Possible resonance anomalies in the $^{16}O+^{12}C$ reaction

1974 J. Phys. A: Math. Nucl. Gen. 7 1193

(http://iopscience.iop.org/0301-0015/7/10/012)

J. Phys. A: Math., Nucl. Gen., Vol. 7, No. 10, 1974. Printed in Great Britain. © 1974

Possible resonance anomalies in the $^{16}O + {}^{12}C$ reaction

D Branford†, J O Newton, J M Robinson and B N Nagorcka

Nuclear Physics Department, Research School of Physical Sciences, Australian National University, Canberra ACT 2600, Australia

Received 23 January 1974, in final form 28 February 1974

Abstract. A strong correlation has been observed between the 0° and 180° excitation functions for the $^{12}C(^{16}O, \alpha)^{24}Mg$ reaction leading to the 13·2 MeV 8^+ level. The possibility that this is due to exciting intermediate structure peaks at E_{cm} = 13·7, 14·7, 16·0 and 18·0 MeV, is considered. It is concluded that the reaction most probably excites a narrow resonance ($\Gamma \simeq 70$ keV) with $J^\pi = 9^-$ or 10^+ at E_{cm} = 13·7 MeV. Weak evidence supporting the existence of anomalies at E_{cm} = 16·0 and 14·7 MeV is presented. The possibility that the reaction excites a band of quasi-molecular states is discussed. An alternative explanation of the strong correlation in the data, based on the assumption that the reaction proceeds preferentially through either even or odd angular momentum states, is also considered.

1. Introduction

The $^{16}O + {}^{12}C$ reaction has received extensive study in the last few years. Halbert *et al* (1967, to be referred to as H) studied the excitation functions and angular distributions of the α-particle groups (α_0–$\alpha_{6\cdot44}$) to the ground state and first six excited states of ^{24}Mg. They concluded that the reaction proceeds essentially 100% by the compound nucleus mechanism and that the results are mainly consistent with the fluctuation theory of Ericson (1963) and Brink and Stephen (1963). However, there is one 'resonance anomaly' at E_{cm} = 13·7 MeV which appears not to be consistent with this theory, although it might be consistent with a fluctuation analysis based on *R*-matrix theory (Moldauer 1967). More recently, further anomalies have been observed in the excitation function of the total reaction cross section at energies in the vicinity of the Coulomb barrier (Patterson *et al* 1971, Nagorcka and Newton 1972) and in the excitation functions for various channels at E_{cm} = 19·7 MeV (Stokstad *et al* 1972, Cosman *et al* 1972, Malmin *et al* 1972) and possibly at 22·7 MeV (Charles *et al* 1973).

A variety of explanations of such relatively narrow (Γ = 150–400 keV) anomalies in this and other reactions have been put forward. Some are based on the assumption that the two nuclei form a quasi-molecule (Bromley 1970). Although this has some plausibility for reactions taking place around the Coulomb barrier, it seems unlikely that it could account for the narrow widths at high bombarding energies. Modifications of this, which take into account excitation of the nuclear cores (Imanishi 1969, Fink *et al* 1972) might possibly explain the data. Another model is that the two ^{12}C cores form a quasi-molecule, bound together by the four correlated valence nucleons of ^{16}O, which

---

† Present address: Physics Department, The University of Edinburgh, Scotland.

may approximate to an alpha particle. Such 'quartet' models (Arima *et al* 1970, Michaud and Vogt 1972) have the attraction that most of the anomalies have been observed in reactions between α-type nuclei. Further, there is some evidence that α exchange plays an important part in the elastic scattering between such nuclei (Von Oertzen 1970).

None of these models has quantitative justification at present. However, it seems plausible that cluster type intermediate structure resonances will be excited in near grazing collisions and have high angular momenta. Hence the effects might appear most strongly in channels involving final states of high angular momentum. We have, therefore, studied the excitation functions for population of the 8^+ state of ^{24}Mg at 13·2 MeV in the ^{12}C(^{16}O, $\alpha_{13\cdot2}$)^{24}Mg reaction.

