Prediction of Enhanced Large-Angle Scattering in Heavy-Ion Elastic Reactions

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(Received 3 June 1983)

Simple total-energy considerations allow an explanation for the nuclear surface transparency in heavy-ion elastic scattering and hence a prediction of the reactions that present a strong backward rise in the angular distributions.

PACS numbers: 25.70.Cd

The observation of large-angle enhanced cross sections and resonancelike behavior in the elastic scattering of some medium-heavy ions has been the subject of various possible explanations, none completely satisfactory.[1] We present here results based on energy considerations that give indications as to which nuclear systems may exhibit this type of phenomena.

A common feature of most interpretations is that they rely on the assumption of a certain degree of transparency of the nuclear surface. Hence, for instance, the orbiting of the colliding systems in the mutual potential will remain unabsorbed or the nuclear surface waves undamped. It will also be present as the basis for parity-dependent optical potentials or the interference between the internal and barrier waves. We seek then for an explanation of the said transparency on the assumption that it is associated with the number of channels available for decay and their relative distance in energy to the elastic channel.

The total energy for a system of heavy ions $({}_{z_1}A_1 + {}_{z_2}A_2)$ "orbiting" at a relative distance R_c is taken to be

$$E = B_1 + B_2 + V_{\mathrm{nucl}} + V_{\mathrm{Coul}} + \hbar^2 l_c(l_c+1)/2\mu R_c, \quad (1)$$

where B_i is the binding energy of the nucleus ${}_{z_i}A_i$ and $V_{\mathrm{Coul}} + V_{\mathrm{nucl}}$ the mutual Coulomb plus nuclear potential. The kinetic energy is supposed to be just the centrifugal term. Whenever, for a given incident energy, and consequent angular momentum l_c, the value of the energy (1) is less than for any other channel (partition of $Z = Z_1 + Z_2$, $A = A_1 + A_2$) we can expect a lowering of the absorption since the resonantlike state lacks other states for its decay. This transparent window should be more evident when the distances in energy between the elastic channel and the other transfer channels are larger.

With the above picture in mind we compare the values of $E - V_{\mathrm{nucl}}$ for the different partitions leading to the same total Z and A. We subtract the nuclear potential V_{nucl} in order to make our estimates independent of its choice. This is equivalent to assuming $V_{\mathrm{nucl}} \approx$ const for all the partitions.

Once the pair ${}_{z_1}A_1 + {}_{z_2}A_2$ of nuclear systems that minimize (1) is found, the total energies for other nonelastic channels are calculated with the radius R_c corresponding to the "orbiting" system. In this way we obtain a lower limit for the gap between the resonant state and the first open channel, ΔE, since the energy of these nonelastic decaying modes should be calculated with an expression that adds to (1) a positive-definite term corresponding to the energy carried by the radial motion.

Table I contains the results for all possible reactions leading to total charge $Z_1 + Z_2$ greater than 8 and smaller than 36. Only cases where a minimum corresponds to stable fragments larger than $A = 8$ are explicitly given. The smaller projectiles (or targets) have been excluded since for them it is not expected that the assumption of $V_{\mathrm{nucl}} \approx$ const is valid. We use[2]

$$R_c = 0.5 + 1.36(A_1^{1/3} + A_2^{1/3}) \text{ fm},$$

and though the total energies depend on the choice of R_c, in most cases the results about which pair of nuclei can present the phenomenon remain unchanged.

The experimental observations can now be explained in terms of the present interpretation. From the vast amount of related data in the following we only consider a few illustrative examples and just one out of many papers is referred to in each case.

