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Persistent success of the orbiting cluster model of heavy-ion resonances

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The orbiting cluster model is applied to the basic presently available data on resonances in heavy-ion-induced reactions. The model is shown to correctly predict the presence of resonances and give a good overall agreement with the measured resonance energies.

Since their discovery in the early 1960s,[1] resonances in heavy-ion reactions (RHIR) have been intensively investigated in order to determine their physical nature. A remarkable quantity of experimental data has been thus collected, stimulating the development of models capable of answering to the two main questions. (1) Why are RHIR present in some composite systems whereas they are absent in others? (2) What are the physical quantities in terms of which resonance properties such as energy and angular momentum can be calculated?

Among the phenomenological models, the orbiting cluster model of resonances[2] (OCM) was an attempt to give an answer to these questions on the basis of the data available at the time of its formulation.[3] This answer was, then, rather satisfactory: All the known resonances were successfully accounted for and the model clearly distinguished between systems where resonances were likely to be observed and those where they were not. Of course, due to its physical limitations, the model gave this information only [together with a simple prescription for the energy versus angular momentum sequence, see further, Eq. (2)]. Information such as the fragmentation of resonances or their width were beyond the scope of the model.

This was the situation in 1980. Since then, a wealth of information has been collected[4] and it is quite interesting to use it for an updated test of the predictive power of the model. Such a study should eloquently speak about the correctness of the basic assumptions of the model, at least in describing the principal features of the resonance phenomena. To this purpose, a comparison is shown in this paper between the 1980 predictions of the model[2] and the new data collected during the last decade.[5-26]

I shall start by recalling the basics of the OCM. This model pictures the RHIR as a structure phenomenon resulting from a prolonged rotation of the two colliding nuclei. Crucial for this rotation is the imaginary part of the potential between the two nuclei,

$$W = i\frac{\pi}{\hbar}|\langle cn \mid V \mid el\rangle|^2 \rho(E,L) \ . \qquad (1)$$

Neglecting the variation of the matrix element, the properties of the imaginary potential are determined by the level density of the composite system: Resonances will occur when this latter quantity has a minimum (no absorption, hence a long rotation and the creation of a long lived resonant state). This model is, thus, a simple one-parameter model with all the advantages (simplicity) and disadvantages (narrow scope) of such a picture. The energies of the resonant levels in the model are obviously given by the rotational sequence

$$E_x \ = \ E_0 \ + \ \frac{\hbar^2}{2\mathcal{J}} \ J(J+1) \ , \qquad (2)$$

where

$$\mathcal{J} = 1.044\{\tfrac{2}{5}(A_1^{5/3} + A_2^{5/3}) + [A_1A_2/(A_1 + A_2)](A_1^{1/3} + A_2^{1/3})^2\}r_0^2 10^{-44}\ \mathrm{MeV\,s^2} \qquad (3)$$

is the moment of inertia of two osculating nuclei with mass numbers A_1 and A_2. Also

$$E_0 = E_B + E_C \ ,$$

where E_B is the binding energy of the colliding nuclei in the composite system and

$$E_C = 1.21 Z_1 Z_2 [r_0(A_1^{1/3} + A_2^{1/3}) + 0.5]^{-1}\ \mathrm{MeV}$$

is the Coulomb energy. The parameter r_0 is usually taken as 1.3 fm.

The results are shown in Tables I and II. Table I lists all the composite systems and respective entrance channels for which resonances were either observed or predicted by the OCM as likely or possible. Column 3 lists the state of art in 1980, taken directly from Ref. 2; column 4 lists the state of art in 1990, i.e., with the experimental results of Refs. 5–26 added to the compilation. Resonances were observed and their energies and angular momenta determined in six more systems: ^{30}Si via ^{14}C+^{16}O (Refs. 5 and 6), ^{32}S via ^{16}O+^{16}O (Refs. 7–13), ^{32}S via ^{12}C+^{20}Ne (Ref. 14), ^{36}Ar via ^{16}O+^{20}Ne (Refs. 15 and 16), ^{44}Ti via ^{12}C+^{32}S (Ref. 17), and ^{56}Ni via ^{28}Si+^{28}Si (Ref. 18). All the above-mentioned systems were classified as "likely" in Ref. 2 (see column 3). In six more systems, ^{22}Na via ^{9}Be+^{13}C (Ref. 19), ^{27}Al via ^{12}C+^{15}N (Ref. 20), ^{29}Si

TABLE I. Resonance classification in the orbiting cluster model.

