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Mechanism and Rate of Long-Range α-Particle Emission in Fission

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The statistical theory of fission has been used in previous works to calculate the energy and angular distributions of the long-range α particle emitted in fission. It is now applied to calculate the probability of long-range α-particle-accompanied fission relative to binary fission. For thermal-neutron fission of U^{235} the calculated rate is 1 α-particle-accompanied fission in 461 binary fissions, which agrees well with the experimental value of 1 in 449. Concerning the mechanism, the large amount of energy required (more than 24 MeV) to emit an α particle at the scission point comes mainly from the reduction of the Coulomb energy between the main fragments through an over-stretched form of deformation. The balance of energy shows that the total excitation energy in α-particle-accompanied fission is reduced by about 4.5 MeV compared with binary fission. According to the statistical theory this reduces the relative probability by several hundred fold.

In a recent paper[1] the energy and angular distributions of the long-range α particle (LRA) emitted in α-particle-accompanied fission (LRA fission) are studied by trajectory calculations based on initial conditions determined by the statistical theory of fission.[2] It was found that the most probable energy and angle of emission as functions of the mass ratio of the two main fragments obtained this way are in good agreement with experimental results.[3] This is considered to lend strong support to the statistical theory because of the sensitive dependence of the distribution curve on the initial conditions of the trajectory calculation. Vitta[4] extended the calculation and determined the dispersion of the energy and emission angle. He found that the dispersion of the scission configuration predicted by the statistical theory is sufficient to account for the dispersion of the energy of the α particle. Furthermore, reasonable agreement on angular dispersion may be obtained if it is assumed that the α particle is emitted a short time after scission, on the order of 3×10^{-22} sec, which is nearly instantaneous compared with the fission time – such an assumption has been made by other workers[5] and it does not compromise the statistical theory, for it deals with an affair after scission. Thus it seems that the energy and angular distributions of the LRA particle may be understood in terms of statistical theory. Still remains to be investigated whether the rate of LRA fission relative to binary fission can be accounted for by the statistical theory. This is the problem to be considered in this paper.

The experimental rate in the thermal-neutron fission of U^{235} is 1 LRA fission for 449 binary fissions.[6] A related problem is the mechanism of emission of the LRA particle. Experimental evidence shows that the LRA particle is created at the scission point at the moment of scission.[7] Halpern[8] estimated that to create an α particle at the scission point at the moment of scission from the nuclear matter of the fissioning system would require an amount of energy of about 28 MeV (5-MeV binding energy, 19-MeV potential energy, and 4-MeV kinetic energy; other authors have smaller estimates of the kinetic energy). He asked the question, how does the fissioning system obtain such a large amount of energy to make the emission possible. The total internal energy of the system (measured by prompt neutrons and γ rays) is only about 24 MeV.[2] Of this amount about $\frac{1}{2}$ is deformation energy.[2] The remaining $\frac{1}{2}$, the excitation energy of the two fragments, is much too small to meet the energy requirement of α emission.

According to the statistical theory the scission configuration is not unique in deformation shape but assumes a wide distribution. Each shape will occur with a relative probability determined by its statistical weight. In some of the more elongated deformation shapes, the potential energy of the two fragments is considerably decreased; the energy thus made available may be used to supply the potential energy for the creation of the α particle. The binding energy and kinetic energy of the α particle may be supplied from the excitation energy at the scission configuration. In fact, in the previous study[1] of the energy and angular distributions of the LRA particle, we have assumed a scission configuration which is similar to that of binary fission except that the two main fragments are not in contact but moved apart by 3.8 F to accommodate the α particle represented by a sphere of 3.8-F diam. Such a scission configuration describes the behavior of LRA fission well; in particular the total kinetic energy of the three particles is comparable to that of the two fragments in the corresponding binary fission, in agreement with experimental results, indicating that the potential energy of the α particle comes from the reduction of the potential energy of the two main fragments.

Halpern also has observed the relation between LRA fission and excessive elongation. On the other hand, from the statistical-theory point of view, there is no need to propose a specific mechanism that will lead to a specific configuration resulting in LRA fission – all possible scission configurations will occur with a probability determined by its statistical weight. Thus the only problem left is the calculation of the relative probability of the above-mentioned scission configuration that leads to LRA fission.

