TIME FOR FORMATION OF THE COMPOUND NUCLEUS AND GAMMA RADIATION FROM INTERACTING NUCLEI

V. V. BABIKOV

Joint Institute for Nuclear Research

Submitted to JETP editor November 14, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **42**, 1244-1248 (May, 1962)

The main characteristics are found for the electromagnetic radiation from a composite system assumed to be composed of two incompletely coalesced nuclei and having a large angular momentum. Analysis of experimental data on γ radiation in reactions with heavy ions shows a qualitative agreement with the expected effects. The time for formation of the compound nucleus as a system which has reached complete equilibrium is estimated to be $\tau = 10^{-14}$—10^{-15} sec.

THE Bohr picture of the compound nucleus as an excited system which is in complete thermodynamic equilibrium has been checked in numerous experiments on irradiation of nuclei with light particles (p, n, d), and the times for formation have been estimated to be $\tau \sim 10^{-18}$ sec (cf., for example, [1]). An important feature of the interaction of heavy ions of medium energy ($\lesssim 10$ MeV/nucleon) with nuclei is the formation of systems with large angular momenta ($\sim 100\,\hbar$) when the centers of mass of the nuclei approach to within $R \sim 10^{-12}$ cm. [2] One naturally expects, and this is confirmed by computations on the liquid drop model (cf., for example, [3]), that the equilibrium shape of the compound system will be close to a highly prolate ellipsoid with its symmetry axis perpendicular to the axis of rotation. But such a system cannot be regarded as being already in thermodynamic equilibrium (i.e., a compound nucleus in Bohr's terminology) so long as the nuclei which compose it retain any individuality. In the present paper it is shown that the study of radiation during interaction of nuclei can clarify the question of the time of formation of the compound nucleus.

Because of the large values of the quantum numbers for the angular momentum ($l \sim 100$), we can treat the compound system as a classical system in rotation with a frequency $\omega = l\hbar/I$ (where I is the moment of inertia), the system consisting of two nuclei which are assumed to be incompletely coalesced. The important point is that if the system is incompletely fused, it will have an electric dipole moment in addition to its quadrupole moment.

Let us simplify the problem by assuming that the nuclei are point charges (Z_1e, Z_2e) with masses (A_1, A_2), which are at a fixed distance R_0 from one another. Reducing the problem to the motion of one point charge around the center of gravity, we get for the electric dipole and quadrupole moments of the systems

$$\mathbf{d} = e_d \mathbf{R}_0, \qquad e_d = e\,(Z_1A_2 - Z_2A_1)/(A_1 + A_2), \tag{1}$$

$$D_{\alpha\beta} = e_q\,(3R_\alpha^0 R_\beta^0 - R_0^2\delta_{\alpha\beta}),$$
$$e_q = e\,(Z_1A_2^2 + Z_2A_1^2)/(A_1 + A_2)^2. \tag{2}$$

Since the effective dipole charge of the system, e_d, is always small compared to the effective quadrupole charge ($e_d/e_q \sim 0.1$), because Z/A is almost the same for all nuclei, the intensities of dipole and quadrupole radiation are comparable, despite the small value of $\lambda\!\!\!^-/R \sim 0.1$.*

Rotation of the system with frequency ω_0 leads to dipole radiation (with energy $\hbar\omega_0$) and quadrupole radiation (with energy $2\hbar\omega_0$) having the following angular distributions (ϑ is the angle between the direction of the radiation and the angular momentum, cf. Fig. 1):

$$dW_d = (e_d^2 R_0^2 \omega_0^4/8\pi c^3)\,(1 + \cos^2\vartheta)\,d\Omega, \tag{3}$$

$$dW_q = (e_q^2 R_0^4 \omega_0^6/2\pi c^5)\,(1 - \cos^4\vartheta)\,d\Omega. \tag{4}$$

To compare the angular distributions (3) and (4) with experiment, one must average over all direc-

*As always, for a two-body system magnetic dipole radiation is absent if one neglects the effect of the radiation (damping). Electric and magnetic radiations of higher multipolarity are weak because of the smallness of the ratio of the system dimensions ($R_0 \sim 10^{-12}$ cm) to the wave length ($\lambda\!\!\!^- \sim 10^{-11}$ cm – cf. below).

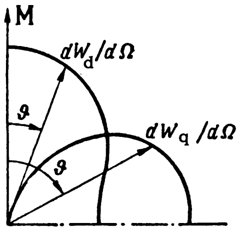

FIG. 1. Directivity diagram for intensities of dipole and quadrupole radiation of a compound system, relative to the angular momentum vector.

tions of the angular momentum in the plane perpendicular to the incident beam. As a result of such averaging one obtains (ϑ is the angle between the direction of the radiation and the incident particles, cf. Fig. 2)

$$dW_{\text{d}}(\omega_0, \vartheta) = (e_{\text{d}}^2 R_0^2 \omega_0^4 / 8\pi c^3)(1 + \tfrac{1}{2}\sin^2\vartheta)\, d\Omega, \quad (5)$$

$$dW_{\text{q}}(2\omega_0, \vartheta) = (e_{\text{q}}^2 R_0^4 \omega_0^6 / 2\pi c^5)(1 - \tfrac{3}{8}\sin^4\vartheta)\, d\Omega. \quad (6)$$

From the results found on the hypothesis of incomplete fusion of the colliding nuclei, one can make the following assertions:

a) There should be symmetry around 90° of the anisotropic radiation given by formulas (5) and (6), and the spectrum at angles 0° and 180° should be harder than at 90°, since the quadrupole radiation is twice as energetic as the dipole radiation.

