ELASTIC SCATTERING OF ^{18}O BY ^{18}O†

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The excitation function at 90° c.m. has been measured between 7.5 and 27.5 MeV c.m. The prominent gross structure observed in ^{16}O-^{16}O is not seen in the present case, and the absolute cross section falls to much lower values at high energies. The results of the comparison of the two systems are discussed in terms of angular momentum restrictions on configurations directly coupled to the elastic channel.

This experiment was motivated by a desire to clarify the origin of the strikingly large and regular gross structure[1] in the elastic scattering of ^{16}O-^{16}O at center-of-mass energies between 20 and 30 MeV. This structure was particularly prominent at 90° c.m., where it was characterized by a width of approximately 2 MeV and by peak-to-valley ratios of 20 to 1. Superimposed on the gross structure is a fine structure describable by Ericson fluctuation theory. The magnitude of the fine structure, however, indicates a compound elastic contribution[2] of less than 10%. The gross structure does not appear in the ^{28}Si-^{4}He exit channel. Studies of elastic scattering in other heavy-ion systems[3,4] of comparable mass have revealed much less structure and smaller cross sections than are seen in the ^{16}O-^{16}O reaction. To gain further insight into the unusual behavior exhibited in the ^{16}O-^{16}O system, we have undertaken scattering measurements for another system of identical bosons, the ^{18}O-^{18}O system. The 90° elastic cross section for the latter system is found to be one to two orders of magnitude less than that of the former. The results are interpreted in terms of an angular momentum dependent, imaginary optical potential.[5-7] The contrasting results for the two systems have enabled us to suggest a model for predicting the critical angular momentum relevant to such a potential.

The ^{18}O beam was obtained by introducing 50% enriched ^{18}O water vapor into the duoplasmatron ion source of the University of Washington two-stage FN Van de Graaff accelerator. Separation of the ^{16}O and ^{18}O beam occurred at both a 20° magnet between the source and the accelerator and (more effectively) at the 90° analyzing magnet following acceleration.

A 40-$\mu g/cm^2$ ^{18}O target was prepared by anodizing aluminum foil in a 3% citric acid solution and chemically removing the unanodized aluminum to obtain self-supporting Al_2O_3 targets. The electrolyte was the 50% enriched ^{18}O water. The target thicknesses were determined by elastic scattering below the Coulomb barrier.

As the target contained comparable amounts of ^{16}O and ^{18}O a coincidence technique exploiting the kinematic differences among the various kinds of scattering was used. Since for a laboratory scattering angle of 45° the ^{18}O-^{18}O and ^{18}O-^{16}O recoils are separated by only approximately 4°, a position-sensitive detector was used for recoil detection. The angle-defining detector subtended 1° in the reaction plane and a total lab solid angle of 1.16×10^{-4} sr. The energy and position (actually energy times position) signals for coincident events were presented to an SDS-930 computer which generated by suitable division an energy-versus-position array from which peaks due to ^{18}O scattered off ^{18}O, ^{18}O scattered off ^{16}O, and ^{16}O recoils could be identified and integrated. The excitation function for ^{16}O-^{18}O scattering at 90° c.m. is in good agreement with the results of Fortune et al.[4]

The absolute cross sections for elastic scattering of ^{18}O-^{18}O are shown in Fig. 1 along with the ^{16}O-^{16}O data of Siemssen et al.[1] and the calculated values for Mott scattering. The ^{18}O cross section drops below the cross section for Mott scattering near 10 MeV c.m. bombarding energy, about 1 MeV below the point at which the ^{16}O first drops. Once the ^{16}O cross section begins to drop below the Mott scattering cross section, it decreases more rapidly than the ^{18}O so that the excitation functions nearly cross around 19 MeV c.m. The ^{16}O cross section then stops decreasing and exhibits broad structure; the ^{18}O cross section continues to decrease exponentially but shows some evidence of strongly damped structure with a periodicity similar to ^{18}O.