According to the statistical theory,[2] a scission configuration with a specific mass and charge division will occur with a relative probability P determined by the excitation energy E of the system at the scission point as follows:

$$P \sim E^{11/4}\{1-\tfrac{19}{4}[(a_1+a_2)E]^{-1/2}\}\exp\{2[(a_1+a_2)E]^{1/2}\}\ , \tag{1}$$

where a_1 and a_2 are the level-density parameters of the two fission fragments. This applies equally well to LRA fission because the LRA particle has only one quantum state. Thus our problem is focused on the value of the excitation energy. A calculation of the excitation energy based on first principles is not feasible. For our purpose we can take advantage of the available experimental information to obtain the values desired. The excitation energy equals the internal energy less the deformation energy of the two fragments, and the internal energy may be measured by the total energy of the prompt neutrons and prompt γ rays. According to Apalin *et al.*[9] the number of prompt neutrons emitted per fission in LRA fission is 1.77 ± 0.09 based on a value of 2.45 for this quantity in binary fission. The decrease of 0.68 prompt neutrons corresponds to a decrease of internal energy of 4.47 MeV calculated on the basis that each prompt neutron takes up an average binding energy of 5.38 MeV[10] and a kinetic energy of 1.2 MeV,[11] the energy of prompt γ rays being assumed to be the same in binary and LRA fission. In our model the deformation energies of the two main fragments in binary and LRA fission are about the same (this does not contradict our earlier statement that LRA fission is associated with excessive elongation and thus with larger deformation energy, because part of the larger deformation energy is used to create the α particle and the remaining part in this particular model of calculation may be about the same as the deformation energy in binary fission). Therefore we conclude that the excitation energy in LRA fission is less than that of binary fission by 4.47 MeV. The most probable excitation energy in binary fission E_b is estimated to be 13.1 MeV,[11] taking into consideration the more recent value of the prompt γ-ray energy. The most probable excitation energy in LRA fission E_t is thus 8.63 MeV. From these figures we calculate the relative probability of LRA to binary fission P_t/P_b according to the statistical theory by the following formula:

$$\frac{P_t}{P_b}=\frac{E_t^{\,11/4}\{1-\frac{19}{4}[(a_1'+a_2')E_t]^{-1/2}\}\exp\{2[(a_1'+a_2')E_t]^{1/2}\}}{E_b^{\,11/4}\{1-\frac{19}{4}[(a_1+a_2)E_b]^{-1/2}\}\exp\{2[(a_1+a_2)E_b]^{1/2}\}}\ , \tag{2}$$

where a_1' and a_2' are the level-density parameters of the two main fragments in the corresponding LRA fission. The values of a_1, a_2, a_1', a_2' are obtained according to Eq. (8) of Ref. 2. This way we obtain the ratio of 1 LRA fission to 461 binary fissions. The result agrees well with the experimental ratio of 1 to 449 ± 30.[6]

Some information is available to enable us to make an estimate in the case of spontaneous fission of Cf^{252}. Nardi and Fraenkel[12] reported the number of prompt neutrons in LRA fission in this case to be 3.11 ± 0.06 based on a figure of 3.71 for binary fission. The decrease in excitation energy is thus 4.10 MeV based on an average neutron-binding-energy value of 5.64 MeV.[10] On the other hand we have no definite information on the most probable excitation energy in binary fission. A very rough estimate is to take $\frac{1}{2}$ of the total internal energy, which may be estimated from the prompt-neutron and γ-ray energies to be about 32 MeV. The probability ratio thus calculated for spontaneous fission of Cf^{252} is 1 LRA fission to 149 binary fissions. The experimental value is 1 to 299 ± 18.[6] While no exact agreement is expected in this case, the fact that LRA fission is more frequent in spontaneous fission of Cf^{252} than in thermal-neutron fission of U^{235} seems to be related to the fact that the excitation energy in the case of Cf^{252} is higher than that in U^{235}.

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[1] P. Fong, Phys. Rev. C 2, 735 (1970).

[2] P. Fong, Phys. Rev. 56, 434 (1956).

[3] Z. Fraenkel, Phys. Rev. 156, 1283 (1967).

[4] P. B. Vitta, Ph.D. dissertation, Emory University, 1970 (unpublished).

[5] G. M. Raisbeck and T. D. Thomas, Phys. Rev. 172, 1272 (1968).

[6] R. A. Nobles, Phys. Rev. 126, 1508 (1962).

[7] S. T. Tsien, J. Phys. Radium 9, 6 (1948).