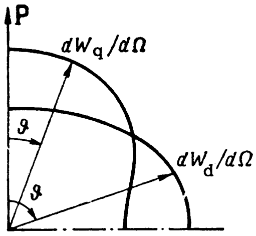

FIG. 2. Directivity diagram for intensities of dipole and quadrupole radiation from a target, relative to the direction of the momentum of the incident particles.

b) Increasing the angular momentum of the system consisting of a pair of nuclei with a fixed total energy should reduce the fusion of the nuclei and consequently result in an increased dipole moment of the system. This in turn leads to a softening of the radiation at 90° compared to that at 0°, although the radiation will actually be somewhat harder because of the increased radiation frequency.

c) For interaction of identical nuclei, there will be no dipole radiation, so one should observe no change in the hardness of the radiation as a function of the angle of observation.

The experimental data on γ radiation in reactions with heavy ions [5,6] show that this increase in hardness of the radiation at small angles actually occurs. The large spread in angular momenta of the composite system for the thick targets used in these experiments and the resultant broad energy distribution of the γ quanta permit only a rough separation of the parts of the spectrum corresponding to dipole and quadrupole radiation. If one assumes that the maximum in the distribution at 90° in the soft part of the spectrum corresponds to dipole radiation from compound systems which have the most probable value of the angular momentum, and that the radiation with twice as large an energy is mainly quadrupole radiation from these same systems, one can make a comparison of the expected and observed anisotropies. The total anisotropy, integrated over the whole spectrum, gives an indication of the relative magnitudes of the dipole and quadrupole moments of the compound systems. In Tables I and II we give a comparison of the ratios of spectral and total intensities at various angles, computed using formulas (5) and (6), with the values found experimentally.

In view of the large experimental errors in the determination of the quantities given in the tables and the great simplifications made in the theoretical treatment, one should not attribute great sig-

Table I

System		Cu+O	Te+C	V+C
		$\varepsilon_\gamma = 0.25$ MeV, $\vartheta_1 = 115°$, $\vartheta_2 = 20°$, $E_i{}^* = 95$ MeV	$\varepsilon_\gamma = 0.6$ MeV, $\vartheta_1 = 90°$, $\vartheta_2 = 45°$, $E_i{}^* = 115$ MeV	$\varepsilon_\gamma = 0.6$ MeV, $\vartheta_1 = 90°$, $\vartheta_2 = 45°$, $E_i{}^* = 58$ MeV
$\dfrac{dW(\varepsilon_\gamma, \vartheta_1)}{dW(\varepsilon_\gamma, \vartheta_2)}$	theor.	1.33	1.2	1.2
	expt.	1.1	1.5	1.6
$\dfrac{dW(2\varepsilon_\gamma, \vartheta_1)}{dW(2\varepsilon_\gamma, \vartheta_2)}$	theor.	0.75	0.69	0.69
	expt.	0.74	0.7	0.7
$\dfrac{dW(\vartheta_1)}{dW(\vartheta_2)}$	theor., dip. rad.	1.33	1.2	1.2
	theor., quad. rad.	0.75	0.69	0.69
	expt.	—	1.2	0.86
e_{d}		0.69	1.1	0.48
e_{q}		5.5	5.8	4.7

*E_i is the ion energy.

Table II

System	α-particle energy, MeV	$dW\,(90°)/dW\,(45°)$ theory, dip. rad.	theory, quad. rad.	expt.	e_d	e_q
Ba+α	45	1.2	0.69	0.70	0.37	2.5
Ho+α	45	1.2	0.69	0.69	0.37	2.5
Ta+α	45	1.2	0.69	0.65	0.38	2.5
Co+α	45	1.2	0.69	0.78	0.16	2.0

nificance to the close agreement of some of the numbers. But one can assert that the model of a composite system having an electric dipole moment, i.e., not yet in complete thermodynamic equilibrium, gives a qualitative understanding of the main features of the radiation—its angular and spectral distributions. From a comparison of the total radiation intensities at angles of 90° and 45° one concludes that the system Te + C has a sizable dipole moment, so that the dipole radiation predominates, while the system V + C has approximately equal intensities of dipole and quadrupole radiation. The large dipole moment of the Te + C system is apparently explained by the comparatively large effective dipole charge computed from (1) ($e_d = 1.1$), and the abovementioned increase of the dipole moment with increasing l (the average angular momentum is $\bar{l} = 38$[16]). The smaller value of the angular momentum ($\bar{l} = 16$) and the relatively small dipole charge ($e_d = 0.48$) of the system V + C results in an increase of the intensity of quadrupole radiation compared to the Te + C reaction.

