# Shell-Structure Effect on Elastic $\alpha$ Scattering

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Back-angle enhancements of elastic $\alpha$-scattering cross sections have been observed for nuclei at the ends of the $1p$, $2s$-$1d$, and $f_{7/2}$ shells. Strong reduction of this enhancement occurs if excess neutrons enter the next open major shell. The results are discussed in terms of intermediate $\alpha$ structure.

In several investigations of elastic $\alpha$ scattering on $^{40}$Ca, a large back-angle enhancement of the cross section has been observed.[1] It occurs together with a very pronounced oscillatory angular distribution and an irregular energy dependence. This behavior is very different from $^{44}$Ca where the cross section decreases continuously towards larger angles, in agreement with the predictions of an average optical model.[1] The enhancement of the $\alpha$-$^{40}$Ca cross section over $^{44}$Ca and the optical model amounts to up to 2 orders of magnitude. This drastic difference between the "anomalous" $^{40}$Ca and the "normal" $^{44}$Ca cross section is clearly outside the domain of the standard optical model. It shows that the specific nuclear structure of the states involved must have a substantial effect on the scattering process.

If this particular structure consisted of $\alpha$-particle correlations or, more generally, quartets in the target ground state, enhanced contributions to backward scattering could occur by means of exchange or heavy-particle stripping mechanisms.[2-4] The isotopic dependence would then be due to a blocking of the quartet components by the neutron excess in the same shell that is occupied by the quartets.

In this paper we want to report a systematic investigation of the shell-structure dependence of anomalous $\alpha$ scattering. The back-angle anomaly has been observed in all $N=Z$ or $N=Z+1$ nuclei between $^{9}$Be and $^{39}$K investigated hitherto, but no extensive investigation of the isotope effect has been undertaken. The present data on various isotopes of nuclei between C and K (together with previous results[1]) demonstrate that anomalous $\alpha$ scattering is related to the neutron excess structure of the nuclei involved.

The experiments which establish this systematics consist of elastic and inelastic $\alpha$-scattering measurements on $^{12,14}$C, $^{14,15}$N, $^{16,18}$O, $^{32,34}$S, $^{36,38,40}$Ar, $^{39-41}$K, and $^{40,42,44,48}$Ca at various incident energies. The data have been taken at the Heidelberg and München MP-tandem accelerators using scattering chambers and standard multidetector arrangements. The Ar and S measurements were made with a gas target, using $H_2S$ in the case of $^{32,34}$S.[5] The remaining targets were made by evaporation of the corresponding elements or compounds onto carbon backings. Angular distributions have been measured in steps of 2° to 4° at different incident energies between 18 and 29 MeV for angles from about 20° up to 176°. The sampled experimental data, displayed in Figs. 1(a)–1(f), show a striking and simple systematics:

(i) The $N=Z$ or $N=Z+1$ nuclei all show back-angle enhancements.

(ii) Higher isotopes of these nuclei do show a back-angle enhancement if the excess neutrons are all in the same major shell as the outer nucleons of the $N=Z$, $Z+1$ isotope.

(iii) A strong reduction of the back-angle cross section occurs if two excess neutrons enter the next higher shell not occupied in the $N=Z$ core. This is most conspicuous for the Ar isotopes where the anomaly of $^{36}$Ar is preserved in $^{38}$Ar (with two additional $d_{3/2}$ neutrons), but it is completely suppressed in $^{40}$Ar (with two $f_{7/2}$ neutrons). The same observation is made at the $^{16}$O shell closure: $^{12,14}$C, $^{14,15}$N, and $^{16}$O all show the same, enhanced cross section, whereas $^{18}$O backward scattering is drastically reduced.