The reactions between pairs of $nx\alpha$ ions are candidates to present the effect due to the larger binding energies of this type of nuclei. We can verify in Table I that the reactions ${}^{12}C + {}^{16}O$,[3] ${}^{12}C + {}^{28}Si$,[4-7] ${}^{16}O + {}^{24}Mg$,[8] ${}^{12}C + {}^{32}S$,[4,5,9] ${}^{16}O + {}^{28}Si$,[6,7,10,11] ${}^{12}C + {}^{40}Ca$,[4,6,10] ${}^{12}C + {}^{24}Mg$,[12] ${}^{16}O + {}^{20}Ne$,[13] and ${}^{20}Ne + {}^{24}Mg$[14] correspond to "orbiting" systems with minimum energies. Also some other cases where the phenomenon has been observed (${}^{10}B + {}^{12}C$,[1] ${}^{12}C + {}^{13}C$,[1] ${}^{12}C + {}^{14}N$,[15] ${}^{16}O + {}^{29}Si$,[7] ${}^{16}O + {}^{30}Si$,[7] ${}^{9}Be + {}^{12}Ca$,[16] and ${}^{11}B + {}^{12}C$[17]) coincide with the results

TABLE I. Predicted elastic reactions that present enhanced large-angle cross sections for angular momentum l_c, total charge Z, and mass A. The number displayed below each reaction gives the difference in energy to the first excited transfer channel ΔE. Asterisks indicate cases where inversion occurs.