The relative behavior of ^{18}O-^{18}O and ^{16}O-^{16}O scattering near the Coulomb barrier may be readily understood. Since ^{18}O has both a larger radius and greater diffuseness[8,9] than ^{16}O, the falloff from Mott scattering occurs at a lower energy for ^{18}O than for ^{16}O. The difference in the behavior at higher energies can be parametrized by the optical model as a difference in

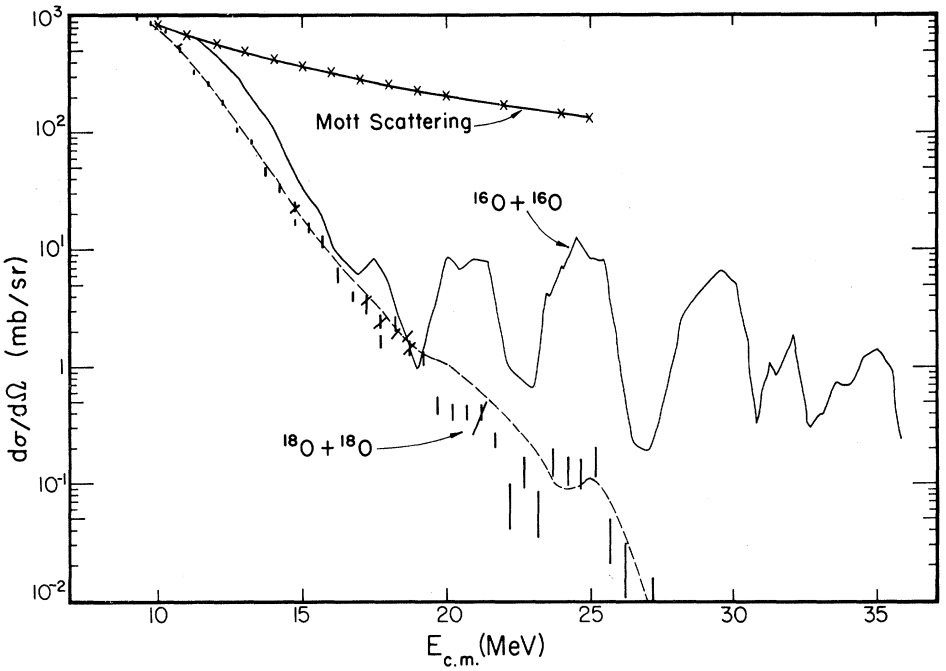

FIG. 1. Elastic scattering cross sections for ^{18}O-^{18}O at 90° c.m. are compared with the ^{16}O-^{16}O results of Maher *et al.* (see Ref. 10). The dashed line is an optical-model calculation for ^{18}O-^{18}O described in the text.

the depth of the imaginary potential, with ^{18}O-^{18}O requiring a much larger imaginary potential.

There has been considerable effort to describe the ^{16}O-^{16}O structure at higher energies by use of an optical potential. The first potential found to reproduce the magnitude and periodicity of the structure qualitatively was characterized by a fairly shallow real potential ($V = 17$) and a very weak ($W = 0.4 \pm 0.1\ E_{c.m.}$) imaginary absorptive potential.[1] It has since been found[10] that there are discrete ambiguities in the depth of the real potential required to obtain a fit, but that all potentials other than the shallowest require a complicated energy dependence. The very weak imaginary potential corresponds to such a long mean free path (~4 F) and such extensive nuclear interpenetration that one becomes concerned about the physical significance of the model. We have attempted a rough fit to the ^{18}O-^{18}O scattering by changing as few parameters as possible of the optical potential[1] derived to fit the ^{16}O-^{16}O scattering. The radius was assumed to vary as $A^{1/3}$ on the basis of previous analyses,[8,9] and only the diffuseness and imaginary potential depth were changed, the former from 0.49 to 0.57, and the latter increased by a factor of 3.5. The result is shown as the dashed line in Fig. 1. Since W for the ^{18}O-^{18}O system has a more reasonable value, an explanation is desired for the origin of the small W in the case of the ^{16}O-^{16}O system. The failure to reproduce the magnitude of the oscillations in the latter system fully even with a small W is of concern.

Chatwin et al.[5-7] have recently suggested a modification to the optical model in which the absorptive part of the optical potential is considered to be a function of angular momentum as well as radius. A smooth cutoff is introduced in the strength of the absorptive potential as l gets larger than a certain critical value. This cutoff is said to be important if the heavy nuclei in the entrance elastic channel carry in a greater amount of angular momentum than any of the reaction channels can carry away. Eck et al.[6] have shown that a significantly better fit to the gross structure can be obtained with this modification, particularly with respect to fitting the magnitude of the peak-to-valley ratio of the structure. Also, since the imaginary potential can now be larger for the lower partial waves, the mean-free path in the nuclear interior assumes a more reasonable value. In these fits the critical angular momentum parameter l_c was obtained essentially empirically, although the form of the energy dependence was obtained from a classical estimate of the maximum angular momentum that any reaction channel can carry off. It was suggested[5] that l_c could be estimated by

examination of the transmission coefficients of the neutron, proton, and alpha exit channels of the compound nucleus. Of these exit channels, alpha emission can take away the most angular momentum.