2. Experimental method

Targets of natural C (15 μg cm^{-2}) and of GeO or W_2O_3 (40 μg cm^{-2}) were deposited on nickel foils. These were bombarded with beams of ^{16}O or ^{12}C ions which stopped in the foil. The α particles were detected at 0° to the beam direction by a single surface barrier detector or counter telescope, each of which subtended a 13° (centre of mass) half angle. The density of levels at 13·2 MeV excitation is high and the particle energy resolution obtained was only about 350 keV FWHM. However, we were able to obtain clean spectra for $\alpha_{13\cdot2}$ by taking advantage of the fact that the 13·2 MeV level has $\Gamma_\gamma \geqslant 0\cdot8$ (Ollerhead *et al* 1968) whilst neighbouring levels have $\Gamma_\gamma \ll 1$ (Branford *et al* 1974). Spectra were taken in coincidence with pulses in the ranges (i) $0\cdot5 < E_\gamma < 3$ MeV, (ii) $3 < E_\gamma < 5\cdot5$ MeV and (iii) $E_\gamma > 5\cdot5$ MeV, from two 12·7 cm × 10·2 cm NaI(Tl) detectors, placed 12·7 cm from the target at angles of 45° and 135°. The $\alpha_{13\cdot2}$ group was seen in coincidence with (ii).

3. Results and discussions

Our results, together with the summed $\alpha_{0-6\cdot44}$ excitation function of H, are shown in figure 1. The 0° and 180° excitation functions for the $\alpha_{13\cdot2}$ group are clearly correlated, with strong peaks occurring at E_{cm} = 13·7, 14·7, 16·0 and 18·0 MeV. It is interesting to note that 13·7 MeV is the energy of the anomaly reported in H and 16·0 MeV is the energy of the second highest peak in the $\alpha_{0-6\cdot44}$ data at 0° (see figure 1). Although this may imply that the reaction excites intermediate structure resonances, it is possible that the reaction is purely statistical and the correlations are accidental. This possibility was considered by comparing the data with the predictions of fluctuation theory. By assuming a smoothly varying average cross section and an effective number of channels N = 1·5 (the value expected for the solid angle subtended) it was found that the $\alpha_{13\cdot2}$ data are largely consistent with fluctuation theory. The only inconsistency is that the cross-correlation coefficient $C_0(0, \pi)$ has the value $0\cdot22 \pm 0\cdot09$, which disagrees with the theoretical value of zero (Dallimore and Hall 1965). To investigate this further and take other channels into account, we added together these data and those of H, appropriately weighted according to the value of N, to give excitation functions with correspondingly larger N. The expected numbers of peaks, higher than those seen at E_{cm} = 13·7, 14·7, 16·0 and 18·0 MeV in the range of data studied, were determined in the manner described by Branford and Newton (1974) and are shown in table 1.