Z	A	l_c = 15	l_c = 20	l_c = 30	l_c = 40
9	20		$^{11}B+^{9}Be$ 1.0	$^{11}B+^{9}Be$ 2.7	$^{11}B+^{9}Be$ 1.2
10	21			$^{12}C+^{9}Be$ 3.7	$^{12}C+^{9}Be$ 3.8
11	22		$^{12}C+^{10}B$ 0.6	$^{12}C+^{10}B$ 5.9	$^{12}C+^{10}B$ 4.9
11	23		$^{12}C+^{11}B$ 2.8	$^{12}C+^{11}B$ 8.9	$^{12}C+^{11}B$ 10.6
11	24	$^{13}C+^{11}B$ 1.3	$^{13}C+^{11}B$ 1.1	$^{13}C+^{11}B$ 0.6	
12	24	$^{12}C+^{12}C$ 3.9	$^{12}C+^{12}C$ 7.4	$^{12}C+^{12}C$ 14.8	$^{12}C+^{12}C$ 15.5
12	25	$^{13}C+^{12}C$ 5.2	$^{13}C+^{12}C$ 7.7	$^{13}C+^{12}C$ 9.9	$^{13}C+^{12}C$ 11.2
13	26	$^{14}N+^{12}C$ 5.4	$^{14}N+^{12}C$ 5.3	$^{14}N+^{12}C$ 4.9	$^{14}N+^{12}C$ 4.3
13	27	$^{15}N+^{12}C$ 4.1	$^{15}N+^{12}C$ 4.6	$^{15}N+^{12}C$ 4.6	$^{15}N+^{12}C$ 3.6
13	28	$^{15}N+^{13}C$ 2.5	$^{15}N+^{13}C$ 2.4	$^{15}N+^{13}C$ 2.1	$^{15}N+^{13}C$ 1.7
14	28	$^{16}O+^{12}C$ 6.9	$^{16}O+^{12}C$ 9.6	$^{16}O+^{12}C$ 8.4	$^{16}O+^{12}C$ 6.6
14	29	$^{16}O+^{13}C$ 1.9	$^{16}O+^{13}C$ 1.9	$^{16}O+^{13}C$ 1.7	$^{16}O+^{13}C$ 1.3
14	31	$^{17}O+^{14}C$ 0.6	$^{17}O+^{14}C$ 0.9	$^{17}O+^{14}C$ 1.8	$^{17}O+^{14}C$ 1.5
15	30	$^{16}O+^{14}N$ 3.3	$^{16}O+^{14}N$ 4.0	$^{16}O+^{14}N$ 4.4	$^{16}O+^{14}N$ 4.0
15	31	$^{16}O+^{15}N$ 4.0	$^{16}O+^{15}N$ 5.0	$^{16}O+^{15}N$ 7.5	$^{16}O+^{15}N$ 8.1
15	32	$^{17}O+^{15}N$ 1.6	$^{17}O+^{15}N$ 1.5	$^{17}O+^{15}N$ 1.3	$^{17}O+^{15}N$ 1.0
15	33	$^{18}O+^{15}N$ 1.7	$^{18}O+^{15}N$ 2.4	$^{18}O+^{15}N$ 3.1	$^{18}O+^{15}N$ 2.7
16	32	$^{16}O+^{16}O$ 3.2	$^{16}O+^{16}O$ 4.3	$^{16}O+^{16}O$ 7.6	$^{16}O+^{16}O$ 11.9
16	33	$^{17}O+^{16}O$ 0.8	$^{17}O+^{16}O$ 2.1	$^{17}O+^{16}O$ 4.8	$^{17}O+^{16}O$ 7.4
16	34	$^{22}Ne+^{12}C$ 0.7	$^{18}O+^{16}O$ 0.1	$^{18}O+^{16}O$ 3.0	$^{18}O+^{16}O$ 3.4
16	35		$^{22}Ne+^{13}C$ 1.1	$^{18}O+^{17}O$ 0.7	$^{18}O+^{17}O$ 1.1
16	36				$^{18}O+^{18}O$ 3.4
17	35	$^{23}Na+^{12}C$ 0.9	$^{23}Na+^{12}C$ 0.2(*)	$^{20}Ne+^{15}N$ 0.1(*)	$^{19}F+^{16}O$ 0.7
17	36			$^{21}Ne+^{15}N$ 0.1(*)	
17	37		$^{22}Ne+^{15}N$ 1.1	$^{22}Ne+^{15}N$ 2.2	$^{22}Ne+^{15}N$ 1.2
18	36	$^{24}Mg+^{12}C$ 0.6	$^{20}Ne+^{16}O$ 0.1	$^{20}Ne+^{16}O$ 4.7	$^{20}Ne+^{16}O$ 11.0