Composite system	Entrance channel	1980 classification	1990 classification	References
^{22}Na	^{9}Be+^{13}C	possible	indications	19
^{24}Mg	^{12}C+^{12}C	observed	observed	
^{27}Al	^{12}C+^{15}N	likely	indications	20
^{28}Si	^{12}C+^{16}O	observed	observed	
^{29}Si	^{13}C+^{16}O	likely	indications	21–23
^{30}Si	^{12}C+^{18}O	observed	observed	
^{30}Si	^{14}C+^{16}O	likely	observed	5,6
^{32}S	^{16}O+^{16}O	likely	observed	7–13
^{32}S	^{12}C+^{20}Ne	likely	observed	14
^{36}Ar	^{12}C+^{24}Mg	observed	observed	
^{36}Ar	^{16}O+^{20}Ne	likely	observed	15,16
^{38}K	^{10}B+^{28}Si	possible		
^{38}K	^{14}N+^{24}Mg	possible		
^{40}Ca	^{12}C+^{28}Si	observed	observed	
^{40}Ca	^{16}O+^{24}Mg	observed	observed	
^{44}Ti	^{12}C+^{32}S	likely	observed	17
^{44}Ti	^{16}O+^{28}Si	observed	observed	
^{54}Fe	^{12}C+^{42}Ca	likely		
^{56}Co	^{14}N+^{42}Ca	likely		
^{56}Ni	^{16}O+^{40}Ca	likely	indications	24
^{56}Ni	^{24}Mg+^{32}S	likely	indications	25
^{56}Ni	^{28}Si+^{28}Si	likely	observed	18
^{58}Ni	^{16}O+^{42}Ca	likely		
^{58}Ni	^{18}O+^{40}Ca	likely		
^{58}Ni	^{26}Mg+^{32}S	likely		
^{58}Ni	^{28}Si+^{30}Si	likely	indications	26

via ^{13}C+^{16}O (Refs. 21–23), ^{56}Ni via ^{16}O+^{40}Ca (Ref. 24) and via ^{24}Mg+^{32}S (Ref. 25), and ^{58}Ni via ^{28}Si+^{30}Si (Ref. 26), the presence of clear nonstatistical structures in the excitation functions was identified. These possible resonant states are labeled as "indications" in column 4 of Table I, since no firm identification of their angular momenta is presently available. Again, five out of these six systems were predicted in Ref. 2 as likely candidates for resonance observation; one (^{22}Na) was predicted as possible. Finally, no resonant behavior has ever been observed in any of the systems for which the OCM has given an unfavorable prediction.

Adding to the test of the predictive power of the OCM given in Table I, Table II compares the moments of inertia calculated using Eq. (3) and those extracted, with the help of Eq. (2), from the experimental E_x vs $J(J+1)$ plots of the new resonance data. The agreement is good for all the six systems for which resonances were observed in the last decade as it was the case with earlier known data.[2]

In conclusion, even though more refined and complete models of RHIR have been proposed in the meantime,[27–29] the basic validity of the orbiting cluster picture has been confirmed by the comparison of the model with the data that appeared in about a decade after its publication. Clearly, this validity only refers to its power of predicting the presence or absence of resonances in a given colliding system and their mean energy and angular momentum sequence. No finer details are within the scope of this model. Even this, however, may

TABLE II. Comparison between extracted and calculated moments of inertia.

Composite system	Entrance channel	$\mathcal{J}$ (10^{-42} MeV s^2) (extracted)	$\mathcal{J}$ (10^{-42} MeV s^2) (calculated)
^{30}Si	^{14}C+^{16}O	4.60	4.49
^{32}S	^{16}O+^{16}O	3.55	5.02
^{32}S	^{12}C+^{20}Ne	5.98	4.80
^{36}Ar	^{16}O+^{20}Ne	6.14	6.05
^{44}Ti	^{12}C+^{32}S	5.19	7.32
^{56}Ni	^{28}Si+^{28}Si	11.51	12.75

be important in the future: In fact, in a recent paper,[4] the OCM was used to predict the presence of resonances in medium-weight composite systems. These predictions need, of course, an experimental confirmation. If the OCM demonstrates its reliability in this zone of masses too, it may be expected to have another decade of success.

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