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Elastic scattering of α particles from ^{16}O near the Coulomb barrier[1])

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Abstract. $^{16}O(\alpha, \alpha)^{16}O$ cross section angular distributions have been measured at energies near the Coulomb barrier, i.e. from 3.5 MeV to 4.9 MeV in steps of 100 keV. Scattering angles ranged from 52° to 166° in steps of 2.5°. The accuracy of the data exceeds ±3% for most points. A phase shift and optical model analysis has been performed. The existence of broad resonances was confirmed implying ^{20}Ne to be strongly clustered into $^{16}O+\alpha$. We attempt to identify the first five members of the 0_4^+ rotational band in ^{20}Ne.

1. Introduction

In recent years many papers dealing with cluster structures or exchange reactions of ^{16}O [1–9] and other light nuclei [10–14] have appeared. Particularly, exchange reactions in scattering processes near the Coulomb barrier have often been reported [12–14]. At such an energy the scattering is more easily interpreted since the direct part is dominated by the Rutherford scattering amplitude. As the elastic transfer of a particle between two identical cores has been observed in many cases [13, 14], scattering of α particles near the Coulomb barrier from the 4α nucleus ^{16}O may show effects of heavy particle (^{12}C) exchange between two α particles.

For such an investigation the appropriate α particle energy lies between 3.5 MeV and 4.9 MeV. In this region only a few excitation functions have been measured previously [15]. These data were analyzed in terms of s- and d-wave phase shifts exhibiting two very broad α-cluster resonances with almost coincident resonance energies. Since the corresponding levels of ^{20}Ne were not seen in any other reaction, and since the data showed typical transfer effects such as a backward enhancement of the cross section we decided to investigate the elastic scattering of α particles from ^{16}O in more detail to verify the dominant reaction mechanism.

2. Experiment

The 3 MV Cockroft-Walton accelerator of the Institut für Physik in Basel [16, 17] was used to produce a suitable α ion beam. The RF ion source had to be

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modified to generate a sufficient amount of He^{++} ions [18]. The ^{16}O target consisted of 20 $\mu g\,cm^{-2}$ B_2O_3 deposited by evaporation on a 20 $\mu g\,cm^{-2}$ carbon backing [18]. To achieve a precision of a few percent, a large scattering chamber and carefully designed electronics and experimental layout had to be used, the details of which may be found in Ref. 18. Incident beam energies were chosen between 3.5 MeV and 4.9 MeV in steps of ~100 keV. These energies were chosen *not* to coincide with sharp resonances reported in Ref. 24.

Scattering angles were selected between 52° and 166° in steps of around 2.5° (center of mass system). The final data are reported in Ref. 18 as the ratio of the cross section divided by the Rutherford cross section. A copy may be obtained upon request from the author or from the Institut für Physik, Basel. Figure 1 shows a few angular distributions.

3. Phase shift analysis

An analysis in terms of partial wave phase shifts was performed. The dominant s-, p- and d-wave phase shifts were found to be ambiguous. One solution could be eliminated as its energy derivative turned out to be unphysically large. Another solution could not be continued to low energies. The remaining solution is the one found by McDermott [15]. No significant changes were observed when up to 7 partial waves were considered as necessary if there is a long range exchange contribution. This indicates that there are no exchange effects or that they are undetectably small. All 7 phase shifts of all solutions are reported in Ref. 18.

4. Optical model analysis

As expected, the determination of a real optical potential from the angular distributions turned out to allow very many solutions, not only as regards the depth of a specific potential, but also with respect to the potential shape.

For a Woods–Saxon potential

$$V(r) = V_0(1 - e^{(r-R)/a})^{-1} \tag{1}$$

the following parameter set yields good results:

$$\begin{aligned} V_0 &= -33.2 \pm 0.7 \ \text{MeV} \\ R &= 2.8 \pm 0.1 \ \text{fm} \\ a &= 0.56 \pm 0.04 \ \text{fm}. \end{aligned} \tag{2}$$

There are further equivalent sets with depths −18.5 MeV, −56.5 MeV and −93.7 MeV etc. with slightly different radius and diffuseness. The phase shifts generated by these potentials coincide fairly well with those found by McDermott [15].