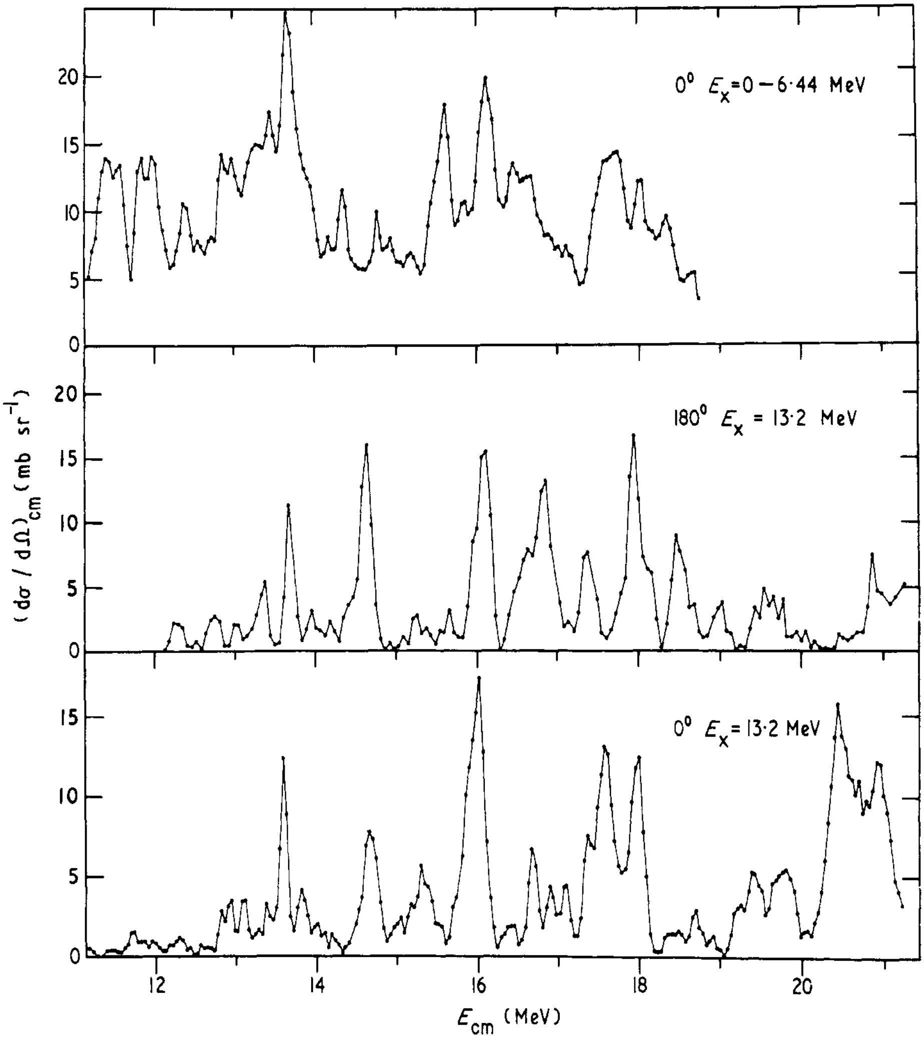

Figure 1. Excitation functions for $\alpha_{13\cdot2}$ at 0° and 180° and $\alpha_{0-6\cdot44}$ at 0° (taken from H) in the $^{12}C(^{16}O, \alpha)^{24}Mg$ reaction. The data labelled 180° were obtained from measurements on the $^{16}O(^{12}C, \alpha)^{24}Mg$ reaction taken at 0°.

Table 1. Number of peaks, expected in the energy range studied, with a height greater than or equal to the summed cross sections at the indicated energies (see text).

	Centre of mass energy (MeV)			
Data included in sum	13·7	14·7	16·0	18·0
$I = \alpha_{13\cdot2}(0°)+\alpha_{13\cdot2}(180°)$	$13^{+15}_{-7} \times 10^{-3}$	$15^{+14}_{-7} \times 10^{-2}$	$12^{+11}_{-6} \times 10^{-2}$	$42^{+35}_{-10} \times 10^{-2}$
$II = I+\alpha_{0-6\cdot44}(0°)+\alpha_{0-4\ 23}(178°)$	$2^{+5}_{-2} \times 10^{-4}$	$41^{+41}_{-20} \times 10^{-2}$	$6^{+10}_{-4} \times 10^{-3}$	$68^{+68}_{-30} \times 10^{-2}$
$III = II+\alpha_{0-6\cdot44}(20°, 69°, 149°)$	$5^{+5}_{-3} \times 10^{-9}$	$21 \pm 4 \times 10^{-1}$	$34^{+17}_{-10} \times 10^{-2}$	51 ± 10

From these data, we concluded that (i) the evidence in favour of the 13·7 MeV peaks not being Ericson fluctuations is overwhelming, and (ii) the reaction most probably excites a resonance at this energy. We measured the width of the peak in the 0° excitation function for $\alpha_{13\cdot2}$ using a 5 μg cm^{-2} C target and found $\Gamma_{\text{cm}} \simeq 70$ keV, which corresponds to a mean lifetime of $8{\cdot}8 \times 10^{-21}$ s. The positions of the first and second minima near 0° and 180° in the α_0 angular distribution reported in H are within ±2° and 6° of those for the $(P_9(\cos\theta))^2$ and $(P_{10}(\cos\theta))^2$ functions respectively. This suggests that the spin of this 'state' is 9^-, or somewhat less likely 10^+, which correspond roughly to the angular momentum of the grazing orbit.

