lisions, and leaves the possibility of even more enhancement due to the existence of unobserved quark flavors. Nonetheless, the experimental difficulty in detecting Higgs bosons, even if they are copiously produced, remains formidable.

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[1] S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, in *Elementary Particle Physics*, edited by N. Swartholm (Almquist and Wiksells, Stockholm, 1968), p. 367.

[2] Evidence for the presence of a significant antiquark distribution in the proton comes primarily from neutrino and antineutrino data. See, for example, M. Holder *et al.*, Phys. Rev. Lett. 39, 433 (1977).

[3] H. Georgi and H. D. Politzer, Phys. Rev. D 14, 1829 (1976); S. Weinberg, Harvard University Report No. HUTP-77/A057 (to be published); H. D. Politzer, Nucl. Phys. B117, 397 (1976).

[4] F. Wilczek, Phys. Rev. Lett. 39, 1304 (1977).

[5] Explicitly, $N = \sum_Q I_Q|$, where

$$I_Q = 3\int_0^1 dx \int_0^{1-x} dy\,(1-4xy)[1-(xym_H^2/m_Q^2)]^{-1}.$$

See L. Resnick, M. K. Sundaresan, and P. J. S. Watson, Phys. Rev. D 8, 172 (1973). Fundamental fermions transforming according to higher representations of color SU(3) than triplets would also contribute to N if they exist and get their masses from the Higgs-boson vacuum expectation value.

[6] The glue fraction at small q^2 ($= 3.5\ \mathrm{GeV}^2$) $\sim 30\%$; see H. D. Politzer, Nucl. Phys. B122, 237 (1977). We are interested in F_G at $q^2 \sim m_H^2$. Equation (5) is roughly correct for large m_H.

[7] Y. Matveev *et al.*, Lett. Nuovo Cimento 7, 719 (1973); S. J. Brodsky and G. R. Farrar, Phys. Rev. Lett. 31, 1153 (1973).

[8] For a review of the phenomenology of Higgs particles, see J. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Nucl. Phys. B106, 292 (1976).

[9] S. W. Herb *et al.*, Phys. Rev. Lett. 39, 252 (1977); W. R. Innes *et al.*, Phys. Rev. Lett. 39, 1240, 1640(E) (1977).

Statistical Analysis of Preequilibrium α-Particle Spectra and Possible Local Heating

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It is shown that energy spectra of preequilibrium α-particle emission in ^{209}Bi + ^{14}N reactions are reproduced well by the statistical formula of Ericson when nuclear temperature is treated as a parameter depending on the emission angle. The resultant temperature shows monotonical decrease with increasing angles, indicating the cooling-down process of the associated composite system.

In reactions induced by heavy ions such as ^{12}C, ^{14}N, and ^{16}O at bombarding energies well above the Coulomb barrier, α particles are known to be emitted with large probability. The α-particle emission occurs predominantly in the forward direction with strong enhancement of the high-energy part when compared to an evaporation spectrum observed in compound reactions.[1,2] As a possible origin of such α-particle emission, Britt and Quinton[1] suggested the breakup of an incident projectile in an interaction with the surface of a target nucleus. A recent work of Inamura *et al.*[3] indicated that this reaction originates from initial channel spins localized just above the critical angular momentum for complete fusion. In other words, the relevant entrance angular momenta lie between those of the grazing collision and those of close collisions leading to rapid formation of a compound nucleus. This is a feature similar to deeply inelastic reactions, in which relaxation phenomena become important because of long interaction times.[4] This suggests the possibility of attributing the above α-particle emission to evaporation from a locally excited nuclear system recently proposed for preequilibrium phenomena by Weiner and Weström.[5]

In this Letter, the same phenomenon is shown to be significant even at low incident energies in the ^{209}Bi + ^{14}N reaction. We further present simple statistical analysis for the energy spectra following the idea of Ref. 5 and discuss possible energy relaxation process of a composite system in heavy-ion reactions.

A self-supporting ^{209}Bi target of about 1 mg/cm^2 thickness was bombarded with 85- and 95-MeV ^{14}N ions from the cyclotron at the Institute of Physical and Chemical Research. The following measurements were carried out. (i) Charged particles with $Z \lesssim 8$ detected with conventional counter telescopes were measured between 20° and 170°. (ii) Angular distributions of fission fragments were taken between 10° and 170° by detecting high-energy particles stopped within a thin (30 μm Si) ΔE counter. (iii) Cross sections for the production of heavy residual nuclei following fusion or fusionlike reactions such as (^{14}N, xn) and (^{14}N, αxn) were measured by detecting α decays of their ground states in-beam in the same way as described in Nomura *et al.*[6] More details will be described elsewhere.