In a similar way the smallness of the angular momentum of the compound systems formed in reactions with α particles can explain the predominant role of the quadrupole radiation (cf. Table II). This is reflected in the angular distributions[6] of the γ radiation. Only one of the angular distributions shows the characteristic increased hardness of the radiation at 45° compared to that at 90°, which is observed in heavy ion reactions. The only exception is the system Co + α, and possibly Ba + α, for which, because of the small mass of the composite system (and the resulting smaller moment of inertia), the effect of the angular momentum is increased, which reduces the fusion of the constituents, so that one may expect a somewhat increased dipole radiation.

If we include the fact that the nuclei can carry out small oscillations about the equilibrium position R_0 with a frequency ω large compared to the rotation frequency ω_0,

$$R = R_0 (1 + \alpha \cos \omega t), \qquad \alpha \ll 1, \qquad \omega \gg \omega_0, \tag{7}$$

these oscillations will have little effect on the rotation spectrum, but one will observe dipole radiation with frequency ω and with a radiation intensity per unit solid angle with the same anisotropy as (5)*

$$dW = (e_d^2 R_0^2 \alpha^2 \omega^4 / 8\pi c^3)\ (1 + \tfrac{1}{2} \sin^2 \vartheta)\, d\Omega. \tag{8}$$

Experiment[6] shows that there apparently is such radiation in the region $\hbar\omega \sim 3$ MeV; its intensity is larger the greater the expected dipole moment of the system. It appears more weakly in reactions with α particles than in reactions with carbon ions. By comparing the radiation intensities at energies $\epsilon_\gamma = 0.6$ MeV and $\epsilon_\gamma = 3$ MeV and assuming that they are determined by the dipole radiation from the same system, one can conclude that the oscillation amplitude is actually small, $\alpha \sim 0.1$.

Since the angular momentum is the main factor which prevents complete coalescence of the nuclei, the time for formation of the compound nucleus can be taken to be the time for deexcitation of the angular momentum of the system through electromagnetic radiation (radiation damping). The change in the angular momentum M of a charge moving in a circle with frequency ω and radiating an intensity W is

$$\frac{d\mathbf{M}}{dt} = \mathbf{R} \times \frac{d\mathbf{p}}{dt} = -\frac{W}{\omega} \frac{\mathbf{M}}{|\mathbf{M}|},$$

so that the duration of the radiation is $\tau \sim l\hbar\omega/W$.

Taking the values (appropriate for the Te + C system) $l = 40$, $\omega = 10^{21}\ \mathrm{sec}^{-1}$, $R = 0.7 \times 10^{-12}$ cm, $W = 2e_d^2 R^2 \omega^4 / 3c^3 = 2 \times 10^{15}$ MeV/sec, we get $\tau = 1 \times 10^{-14}$ sec. Including the quadrupole radiation may reduce this value somewhat.

Thus one should assume that the times for formation in reactions with heavy ions of a compound nucleus in complete equilibrium are of the order of $\tau \sim 10^{-14}$—10^{-15} sec., i.e., three to four orders of magnitude longer than in reactions with light particles.

It should be noted that we have considered only one of the possible mechanisms of γ radiation, namely the collective rotational and vibrational

*Including the finite dimensions of the vibrating nuclei can lead to quadrupole radiation with an intensity distribution having a minimum at 90° to the direction of the ion beam.

motions of a system having electric dipole and quadrupole moments. The treatment of single-nucleon transitions and the associated γ radiation is a problem of intrinsic theoretical interest, but this problem has not been studied well enough because of our poor knowledge of the mechanism for interaction of heavy ions with nuclei.

In conclusion we note that the success of computations of the elastic scattering of nitrogen ions by carbon and beryllium nuclei on the optical model [7] also points out the stability of nuclei during the process of interaction.

The author is grateful to Yu. Ts. Oganesyan for preparing the experimental data for publication and to B. N. Kalinkin for valuable discussion.

[1] T. Ericson, Advances in Physics **9**, 425 (1960).

[2] V. V. Babikov, JETP **38**, 274 (1960), Soviet Phys. JETP **11**, 198 (1960). T. D. Thomas, Phys. Rev. **116**, 703 (1959).

[3] R. Beringer and W. J. Knox, Phys. Rev. **121**, 1195 (1961).

[4] L. D. Landau and E. M. Lifshitz, Classical Theory of Fields, Pergamon, 1962.

[5] Oganesyan, Lobanov, Markov, and Flerov, preprint, Joint Inst. Nuc. Res., 1961.

[6] J. F. Mollenauer, preprint, Univ. Calif., 1961.

[7] R. H. Bassel and R. M. Drisko, Proc. Int. Conf. Nuclear Structure, Kingston, Canada, 1960.

Translated by M. Hamermesh
205