Regarding the 16·0 MeV peaks, the summed 0° and 180° data (table 1) suggest that these are also anomalous, yet there is little indication of this when the 20° and 69° data of H are included. This result might be due to the angular distributions from the 16·0 MeV state having minima at these angles. We conclude, therefore, that there is some evidence for an anomaly at 16·0 MeV.

There is negligible support from table 1 for the existence of anomalies at 14·7 and 18·0 MeV. However, the excitation functions for the total ^{12}C(^{16}O, α)^{24}Mg and ^{12}C(^{16}O, $\alpha\alpha$)^{20}Ne cross sections (Nagorcka 1973) do show a peak at $E_{\text{cm}} = 14{\cdot}7$ MeV with $\Gamma_{\text{cm}} = 150 \pm 20$ keV ($\Gamma_{\text{cm}}(\alpha_{13\cdot2}) \simeq 182$ keV) and consequently give weak support for an anomaly at this energy.

We now consider further the possibility that the correlation observed in our data arises from intermediate structure resonances having a rather small width (Γ = 150–400 keV). The data suggest strongly that this may be so for the 13·7 MeV peak and perhaps for that at 16·0 MeV, but do not support the explanation for the other peaks. It is interesting to note that if we assume the 13·7 and 16·0 MeV 'states' to have spins $J = 9^-$ and 11^- and plot their energies, together with those of the proposed 14^+ (Stokstad *et al* 1972, Cosman *et al* 1972, Malmin *et al* 1972) and 16^+ (Charles *et al* 1973) 'states', against $J(J+1)$, then they lie on a good straight line (see figure 2). It is of further

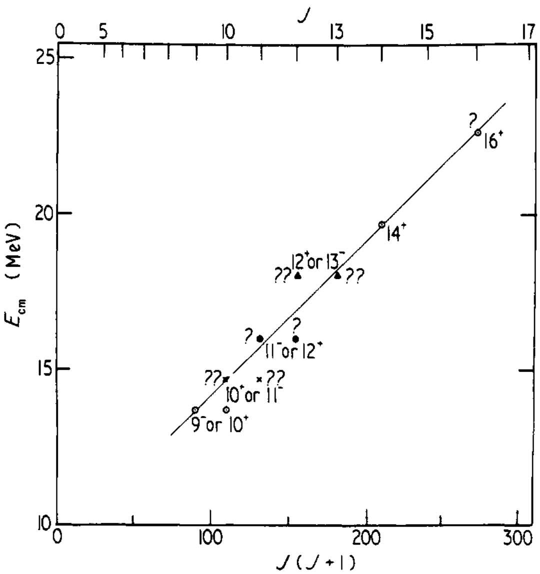

Figure 2. Energies of anomalous 'states' plotted against $J(J+1)$. In some cases two possible spins are shown. The degree of confidence in the existence of the 'state' is indicated.

interest that this line corresponds to that obtained from the semi-classical expression for the energy of the 'grazing orbit', where the radius parameter r_0 was found to have a value of 1·65 fm by fitting the expression to the energy and spin of the 14^+ anomaly. A superficially attractive explanation of this might be that these states are members of a quasi-molecular rotational band, formed by rotation of the ^{16}O and ^{12}C components about their mutual centre of mass. However, if this were a normal rotational band, where all the members had the same intrinsic structure, one might expect some regularity in decay behaviour, but this does not seem to be the case. For example, the 19·7 MeV 'state' does not appreciably populate the ^{24}Mg 13·2 MeV state. If anomalous states are formed from grazing orbits, then both the spacings and spins may correspond roughly to those of a rotational band, though an exact energy correspondence would be surprising. However, the states might all have different structures.