The measured cross sections are summarized in Table I. The following points should be noted. (i) Fission is the almost exclusive mode of the deexcitation of the compound nucleus, neutron evaporation being unimportant. Since α-particle evaporation is far less probable than neutron in this mass region, we expect no significant contribution from the compound reaction to the observed α particles. (ii) The cross section for the emitted α particles is roughly equal to the sum of cross sections for heavy residual nuclei produced by (^{14}N, αxn) and (^{14}N, $2\alpha xn$) reactions, indicating that a possible composite system formed in this projectile-target combination fuses after emitting α particles and decays by neutron emission without fissioning.

The measured angular and energy distributions of α particles were transformed into those in the c.m. system under the assumption of a binary reaction, i.e., $^{209}\mathrm{Bi} + {}^{14}\mathrm{N} \to \alpha + {}^{219}\mathrm{Ra}$, which seems reasonable from the above-mentioned facts. The present angular distributions are similar to those reported by Britt and Quinton[1] in similar reactions at higher bombarding energies. The yield decreases rapidly with increasing angles up to around 70°, and still continues to decrease slowly at more backward angles; in particular, there is no such rise near 180° as expected from the compound reaction. A main difference between the present results and those reported in Ref. 1 is that we observed a small bump or shoulder near grazing angles at both incident energies, i.e., at around 100° (85 MeV) and 80° (95 MeV), where heavier ejectiles like B and C isotopes had clear peaks in their angular distributions. This suggests that the above bumps are due to direct α particle and/or ^{8}Be emission corresponding to ^{10}B and/or ^{6}Li transfer reactions. More details will be described elsewhere.

TABLE I. Summary of experimental cross sections.

	Cross section (mb) 85 MeV	 95 MeV
α particles	42 ± 6	(63) [a]
Other charged particles with $3 \leq Z \leq 8$	80 ± 10	Not measured
Fission	890 ± 65	1350 ± 100
(^{14}N, xn)	5 ± 1	3 ± 1
(^{14}N, αxn)	31 ± 3	49 ± 8
(^{14}N, $2\alpha xn$)	3 ± 1	3 ± 1

[a] The given value has a large error due to lack of statistics at forward angles.

The energy spectra at backward angles are peaked around 19–19.5 MeV and have nearly exponential tails toward high energies. They are similar to a spectrum expected from the evaporation process in the compound reaction. The forward spectra are very broad and apparently quite different from the evaporation spectrum. However, there still exist high-energy tails which also fall almost exponentially but very slowly, indicating high "nuclear temperature" of the associated system. It should be noted that the nuclear temperature is not necessarily independent of observed angles in the case of the preequilibrium emission.[5] We shall therefore analyze the experimental spectra $N(E_\alpha)$ by the following simple statistical formula of Ericson[7]:

$$N(E_\alpha) \propto E_\alpha \sigma_c(E_\alpha) \exp(-E_\alpha/T). \tag{1}$$

Here, E_α is the kinetic energy of an α particle, σ_c the inverse cross section, and T the nuclear temperature of the residual nucleus which is related to the usual level density parameter a and the averaged excitation energy U_{av} of the residual nucleus with $T^2 \simeq U_{\mathrm{av}}/a$. When the initial kinetic energy is fully converted to the excitation energy of the relevant system, U_{av} roughly amounts to 30 and 40 MeV in cases of 85 and 95 MeV incident energies, respectively. This is assumed throughout the present analysis.

Equation (1) assumes the spin-independent constant temperature. This may be justified because we are treating high excitation energies and relatively low angular momenta [the maximum spin estimated from the sharp cutoff approximation is $39\hbar$ (85 MeV) and $52\hbar$ (95 MeV)]. In fact, the spin-dependent temperature T_j defined by Williams and Thomas[8] as $T_j \simeq T[1 - E_{\mathrm{rot}}(j)/U_{\mathrm{av}}]^{1/2}$ is close to T provided the rotational energy $E_{\mathrm{rot}}(j)$ is calculated by the rigid-body moment of inertia.