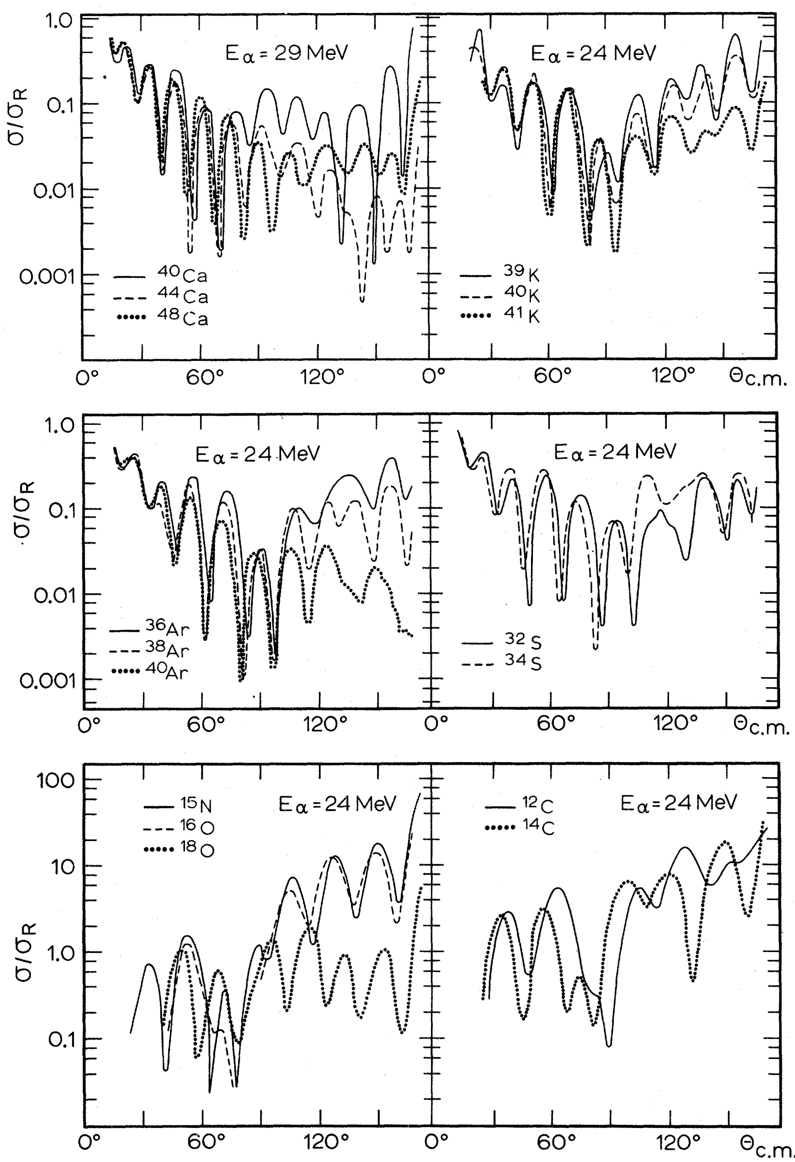


FIG. 1. Experimental angular distributions for elastic backward $\alpha$ scattering in the vicinity of the $^{48,40}$Ca and $^{16}$O shell closures.

The above observations suggest the following picture: At the end of the major shells the nuclei all show back-angle enhancements independent of their neutron excess. The anomaly disappears if we cross the closed shell, and emerges again if we approach the next shell closure. The earlier results on the Ca isotopes,[1] which are partially included in Fig. 1 for comparison, confirm this picture. The $^{40}$Ca back-angle enhancement is strongly reduced in $^{42}$Ca and $^{44}$Ca but reappears to a certain extent with the $f_{7/2}$ neutron shell closure in $^{48}$Ca. At energies above 30 MeV, the enhancement of the $^{48}$Ca cross sections with respect to $^{42,44}$Ca becomes even more significant.[6]

Although many explanations[2-4,7-10] have been proposed, the character of the anomaly is not yet firmly understood. Since the observed back-angle structure seems to be caused by very few partial waves (close to the grazing collision value $L \approx kR$), all approaches have to reinforce the contributions from those partial waves relative to the normal optical or diffraction model. Cowley and Heymann[9] and McVoy[10] parametrize the back-angle part of the scattering amplitude by a Regge-pole expansion in angular momentum space. It is characterized by the sequence of poles $l_0^n(E)$ with corresponding elastic width $D^n(E)$, and a total width $\Gamma^n(E)$ appearing in the denominator of the Breit-Wigner resonance term. The index $n$ characterizes the principal quantum number of the scattering state. The resonant contribution to backward scattering is thus proportional to $|D^n/\Gamma^n|^2$ in the case that a single partial-wave dominates. The isotope effect we observe must, therefore, be sought in the nuclear structure dependence of $D^n/\Gamma^n$ or either one of these quantities, if their influence can be assessed separately.