It is interesting to note that, even if we remove the data in the region of the well established 13·7 MeV anomaly, we still obtain a value for $C_0(0, \pi)$ of $0{\cdot}18 \pm 0{\cdot}09$. A possible explanation might be that either even or odd incoming orbital angular momenta (possibly alternating) dominate the partial cross section leading to the 8^+ state. Assuming that the cross sections for populating the $m = 0$ and $m = 1$ magnetic substates are uncorrelated, we obtained a value of $0{\cdot}27 \pm 0{\cdot}13$ for $C_0'(0, \pi)$, the cross correlation coefficient for population of one magnetic substate. From the expression

$$C_0'(0, \pi) = \langle\sigma(0)\rangle^{-2}|\langle\sigma(0)\rangle_{\text{even}} - \langle\sigma(0)\rangle_{\text{odd}}|^2$$

(Brink *et al* 1964), we then obtain the result $\langle\sigma(0)\rangle_{\text{even}} = (3{\cdot}2^{+1{\cdot}2}_{-1{\cdot}0})\langle\sigma(0)\rangle_{\text{odd}}$, or vice versa. This result might arise if, for example, molecular alpha exchange states between two ^{12}C cores (Von Oertzen 1970) were important for the $\alpha_{13{\cdot}2}$ channel; in this case only even l values are allowed due to the identical cores. A similar result might occur if the optical potential for the $^{16}\mathrm{O} + {}^{12}\mathrm{C}$ is weakly absorbing and possibly l dependent for grazing collisions (Siemssen 1971).

In summary, we conclude that the evidence presented here strongly suggests that the $^{12}\mathrm{C}(^{16}\mathrm{O}, \alpha)^{24}\mathrm{Mg}$ reaction is not entirely statistical in nature. At least in part, this is most probably due to some form of intermediate structure. However, elucidation of the true nature of this structure requires further experimental and theoretical work.

References

Arima A, Gillet V and Ginocchio J 1970 *Phys. Rev. Lett.* **25** 1043–6
Branford D, McGough A C and Wright I F 1974 to be published
Branford D and Newton J O 1974 to be published
Brink D M and Stephen R O 1963 *Phys. Lett.* **5** 77–9
Brink D M, Stephen R O and Tanner N W 1964 *Nucl. Phys.* **54** 577–85
Bromley D A 1970 *Proc. Int. Conf. on Nuclear Reactions Induced by Heavy Ions, Heidelberg* ed R Bock and D A Hering (Amsterdam: North Holland/New York: American Elsevier) pp 27–59
Charles P *et al* 1973 *Proc. Int. Conf. on Nuclear Physics, Munich* vol 1 (Amsterdam: North Holland) p 539
Cosman E R *et al* 1972 *Phys. Rev. Lett.* **29** 1341–4
Dallimore P J and Hall I 1965 *Phys. Lett.* **18** 138–9
Ericson T 1963 *Ann. Phys., NY* **23** 390–414
Fink H J, Scheid W and Greiner W 1972 *Nucl. Phys.* A **188** 259–88
Halbert M L *et al* 1967 *Phys. Rev.* **162** 899–933
Imanishi B 1969 *Nucl. Phys.* A **125** 33–56
Malmin R E *et al* 1972 *Phys. Rev. Lett.* **28** 1590–3
Moldauer P A 1967 *Phys. Rev. Lett.* **18** 249–52

Michaud G J and Vogt E W 1972 *Phys. Rev.* C **5** 350–68
Nagorcka B N 1973 *PhD Thesis* Australian National University
Nagorcka B N and Newton J O 1972 *Phys. Lett.* **41B** 34–8
Ollerhead R W *et al* 1968 *Can. J. Phys.* **46** 1381–401
Patterson J R *et al* 1971 *Nucl. Phys.* A **165** 545–59
Siemssen R H 1971 *Argonne National Laboratory Report* ANL-7837 145–86
Stokstad R *et al* 1972 *Phys. Rev. Lett.* **28** 1523–5
Von Oertzen W 1970 *Nucl. Phys.* A **148** 529–47