18	37		$^{25}Mg+^{12}C$ 0.3(*)	$^{21}Ne+^{16}O$ 1.8	$^{21}Ne+^{16}O$ 1.1
18	38		$^{26}Mg+^{12}C$ 0.9(*)	$^{22}Ne+^{16}O$ 3.4	$^{22}Ne+^{16}O$ 2.2
18	39			$^{22}Ne+^{17}O$ 0.0	$^{22}Ne+^{17}O$ 0.8
18	40		$^{26}Mg+^{14}C$ 0.8		$^{22}Ne+^{18}O$ 1.6
19	38		$^{24}Mg+^{14}N$ 0.3		
19	39	$^{27}Al+^{12}C$ 0.5	$^{27}Al+^{12}C$ 0.6(*)	$^{23}Na+^{16}O$ 1.2	$^{23}Na+^{16}O$ 2.3
19	41		$^{26}Mg+^{15}N$ 0.4	$^{26}Mg+^{15}N$ 1.1	
20	40	$^{28}Si+^{12}C$ 2.6	$^{28}Si+^{12}C$ 0.8(*)	$^{24}Mg+^{16}O$ 2.7	$^{24}Mg+^{16}O$ 0.7(*)
20	41	$^{29}Si+^{12}C$ 2.7	$^{29}Si+^{12}C$ 1.8	$^{25}Mg+^{16}O$ 1.9	$^{25}Mg+^{16}O$ 0.6(*)
20	42	$^{30}Si+^{12}C$ 1.9	$^{30}Si+^{12}C$ 1.2	$^{26}Mg+^{16}O$ 3.2	$^{26}Mg+^{16}O$ 0.7(*)
21	42				$^{22}Ne+^{22}Ne$ 1.6
21	43	$^{31}P+^{12}C$ 2.4	$^{31}P+^{12}C$ 0.7(*)	$^{27}Al+^{16}O$ 1.2	$^{27}Al+^{16}O$ 0.1(*)
21	45		$^{30}Si+^{15}N$ 0.2	$^{30}Si+^{15}N$ 0.7	$^{23}Na+^{22}Ne$ 1.7
22	44	$^{32}S+^{12}C$ 0.1(*)	$^{28}Si+^{16}O$ 1.7	$^{28}Si+^{16}O$ 2.8	$^{24}Mg+^{20}Ne$ 0.1
22	45	$^{33}S+^{12}C$ 0.3(*)	$^{29}Si+^{16}O$ 1.6	$^{29}Si+^{16}O$ 2.9	$^{29}Si+^{16}O$ 0.5(*)
22	46	$^{34}S+^{12}C$ 1.0	$^{30}Si+^{16}O$ 0.8	$^{30}Si+^{16}O$ 3.0	$^{24}Mg+^{22}Ne$ 0.0
22	47				$^{26}Mg+^{21}Ne$ 0.1(*)
22	48	$^{36}S+^{12}C$ 2.0	$^{36}S+^{12}C$ 0.2(*)		$^{26}Mg+^{22}Ne$ 2.5
22	49	$^{36}S+^{13}C$ 1.0	$^{36}S+^{13}C$ 0.5		
23	47	$^{35}Cl+^{12}C$ 0.5(*)	$^{31}P+^{16}O$ 1.4	$^{31}P+^{16}O$ 2.3	$^{24}Mg+^{23}Na$ 0.7
23	49	$^{37}Cl+^{12}C$ 1.2			
23	51	$^{36}S+^{15}N$ 0.4	$^{36}S+^{15}N$ 1.1		
24	48	$^{36}Ar+^{12}C$ 0.4(*)	$^{32}S+^{16}O$ 1.5	$^{28}Si+^{20}Ne$ 0.0(*)	$^{24}Mg+^{24}Mg$ 1.0
24	49		$^{33}S+^{16}O$ 1.4	$^{29}Si+^{20}Ne$ 0.1	$^{25}Mg+^{24}Mg$ 0.2
24	50	$^{38}Ar+^{12}C$ 0.9	$^{34}S+^{16}O$ 1.0	$^{34}S+^{16}O$ 0.6(*)	$^{26}Mg+^{24}Mg$ 0.9
24	51			$^{29}Si+^{22}Ne$ 0.3	$^{26}Mg+^{25}Mg$ 0.2
24	52		$^{36}S+^{16}O$ 1.4	$^{26}Mg+^{26}Mg$ 0.3	$^{26}Mg+^{26}Mg$ 1.0
24	53		$^{40}Ar+^{13}C$ 0.2(*)		
25	51	$^{39}K+^{12}C$ 1.3	$^{35}Cl+^{16}O$ 0.6	$^{27}Al+^{24}Mg$ 0.0	$^{27}Al+^{24}Mg$ 0.2
25	52	$^{40}K+^{12}C$ 0.5(*)		$^{29}Si+^{23}Na$ 0.6	$^{27}Al+^{23}Na$ 0.4