[8] I. Halpern, *Physics and Chemistry of Fission* (International Atomic Energy Agency, Vienna, Austria, 1965), Vol. 2, p. 369.

[9] V. F. Apalin, Yu. P. Dobrynin, V. P. Zakharova, I. E. Kutikov, and L. A. Mikaelyan, At. Energ. (USSR) 7, 375 (1959) [transl.: J. Nucl. Energy 13A, 86 (1960)].

[10] Calculated by the Wing-Fong mass formula [J. Wing and P. Fong, Phys. Rev. 136, B923 (1964)] based on the most probable charge values given by J. Wing and P. Fong, Phys. Rev. 157, 1038 (1967).

[11] P. Fong, *Statistical Theory of Nuclear Fission* (Gordon and Breach, New York City, 1969).

[12] E. Nardi and Z. Fraenkel, Phys. Rev. Letters 20, 1248 (1968).

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Investigation of the ^{207}Pb(α, d)^{209}Bi Reaction*

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Energy levels and differential cross sections for the ^{207}Pb(α,d)^{209}Bi reaction have been determined at an incident bombarding energy of 42 MeV. Two-nucleon distorted-wave Born-approximation (DWBA) analysis was performed for the ground and first excited levels of ^{209}Bi in order to obtain a normalization for the (α,d) and (d,α) reactions. The results of calculations using this normalization were compared with data for the 1.097-MeV 7^+ level of ^{48}Sc excited in the ^{50}Ti(d,α)^{48}Sc reaction and for the first excited state of ^{206}Tl excited in the ^{208}Pb(d,α)^{206}Tl reaction. This latter comparison confirmed an earlier agrument that cross sections to the low-lying ^{206}Tl levels are considerably enhanced over pure two-hole configuration estimates. The normalized DWBA was then used to study higher-lying two-particle–one-hole excited states in ^{209}Bi.

I. INTRODUCTION

Recent interest in the structure of nuclei near ^{208}Pb, as well as the growing interest in the two-nucleon transfer reactions, has led us to investigate the ^{207}Pb(α, d)^{209}Bi reaction. Neutron and proton stripping[1-3] and pickup[4] reactions, ^{208}Pb(t, d)-^{209}Pb, ^{208}Pb(^{3}He, d)^{209}Bi, ^{208}Pb(d, t)^{207}Pb, and ^{208}Pb-(d, ^{3}He)^{207}Tl, are all consistent with nearly unity spectroscopic factors for the ground and lowest-lying levels. In this work we use our knowledge of single-nucleon transfer reactions as a point of departure for studying the ^{207}Pb(α, d)^{209}Bi reaction. The purpose of this work is specifically to examine the quantitative aspects of the (α, d) or (d, α) reaction and not attempt to fit the shapes of angular distributions, particularly since it has already been shown[5] that one should not expect much structure in the angular distributions of (d, α) reactions when l mixture is allowed, as is the case for the ^{207}Pb(α, d)^{209}Bi reaction.

On the other hand, the ^{207}Pb(α, d)^{209}Bi reaction is ideally suited for studying the absolute cross-section predictions by distorted-wave Born approximation (DWBA). This is true because of the relative simplicity of both the initial target state and at least the ground and first few final excited states in the reaction. This can readily be seen by expressing the (α, d) one-step reaction cross section in the notation of Glendenning[6]:

$$\frac{d\sigma}{d\Omega}\propto\frac{2J_f+1}{2J_i+1}\sum_{LJM}\Big|\sum_{\gamma}\beta_{\gamma L l J}B^{M}_{\gamma L}\Big|^2\,, \qquad (1)$$

where J_i and J_f are the initial and final spins in the reaction; L, l, J, and M refer to the orbital, spin, total, and orbital-projection angular momentum quantum numbers of the transferred neutron-proton pair. The β_γ contains all the (shell-) model configuration amplitudes of initial and final states and related angular momentum coupling coefficients, while the amplitude $B^M_{\gamma L}$ is analogous to the similarly denoted amplitude[6] in the case of one-nucleon transfer reactions. The sum over L, J, and M is incoherent as in one-nucleon transfer reactions. On the other hand, the sum over β_γ is in effect a coherent sum over the configuration amplitudes including their sign. We attempt then to choose a reaction in which this coherent sum is effectively reduced to one term with unity configuration amplitudes. This implies a reaction in