It is not clear to us why the l dependence of W should be related to the decay rate of reaction channels which are connected to the entrance channel by a compound nucleus. W is determined by interactions that remove flux from the elastic entrance channel, leading either to other direct reaction channels or to more complicated configurations which may, after subsequent interactions, lead to compound-nucleus information. It would seem that if and when a compound nucleus of high angular momentum is formed at that later stage in the process, any angular momentum inhibition of its eventual decay by other channels is irrelevant to the estimation of the initial interactions responsible for the imaginary potential.

More recently[7] the angular momentum matching problem has been treated in a more formal and less restrictive manner, but the distinction between nonelastic channels which are expected to be directly coupled to the elastic channel, and reaction channels which are only coupled through relatively long-lived intermediates, has not been clearly made. In the paragraphs that follow we show that angular momentum restrictions in the alpha exit channels of the compound nucleus do not predict either the correct energy dependence of l_c for ^{16}O-^{16}O, or the great difference between the ^{16}O-^{16}O and ^{18}O-^{18}O system. We also show how better a priori estimates of l_c can be obtained from reaction channels more strongly coupled to the entrance channel such as nucleon and alpha-particle transfer channels.

It is useful for purposes of discussing either the maximum angular momentum brought in by the elastic channel or carried away by other channels to characterize by l_{max} the l value for which the transmission coefficient T_l has fallen to one-half its maximum value of unity. In Fig. 2 we show by the heavy full lines the l_{max} values in the elastic entrance channel for the two systems. Also shown by the intersecting curved segments are the l_c values empirically obtained by Chatwin et al.[7] in a fit to the ^{16}O-^{16}O excitation function. The l_{max} values for the $^{28}Si + \alpha$ and $^{32}Si + \alpha$ ground-state exit channels are also shown for the ^{32}S and ^{36}S compound systems, following the suggestion of Chatwin et al.[5] If alpha exit channels of the compound nucleus were to be relevant to the problem, a more appropriate

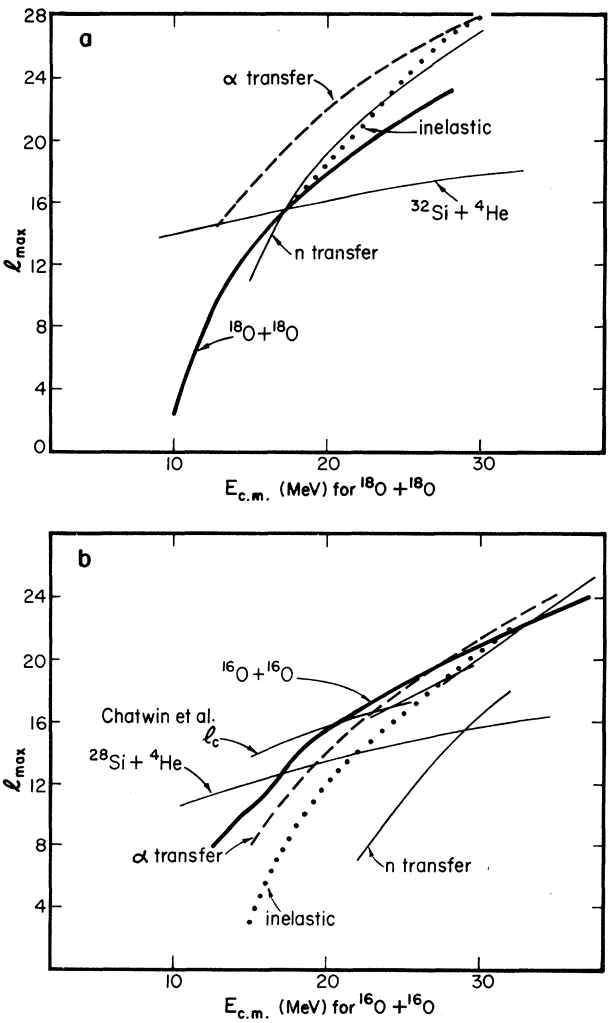

FIG. 2. The heavy full curve gives l_{max}, the l value for which the transmission coefficient has fallen to one-half its maximum value, for the entrance channels (a) ^{18}O-^{18}O and (b) ^{16}O-^{16}O as a function of the center-of-mass energy in the entrance channels. Also shown are l_{max} values for the ground-state alpha exit channel of the compound nucleus. The dashed, dotted, and thin full line are the J_{max} values for transfer reactions and inelastic scattering and are equal to l_{max} for these channels including channel spin. The intersecting segments in (b) labeled l_c are the empirical values Chatwin *et al.* (see Ref. 7) found in a fit to the $^{16}O + ^{16}O$ excitation function.

measure might be the maximum angular momentum associated with any alpha channel including decay to excited high-spin states of ^{28}Si. Our calculations show that such considerations do not provide either the correct energy dependence of l_c for ^{16}O-^{16}O or the required difference between the ^{16}O-^{16}O and ^{18}O-^{18}O system. Similarly, one finds that levels are available in the compound systems of ^{32}S and ^{36}S of significantly higher spin

than that brought in by the entrance channel[11]; hence, absorption could not be inhibited by a lack of high-spin levels in the compound system.