TABLE I. (Continued).

Z	A	l_c 15	20	30	40
25	53		$^{37}Cl+^{16}O$ 1.0	$^{30}Si+^{23}Na$ 0.2	$^{27}Al+^{26}Mg$ 0.3
26	52	$^{40}Ca+^{12}C$ 1.4	$^{36}Ar+^{16}O$ 0.4(*)	$^{28}Si+^{24}Mg$ 3.1	$^{28}Si+^{24}Mg$ 4.6
26	53			$^{28}Si+^{24}Mg$ 3.1	$^{28}Si+^{24}Mg$ 4.6
26	54		$^{38}Ar+^{16}O$ 1.3	$^{30}Si+^{24}Mg$ 0.2	$^{28}Si+^{26}Mg$ 0.1
26	55		$^{43}Ca+^{12}C$ 0.2(*)	$^{29}Si+^{26}Mg$ 0.7	$^{29}Si+^{26}Mg$ 0.8
26	56		$^{44}Ca+^{16}O$ 0.9(*)	$^{30}Si+^{26}Mg$ 2.9	$^{30}Si+^{26}Mg$ 3.6
26	58		$^{46}Ca+^{12}C$ 0.3(*)		
27	55		$^{39}K+^{16}O$ 1.3(*)	$^{28}Si+^{27}Al$ 0.6	$^{28}Si+^{27}Al$ 1.0
27	56		$^{40}K+^{16}O$ 0.4(*)	$^{29}Si+^{27}Al$ 0.7	$^{29}Si+^{27}Al$ 0.7
27	57		$^{45}Sc+^{12}C$ 0.7(*)	$^{30}Si+^{27}Al$ 0.8	$^{30}Si+^{27}Al$ 1.0
27	58			$^{30}Si+^{28}Al$ 0.8	$^{30}Si+^{28}Al$ 1.0
28	56		$^{28}Si+^{28}Si$ 1.1	$^{28}Si+^{28}Si$ 3.1	$^{28}Si+^{28}Si$ 3.7
28	57		$^{29}Si+^{28}Si$ 1.4	$^{29}Si+^{28}Si$ 3.1	$^{29}Si+^{28}Si$ 3.8
28	58		$^{46}Ti+^{12}C$ 0.6(*)	$^{30}Si+^{28}Si$ 2.1	$^{30}Si+^{28}Si$ 2.1
28	59		$^{47}Ti+^{12}C$ 0.9(*)	$^{30}Si+^{29}Si$ 2.0	$^{30}Si+^{29}Si$ 2.0
28	60		$^{48}Ti+^{12}C$ 0.9(*)	$^{30}Si+^{30}Si$ 2.7	$^{30}Si+^{30}Si$ 3.1
28	61		$^{49}Ti+^{12}C$ 1.7		
28	62		$^{50}Ti+^{12}C$ 2.9		
29	59		$^{31}P+^{28}Si$ 0.3	$^{31}P+^{28}Si$ 2.6	$^{31}P+^{28}Si$ 2.7
29	60			$^{31}P+^{29}Si$ 0.6	$^{31}P+^{29}Si$ 0.7
29	61			$^{31}P+^{30}Si$ 1.2	$^{31}P+^{30}Si$ 1.4
29	62		$^{50}V+^{12}C$ 1.7		
29	63		$^{51}V+^{12}C$ 2.5		
30	60			$^{32}S+^{28}Si$ 3.3	$^{32}S+^{28}Si$ 4.2
30	61			$^{33}S+^{28}Si$ 0.0(*)	$^{32}S+^{29}Si$ 1.1
30	62		$^{50}Cr+^{12}C$ 1.7	$^{34}S+^{28}Si$ 0.7	$^{34}S+^{28}Si$ 0.5
30	63			$^{34}S+^{29}Si$ 0.7	$^{34}S+^{29}Si$ 0.6
30	64		$^{52}Cr+^{12}C$ 2.4	$^{34}S+^{30}Si$ 2.6	$^{34}S+^{30}Si$ 2.8
30	65		$^{53}Cr+^{12}C$ 1.2		
30	66		$^{54}Cr+^{12}C$ 1.6	$^{36}S+^{30}Si$ 0.9	$^{36}S+^{30}Si$ 0.7
31	63			$^{35}Cl+^{28}Si$ 0.0	$^{32}S+^{31}P$ 0.3
31	64			$^{33}S+^{31}P$ 0.0	$^{33}S+^{31}P$ 0.2
31	65			$^{34}S+^{31}P$ 0.7	$^{34}S+^{31}P$ 0.8
31	67		$^{55}Mn+^{12}C$ 1.8		
32	64			$^{32}S+^{32}S$ 0.1	$^{32}S+^{32}S$ 0.5
32	65			$^{33}S+^{32}S$ 0.1	$^{32}S+^{32}S$ 0.4
32	66		$^{54}Fe+^{12}C$ 2.8	$^{38}Ar+^{28}Si$ 0.3	$^{34}S+^{32}S$ 0.2
32	67			$^{38}Ar+^{29}Si$ 0.2	$^{34}S+^{33}S$ 0.1
32	68		$^{56}Fe+^{12}C$ 2.0	$^{34}S+^{34}S$ 0.0	$^{34}S+^{34}S$ 0.7
32	69		$^{57}Fe+^{12}C$ 1.3	$^{53}Cr+^{16}O$ 0.8(*)	
32	70		$^{58}Fe+^{12}C$ 2.0	$^{54}Cr+^{16}O$ 0.5(*)	$^{36}S+^{34}S$ 1.4
32	72			$^{36}S+^{36}S$ 0.7	$^{36}S+^{36}S$ 2.1
33	67			$^{39}K+^{28}Si$ 0.5	$^{35}Cl+^{32}S$ 0.0
33	68				$^{39}K+^{29}Si$ 0.0(*)
33	69				$^{38}Ar+^{31}P$ 0.1(*)
33	71		$^{59}Co+^{12}C$ 1.5	$^{55}Mn+^{16}O$ 0.9(*)	$^{37}Cl+^{34}S$ 0.5
33	73			$^{58}Fe+^{15}N$ 0.8(*)	$^{37}Cl+^{36}S$ 1.1
34	70	$^{58}Ni+^{12}C$ 1.3	$^{58}Ni+^{12}C$ 1.4(*)	$^{54}Fe+^{16}O$ 2.3(*)	$^{38}Ar+^{32}S$ 0.3
34	71				$^{38}Ar+^{33}S$ 0.3
34	72	$^{60}Ni+^{12}C$ 0.7	$^{60}Ni+^{12}C$ 1.3(*)	$^{56}Fe+^{16}O$ 2.3(*)	$^{38}Ar+^{34}S$ 1.5
34	74	$^{62}Ni+^{12}C$ 0.1	$^{62}Ni+^{12}C$ 2.0	$^{58}Fe+^{16}O$ 1.8(*)	$^{44}Ca+^{30}Si$ 0.3(*)
34	76		$^{64}Ni+^{12}C$ 0.9	$^{50}Ti+^{26}Mg$ 1.1	$^{46}Ca+^{30}Si$ 0.0
35	73			$^{58}Ni+^{15}N$ 0.1(*)	$^{42}Ca+^{31}P$ 0.9
35	75	$^{63}Cu+^{12}C$ 0.6	$^{63}Cu+^{12}C$ 1.1(*)	$^{59}Co+^{16}O$ 1.2(*)	$^{38}Ar+^{37}Cl$ 0.8
35	77		$^{65}Cu+^{12}C$ 0.8(*)	$^{51}V+^{26}Mg$ 0.2	