The total width $\Gamma(E)$ is related to the optical model absorption. In the $l$-dependent optical model, $\Gamma(E)$ would become dependent on the nuclear structure of the target. In this model, the absorption of the surface partial waves around $L \approx kR$ is taken to be proportional to the number of energy-conserving reaction channels available to carry away $L$ units of angular momentum. For low density of exit channels $L$, $W_L$ is reduced and $\Gamma(E)$ would be small, resulting in a pronounced backward oscillation characterized by a few, or even a single $P_l(\cos\theta)$, as well as an overall backward enhancement.

Although not too much is known about the density of exit channels, e.g., of the compound system $^{44}$Ti as compared to $^{46,48,52}$Ti, there should be an effect of the core shell closure for $^{44}\mathrm{Ti} = {}^{40}\mathrm{Ca} + \alpha$ and for $^{52}\mathrm{Ti} = {}^{48}\mathrm{Ca} + \alpha$. Thus, the $l$-dependent absorption model might prove successful to explain the isotope effects. If, however, the $(\alpha, n)$ channel is considered responsible for the dominant part of the absorption,[8] one is led to disagreement with the present data. In particular, the $(\alpha, n)$ thresholds for the targets $^{14}$C, $^{38}$Ar, $^{40}$K, and $^{48}$Ca are much lower [and thus the density of $(\alpha, n)$ channels much higher] than for $^{12}$C, $^{36}$Ar, $^{39}$K, and $^{42,44}$Ca. Thus, this model would predict a smaller backward anomaly for the former as compared to the latter set of isotopes, in contradiction to the experimental results.

The observed effects may alternatively be caused by the structural dependence of the elastic width. Aside from kinematical factors, $D^n$ is proportional to a reduced $\alpha$-particle width of the compound state $E_l^n$. With a large $D^n$, the resonance could be envisaged as an "$\alpha$-cluster rotator" state.[10,11] The sequence of $l$ poles would then correspond to a cluster rotational band, labeled by its main quantum number $n$. With the Ca isotopes as targets, the lowest band would have the $\alpha$ rotator occupying the $f$-$p$ shell in the continuum. With an increasing number of excess neutrons in the $f$ shell, there would result a coupling of single neutron excitations to the simple rotator state, and thus a blocking effect on the elastic width. At the $^{48}$Ca shell closure the neutron $f_{7/2}{}^8$ configuration is inert again, and a higher width would result with only $p$- or $g$-shell orbits occuring in the rotator. This behavior would thus be analogous to the decrease of the spectroscopic factor $S_j$ in single-nucleon transfer with the number of nucleons already present in the shell $j$. Such a model could also explain our observation that $^{36}$Ar and $^{38}$Ar or $^{12}$C and $^{14}$C have rather similar backward scattering, since the corresponding $\alpha$ rotator would occupy the next higher shell and not the one in which the neutron excess is built up.

The picture of an intermediate $\alpha$-rotator structure has consequences for other reactions related to the elastic scattering as, e.g., inelastic $\alpha$ scattering to $0^+$ states. In the $^{40}$Ca$(\alpha, \alpha')$ experiment[12] at 29 MeV (the only data extending to the very backward angles), the angular distributions for the $0^+$ states at $E_x = 3.35$ MeV and $E_x = 7.30$ MeV show the same sharpness of backward enhancement structure and the same phase of the oscillations as the elastic scattering. Regarding the large difference in $Q$ value for these states, this result is not expected from a direct reaction mechanism. It gives strong support to the assumption of an intermediate entrance-channel state of definite $L$. Heavy-ion reactions, which populate the same intermediate state in a different way, are presently being investigated experimentally.