Thus, both from empirical considerations and from the physical basis of the optical model, one is led to focus attention on the reaction channels and intermediate states most directly connected to the entrance channel. Ideally one would treat directly coupled reaction channels with a coupled-channel calculation,[12] but in the absence of such a calculation these effects must be included in the absorption described by the imaginary potential.

We have attempted to estimate angular momentum restrictions in nonelastic channels that would be expected to be simply and strongly connected to the entrance channel in the following way. For each type of channel (nucleon transfer, alpha-particle transfer, inelastic scattering) we have searched for the maximum angular momentum which can be obtained by coupling the intrinsic spins of possible particular final-state combinations with the l_{max} value of the reaction leading to such states. For the alpha-transfer channel the highest angular momentum can usually be obtained when the final states are excited, whereas for nucleon transfer in the ^{18}O-^{18}O system, the ground-state spins are large enough to make that channel most favorable. The resulting l_{max} values are illustrated in Fig. 2, and for alpha transfer are qualitatively similar to the empirical values of l_c required to fit the structure in the ^{16}O-^{16}O system. The qualitative difference in the ^{18}O-^{18}O system is also accounted for, as the greatly damped elastic cross section experimentally observed implies that l_c is larger than l_{max}. The dramatic and unique gross structure observed in the ^{16}O-^{16}O system can thus be qualitatively attributed to the energetic inhibitions against simple excitations of this double-closed-shell nucleus.

The l_{max} values appropriate to the ^{18}O-^{16}O system have also been calculated in the same way, and are found to be intermediate to the ^{16}O-^{16}O system and the ^{18}O-^{18}O system, although more similar to the latter. This is consistent with the experimental observations, which show the magnitude of the elastic cross section to be intermediate between the two systems of identical particles, although again more similar to the ^{18}O-^{18}O system.

The importance of transfer reactions has been indicated in other investigations. von Oertzen et al.[13,14] have concluded from analysis of ^{12}C-^{16}O elastic anguiar distributions at $E_{c.m.} = 35$ and 42 MeV that there is a significant contribution from alpha-particle transfer for high angular momenta corresponding to grazing collisions. Gridnev, Volkov, and Wilczynski[15] have also interpreted energy spectra for transfer reactions at higher energies for heavier targets in terms of angular momentum limitations.

It must be emphasized that the reaction channels considered here are not the only channels which can couple to the entrance channel. There must also be intermediate states associated with the beginning of amalgamation of the two nuclei, but their properties cannot be easily calculated. It is our view that these intermediate states will more closely resemble the channels just considered than the exit channels of the compound nucleus. At energies below the elastic structure (<20 MeV c.m.) the problems of angular momentum matching are not so stringent as they are at higher energies. Study of α decay for the ^{16}O-^{16}O system in the energy region just below 20 MeV c.m. revealed[2] that decay to the O^+ ground state of ^{28}Si is primarily from $J = 12$ levels in the ^{32}S compound nucleus.

In summary we have the following picture of the ^{16}O-^{16}O collision process. For energies below 20 MeV configurations exist to carry all l partial waves out of the entrance channel. Above 20 MeV, there are no available configurations to allow absorption of the highest l waves until, above 30 MeV, configurations again become available.[7] Below 20 MeV these configurations lead into the compound system; above 30 MeV decay into direct reaction channels becomes important. The elastic scattering cross-section structure at large angles is due almost entirely to grazing collisions.[7] The case of ^{16}O-^{16}O scattering is special in that the elastic scattering due to these grazing collisions is particularly enhanced due to the strong binding of the ^{16}O which limits the angular momentum capacity of configurations directly coupled to the ^{16}O-^{16}O entrance channel. The ^{18}O nucleus is not so strongly bound and hence the absorption of grazing partial waves is not similarly inhibited.

Although we believe that we have strong circumstantial evidence for the role and origin of angular momentum restrictions, further work would be desirable. It would be of interest to look for this effect in other cases, e.g., the scattering of ^{16}O with the isotopes of calcium. We are also planning studies of the alpha-transfer reaction for the ^{16}O-^{16}O and ^{18}O-^{18}O system.

