluster structures is through elastic scattering. In the simplest form of this method a beam of α-particles would hit a very thin foil of target material. If no interaction takes place the observed spectrum of scattered α-particles is just that of Rutherford scattering. But as the beam energy is varied some energies will correspond to resonance states and the pattern of the scattered particles will be different, depending on the structure of the resonant state. It is usually possible to separate elastic and inelastic scattering. The strongest deviation from Rutherford scattering will be at backward angles, and if several angles are measured a squared Legendre polynomial can be fitted to find the spin of the corresponding state.
Interpreting the meaning of these states is not always easy. The high energy and the positive Q-values needed to penetrate the Coulomb barrier means the resonances are highly excited states in the compound nucleus of target and \( \alpha \)-particle. Putting together the experimental data into an excitation function, showing the cross section as a function of energy, one can see many different resonant states in a spectrum. Different characteristics of the peaks in the spectrum, such as width (corresponding to a lifetime), height (corresponding to intensity) and spin distribution, all tell something about the compound nucleus from the point of view of \( \alpha \)-clustering.

Detailed studies of this type have been preformed on \( ^{28}\text{Si} \) [3, 4], as it is one of the few chemically suitable elements in the area. It has a high natural isotope abundance and is mechanically tough enough to make a thin target, has a high melting point and is not very chemically reactive.

3. Thick-Target Method

The traditional stepping method works well and gives interesting results, but is very slow. The example in [5] covering just about 1 MeV energy range took 225 steps and weeks of beam time. For the reaction \( \alpha + ^{28}\text{Si} \) the excitation function shows interesting structures for the whole energy interval between 3 and 35 MeV in laboratory energy. It is clearly not a practical and efficient method for large-scale examination of excitation functions for many nuclides. And what is more, few other elements in the region of interest share the good chemical properties if silicon, making the traditional stepping method impossible. There is clearly a need to improve experimental techniques.

As part of an answer to this problem the Thick-Target Backscattering Technique was developed at Åbo Akademi University and covered in detail in [5]. In short, the technique uses a thick slice of the target material to slow down the incoming beam and lets reactions happen at different depths in the material, corresponding to events at many different energies at once (see figure 1). To be able to separate elastic scattering from inelastic, the step between incoming beam energies is limited by the energy of the first excited state in the target nucleus. And since the \( \alpha \)-particle is slowed down both entering and exiting the target material, the step has to be less than half of the energy difference between ground state and first excited state in the target nucleus. In practice for the \( ^{28}\text{Si} \) case a step of about 400 keV has been used with success and cuts the number of steps needed by at least one order of magnitude, compared to the traditional method. The resolution of the method can be shown to be better than the resolution of most \( \alpha \)-particle detectors at relevant energies.
energies.

Some of the results from a number of experiments done with this method are compiled and presented in figure 3. A lot of structure can be seen in the excitation function. The structures are consistent over many different angles and have other properties that show they are not just statistical fluctuations but real resonances. The full line represents a theoretical excitation function based on potential calculations. The main features of the calculation are consistent with the experiment, but a potential model cannot explain the rich structure seen. Also, spins of the peaks in the spectrum can be calculated and it turns out they come in nice groups of the same spin spread out over about a one MeV area with some overlap between the groups. Spins range from $3\hbar$ at 7 MeV up to $12\hbar$ at 30 MeV.

4. Reverse Geometry Method

Using the Thick-Target Method speeds things up considerably, but it still requires weeks of beam time to examine one excitation function completely and many of the problems with the chemical properties of different materials remain. Therefore the method of Reverse Geometry, first invented and tested by the group of Goldberg in Moscow [6], has been further developed and put to use to study elastic $\alpha$-scattering [7].

The Reverse Geometry Method uses heavy ions accelerated into a chamber filled with helium gas (see figure 2). The pressure of the gas is adjusted so that the beam is stopped inside the scattering chamber. In that way a beam consisting of all possible energies between maximum and zero is always present in the chamber, and reactions at different places along the beam will correspond to events at different energies. Using detectors at many angles one can use a computer code to reconstruct an excitation function that is in principle continuous in both energy and angle.

The great advantage is to get a whole range of energy covered in one single run. Also, since there is no stepping, there is no risk of losing valuable information between the steps (between the measuring points in traditional stepping or where the bigger chunks of the excitation function are merged in the Thick Target Method). And the method in an elegant way makes it possible to do experiments on elements like sulfur and argon, elements that would be chemically difficult or impossible to make normal targets from. The weaknesses of the method are a slightly poorer resolution, no way of separating inelastic scattering without complicated time-of-flight measurements and very high laboratory energies of scattered $\alpha$-particles, making it difficult to find good detectors.

At the moment data gathered with this method is being analyzed for the reactions $^{28}\text{Si} + \alpha$, $^{30}\text{Si} + \alpha$, $^{36}\text{Ar} + \alpha$ and $^{40}\text{Ar} + \alpha$.

5. Looking forward

The experimental data obtained leave many open questions at the moment. Why does the $\alpha$-clustering seem so strong in this area? How can it retain the structure up to such high energies? Why does the elastic cross section so suddenly drop off at certain energies? What are the underlying structures that seem to split broad resonances with a single spin into the many narrow peaks with the same spin we see? Also a very intriguing connection to nuclear astrophysics is opening up, as scientists modeling
nucleosynthesis in stars are in desperate need of better models for the $\alpha$–nucleus interaction. The data obtained through elastic scattering give the possibility to calculate experimental $\alpha$–nucleus potentials that can be of great importance to this field, but our data also indicates that resonances might be very important for many reactions.

The new experimental methods outlined above makes it possible to examine the region between $^{16}\text{O}$ and $^{44}\text{Ti}$ in the Chart of the Nuclides. There are 32 stable isotopes in this area and a number of long-lived radio active ones, and only a few have been probed through $\alpha$-scattering. The eight $n\cdot\alpha$ nuclei are of special interest, but also the behavior of nuclei with “extra” neutrons or protons is very interesting, especially as there is new evidence (e.g. [8]) that excess neutrons might actually enhance $\alpha$-clusterization.

References

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