Following von Oertzen [13] a Majorana potential should yield a much better reproduction of the angular distribution if there is a heavy particle exchange contribution. We have tried to add a Majorana term to the potential and to determine its importance. Again it turned out that the necessary exchange

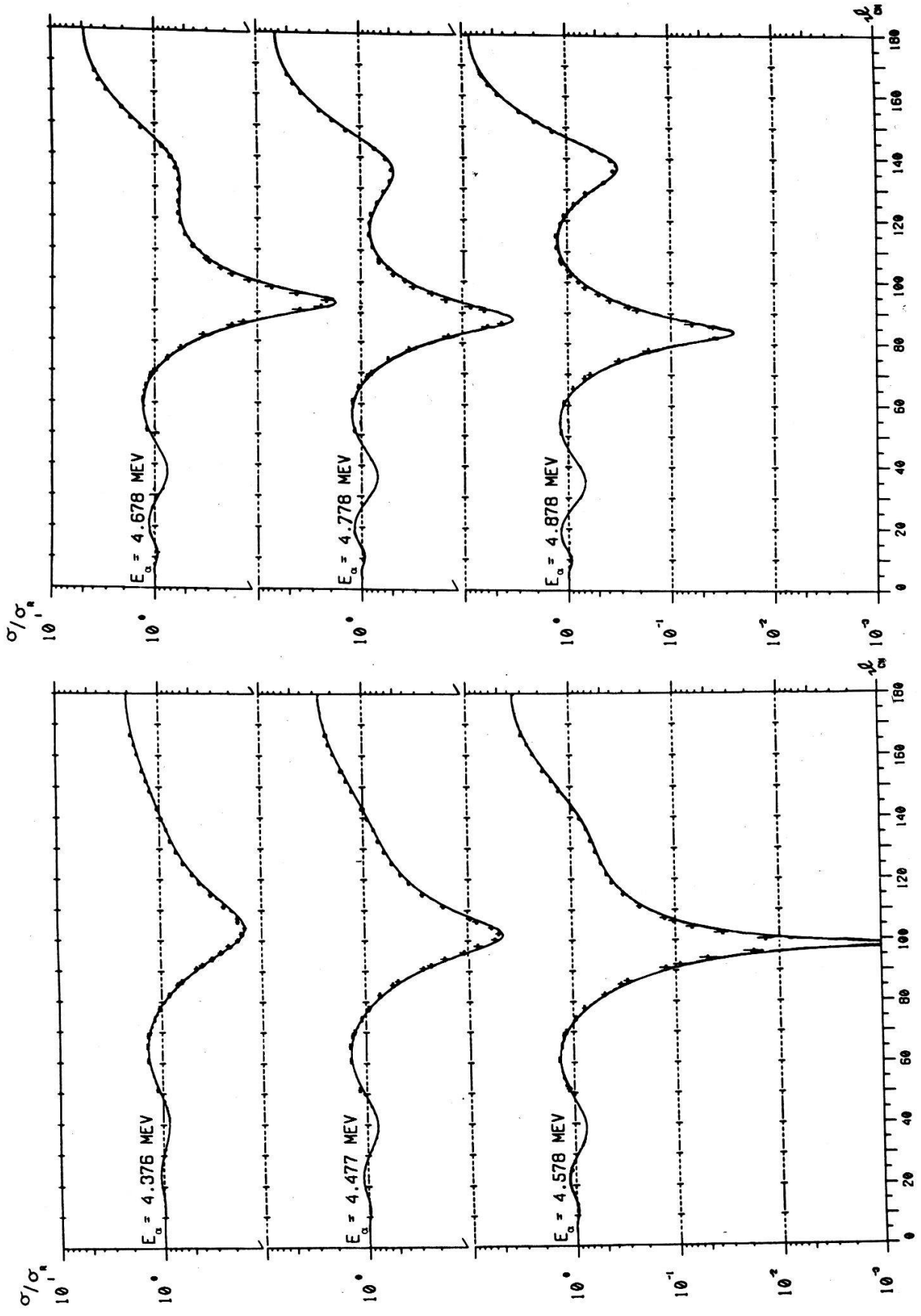

Figure 1.
A few cross section angular distributions of elastic $^{16}O(\alpha, \alpha)^{16}O$ scattering. The ratio of the cross section σ divided by the Rutherford cross section σ_R is plotted versus the center of mass scattering angle θ_{cm}. E_α denotes the incident α particle energy.

contribution is compatible with zero. Therefore we may conclude that there is no heavy particle exchange and that the dominant reaction mechanism is given by the observed α-cluster (or "shape") resonances.