of Table I.

As a result of the many possible refinements left aside in the calculations it is not possible to claim that systems that do not appear in Table I will not present resonance behavior. Nevertheless, we can note that cases where the effect is found to be much smaller or barely observed at all ($^{10}B+^{13}C$,[17] $^{9}Be+^{28}Si$,[1] $^{13}C+^{28}Si$,[4] $^{18}O+^{28}Si$,[1,4] $^{11}B+^{40}Ca$,[18] or $^{16}O+^{58}Ni$[10]) do not correspond to minima (Table I).

Two cases have been found that exhibit the effect and do not appear in Table I: $^{12}C+^{20}Ne$ (Ref. 5) and $^{16}O+^{40}Ca$ (Ref. 10 and Kubono *et al.*[19]). They come, respectively, second to the reactions $^{16}O+^{16}O$ and $^{28}Si+^{28}Si$ which are then the only open transfer channels for each case.

More interesting and challenging is the prediction of many reactions still not studied experimentally that according to Table I should present "orbiting." It is even possible that some related observations, as the resonant structures in alpha transfer reactions and the absence of effects in two-nucleon transfer reactions, could be also understood on the basis of similar total-energy considerations.

Helpful discussions with Professor B. Bayman, Dr. D. DiGregorio, and D. A. Pacheco are gratefully acknowledged.

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