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[1]R. H. Siemssen, J. V. Maher, A. Weidinger, and D. A. Bromley, Phys. Rev. Lett. 19, 369 (1967), and 20, 175 (1968).

[2]R. W. Shaw, Jr., J. C. Norman, R. Vandenbosch, and C. J. Bishop, Phys. Rev. 184, 1040 (1969).

[3]L. A. Jacobson, Phys. Rev. 188, 1509 (1969); W. Reilly *et al.*, in Proceedings of the Heidelberg International Conference on Heavy Ions, Heidelberg, July 1969 (to be published).

[4]H. T. Fortune, A. Richter, R. H. Siemssen, and J. W. Tippie, in Proceedings of the Heidelberg International Conference on Heavy Ions, Heidelberg, July 1969 (to be published).

[5]R. A. Chatwin, J. S. Eck, A. Richter, and D. Robson, in Proceedings of the Heidelberg International Conference on Heavy Ions, Heidelberg, July 1969 (to be published).

[6]J. S. Eck, R. A. Chatwin, R. A. LaSalle, A. Richter, and D. Robson, in Proceedings of the Heidelberg International Conference on Heavy Ions, Heidelberg, July 1969 (to be published).

[7]R. A. Chatwin, J. S. Eck, D. Robson, and A. Richter, Phys. Rev. C, 1, 795 (1970).

[8]G. Goldring, H. M. Loebenstein, I. Plesser, and M. W. Sachs, Phys. Lett. 25B, 538 (1967).

[9]S. Faivre, H. Krivine, and A. M. Papidu, Nucl. Phys. 108, 508 (1967).

[10]J. V. Maher, M. W. Sachs, R. H. Siemssen, A. Weidinger, and D. A. Bromley, Phys. Rev. 188, 1665 (1969).

[11]We are indebted to M. Hillman for providing us with calculations for the yrast levels of ^{32}S and ^{36}S according to the model of Hillman and Grover: M. Hillman and J. R. Grover, Phys. Rev. 185, 1303 (1969).

[12]T. Tamura, Rev. Mod. Phys. 37, 679 (1965).

[13]W. von Oertzen, H. H. Gutbrod, M. Müller, U. C. Voos, and R. Bock, Phys. Lett. 26B, 291 (1968).

[14]U. C. Voos, W. von Oertzen, and R. Bock, Nucl. Phys. A135, 207 (1969).

[15]G. F. Grindnev, V. V. Volkov, and J. Wilczynski, Nucl. Phys. A142, 385 (1970).

INTERNAL BREMSSTRAHLUNG IN THE PION-CHARGE-EXCHANGE REACTION AND THE REACTION MECHANISM

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The threshold singularities of internal bremsstrahlung spectrum in the pion-charge-exchange reaction are used for the identification of the reaction mechanism.

The interactions of pions with light nuclei have been intensively investigated recently. It is clear that these interactions belong to direct nuclear processes. Since the experimental data[1] indicate that as a rule the incident pions interact with more than one nucleon from the target nucleus, it is convenient to describe these processes by a diagram technique which enables us to consider the nuclear cluster structure in a very natural way. However, very little is known up until now about the details of the reaction mechanism.

Certain information about the reaction mechanism for reactions with more than three particles in the final state may be obtained from the Treiman-Yang criterion or from the analysis of moving complex singularities.[2] The identification of the mechanism for binary reactions is much more complicated, since the indicated criteria are not applicable here.

In the present paper we wish to discuss a new possibility for identification of the pion-charge-exchange reaction mechanism in the reaction $X^{A,Z}(\pi^{\pm},\pi^{0})X^{A,Z\pm1}$. This method is an extension

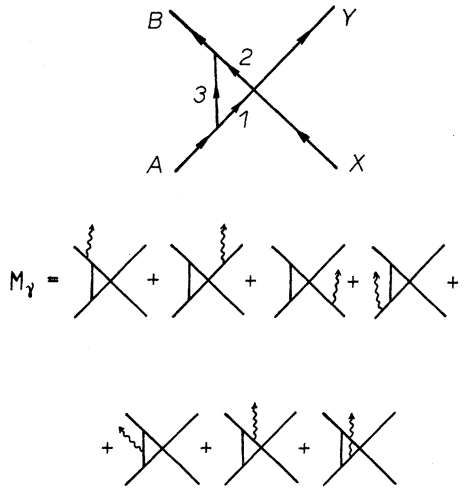

FIG. 1. The radiative triangle diagrams.