5. The 0_4^+ rotational band of ^{20}Ne

The present experiment includes the first two undisputed members of the 0_4^+ rotational band of ^{20}Ne [24]:

$$\begin{aligned} &J^\pi = 0^+ \quad \text{at} \quad E_x = 8.3\,\text{MeV}, \qquad \Gamma_{cm} > 800\,\text{keV}, \\ &J^\pi = 2^+ \quad \text{at} \quad E_x = 8.8\,\text{MeV}, \qquad \Gamma_{cm} > 800\,\text{keV}. \end{aligned} \tag{3}$$

The third 0_4^+ level $J^\pi = 4^+$ is usually assigned to the resonance at $E_x = 10.79$ MeV ($\Gamma_{cm} = 350$ keV) [19–24], Strazzieri [20] puts it at $E_x = 11.92$ MeV and Tomoda [22] at $E_x = 10.548$ MeV.

The fourth level $J^\pi = 6^+$ is placed at as many different excitation energies as there are authors writing on that subject [19–23].

The fifth 0_4^+ member $J^\pi = 8^+$ is generally not discussed. If it is, the authors assign it to different resonances [20, 21].

The question arises if the potential extracted from the present experiment does generate this series of shape resonances. The Woods–Saxon potential of equations 1 and 2 does not even generate a correct $J^\pi = 4^+$.

The failure to reproduce the higher-spin resonance may be due to the incorrect shape of the phenomenological Woods–Saxon potential used. A folding potential can be expected to have more realistic large-r behaviour. Therefore we have fitted our data with a folding potential [25, 26] with an energy dependent normalization factor. It generates all of the first three 0_4^+ members. The necessary normalization factor increases by more than 10% in this energy interval. An extrapolation to higher energies to locate the $J^\pi = 6^+$ and 8^+ levels would therefore become rather arbitrary.

The energy dependence of the folding potential can however be considerably reduced to a few percent by adding a constant correction factor:

$$V'(r) = N(E_\alpha) \cdot V_f(r) \cdot \{1 + a r^b\}, \tag{4}$$

$$\left.\begin{aligned} a &= 6.5 \cdot 10^{-3} \pm 8 \cdot 10^{-4} \\ b &= 2.0080 \pm 10^{-4} \end{aligned}\right\} \text{ for all energies } E_\alpha, \tag{5}$$

and the normalization factor $N(E_\alpha)$ increasing from 0.96 (for $E_\alpha = 3.778$ MeV) to 1.00 (for $E_\alpha = 7.58$ MeV).

If this normalization factor is linearly extrapolated towards higher energies, the other 0_4^+ members are found at the following energies:

$$\begin{aligned} &E_x(4^+) = 10.8\,\text{MeV} \text{ (coincides with the usual assignment)} \\ &E_x(6^+) = 14.3\,\text{MeV} \text{ (coincides with the assignment by Hunt [19])} \\ &E_x(8^+) = 19.8\,\text{MeV}. \end{aligned} \tag{6}$$

However, the resonances generated by the potential are somewhat broader than the observed levels.

6. Conclusions

The interpretation of carefully measured angular distributions of the elastic scattering of α particles from ^{16}O around the Coulomb barrier yields the following results:

1. From a phase shift analysis and particularly from an optical model analysis we conclude that there is no heavy particle exchange contribution to the dominant shape resonances.
2. From the width of the resonances we infer that there is indeed an obvious cluster structure $^{16}O+\alpha$ in ^{20}Ne.
3. The folding potential extrapolation implies that the first four members of the 0_4^+ rotational band may be identified with observed levels. The $J^\pi = 8^+$ level is predicted to lie near $E_x = 19.8$ MeV, but there is no level known near this excitation energy.

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