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# Complete Fusion Nuclear Reactions Induced by Krypton Ions. Effective Threshold and Minimum Distance of Approach for the Reactions $Cd^{116}$ + $Kr^{84}$ and $Ge^{72}$ + $Kr^{84}$

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Effective energy thresholds have been measured for the cross sections of complete fusion reactions induced by krypton ions on $Cd^{116}$ and $Ge^{72}$. They show that the minimum distance of approach for the reaction is shorter than with lighter projectiles and corresponds to a Coulomb repulsion at a distance of $r_0(A_1^{1/3}+A_2^{1/3})$ fm with $r_0=1.32$ fm instead of 1.45 fm.

Several questions have arisen on the problem of making a complete fusion nucleus by very heavy-ion–induced reactions, particularly with the purpose of synthesis of new heavy and superheavy nuclides. One of them is related to the height of the Coulomb barrier which might be enhanced because of a deformation of the target nucleus at the approach of the highly charged projectile.[1] Also some doubts were expressed as to the possibility of formation of a fusion nucleus.[2]

We have undertaken a study of these two points with $Ar^{40}$ and $Kr^{84}$ beams which are now available at Orsay from the accelerator ALICE.[3] A first set of results on the reaction Ar + Dy has shown[4] that the experimental threshold is in good agreement with a minimum distance of approach necessary for fusion calculated with $r_0 = 1.45\times10^{-13}$ cm, i.e., at the same value of $r_0$ as for lighter ions like $C^{12}$, $O^{16}$, or $Ne^{20}$. The calculation is made on the assumption of pure Coulomb repulsion between two centers placed at a distance of approach $r_0(A_1^{1/3}+A_2^{1/3})$. Such a behavior does not hold for krypton projectiles, as is shown for two sets of experiments on $Cd^{116}$ and $Ge^{72}$. We have measured the yields of reaction products resulting from the compound nucleus $Po^{200}$ in the case of $Cd^{116}$, and from $Er^{156}$ in the case of $Ge^{72}$, after de-excitation by emission of a number of neutrons. The apparent threshold has been determined with fairly good precision. It was 147 MeV (c.m.) for the reaction $Kr^{84}$ + Ge and 204 MeV for $Kr^{84}$ + Cd. Both values correspond to a minimum distance of approach calculated with $r_0 = 132$ fm, corresponding to a classical Coulomb barrier 10% higher than for lighter ions including $Ar^{40}$.

Energy determinations were done in another set of experiments[5] with a magnetic analyzer by measuring magnetic-rigidity values for direct beams of $Kr^{24+}$ (505 ± 5 MeV) and $Kr^{23+}$ and $Kr^{22+}$ (360 ± 4 MeV). Also krypton ions were scattered at small angles by thin gold or carbon foils and magnetic-rigidity measurements were made on various charges around $Kr^{31+}$. More details on the charge distribution after stripping by the target are given by Baron.[5] Nickel foils were used in some experiments for degrading the energy down to 350 MeV in the laboratory system. The energy loss was calculated according to Northcliffe and Schilling's data.[6] However, the stopping power of heavy ions in such an energy range is not very well known. But we have shown in preliminary experiments that the same cross sections were found for $Er^{153}$ produced either with $Kr^{22+}$ without degrader or by $Kr^{24+}$ with a degrader on the beam.

The krypton beam energy was varied between 350 and 494 MeV at an intensity in the range of $10^8$–$10^9$ ions per sec. The beam passed through a nickel foil in which the energy loss had been calculated, and bombarded targets placed in a reaction chamber filled with helium. The recoiling nuclei were collected away from the beam with a helium-jet apparatus. $\alpha$ emitters were counted with an annular surface-barrier detector and an overall efficiency of the order of 10% was measured when half-lives were longer than 1 sec. More details are given elsewhere on the "helium-jet" collection apparatus.[7] Targets were