As for $\sigma_c(E_\alpha)$, we used reaction cross sections calculated by Igo,[9] who showed the results as a function of E_α/B_α, where B_α is the barrier height of the optical potential used. A spherical nucleus is assumed in Ref. 9, in which $B_\alpha \simeq 21.5$ MeV. Equation (1) turned out to reproduce well the spectral shape at backward angles when T is taken to be a "compound-nucleus value" described later, but the calculated peak position is by 2–3 MeV higher than the experimental one. A similar discrepancy has been pointed out by Knox, Quniton, and Anderson[10] and was attributed to the nuclear distortion resulting in a smaller Coulomb barrier in average. In order to take this effect into account in the calculation of σ_c, we treat B_α as a parameter and assume, for simplicity, the same dependence of σ_c on E_α/B_α as in the case of a spherical nucleus. It turned out that all the observed spectra could be fitted excellently by Eq. (1) when we assume $B_\alpha = 19.5$ MeV and treat T as another fitting parameter. To show this, we plotted the quantity $N(E_\alpha)/E_\alpha\sigma_c(E_\alpha)$ vs E_α on a semilog scale, where $N(E_\alpha)$ were taken from experimental spectra. If Eq. (1) can reproduce the experiment, the resultant plot must be a straight line. This is indeed the case at all angles as seen in Fig. 1. The slope of a straight line at each angle gives the best value of nuclear temperature. The values of T thus obtained are shown in Fig. 2. The temperature decreases monotonically with increasing angles and almost reaches a compound-nucleus value expected from an energetically equilibrated system, which is calculated from $T^2 \simeq U_{\text{av}}/a$ and $a = A/9$ MeV^{-1} with $A = 219$. This value of a is rather arbitrarily chosen here but is believed to be close to the empirical value in this mass region.[11]

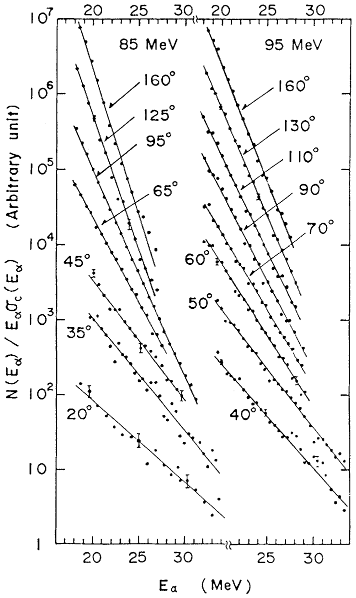

FIG. 1. Plot of $N(E_\alpha)/E_\alpha\sigma_c(E_\alpha)$ vs E_α, where $N(E_\alpha)$ are taken from experimental spectra in ^{209}Bi + ^{14}N reactions. The meaning of the relevant quantities is given in the text. The observed lab angles are indicated.

Weiner and Weström[5] have recently attempted to describe preequilibrium phenomena in terms of diffusion of heat in nuclear matter, starting from a "hot spot" created by a reaction at the nuclear surface. They have shown that evaporated particles from such a locally excited system are expected to show enhancement of high-energy parts in spectra and a large asymmetry in angular distributions. The present result seems to be consistent with this interpretation. Following the above idea, let us consider a possible local heating in the present case. Suppose a projectile captured by a shallow potential between projectile and target. It seems reasonable to assume that such a composite system is quickly heated at the contact point (hot spot) due to large radical frictional forces, but the relative angular momenta are transformed mainly to the rotation of the heavier nucleus (^{209}Bi in our case) due to its large moment of inertia. α particles are supposed to be emitted from this hot spot sitting on the surface of the rotating nucleus, but not from the other cold part of the system. This is consistent with the small effective Coulomb barrier deduced from the energy spectra. The emission occurs in the direction of the tangential velocity at the surface in average. Then, the emission angle can be related to the reaction time in the similar manner as suggested in deeply inelastic phenomena (the concept of negative deflection angle, for instance).[12] It seems therefore that

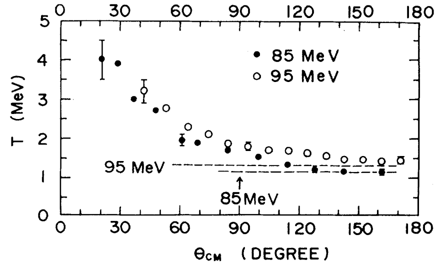

FIG. 2. Nuclear temperature T of the hot spot plotted vs the emission angles. The compound-nucleus values (see text) are given by dashed lines.

the nuclear temperature deduced from the present analysis can be interpreted to have physical significance, i.e., to show the degree of energy relaxation of a composite system versus the reaction time. The lowering of temperature is considered to be a consequence of nucleon-nucleon multiple scatterings.[5] The nuclear relaxation time estimated in Ref. 5 becomes about 5×10^{-21} sec in the present case when the temperature-averaged heat conductivity and specific heat are used. This is roughly equal to half a period of the rotational motion mentioned above, provided that the maximum angular momentum is transferred and a rigid-body moment of inertia is assumed, indicating the importance of the energy relaxation during rotation.

The above interpretation should be considered as a preliminary one. An essential point deduced from our analysis is that energy spectra of pre-equilibrium α particles are determined by penetrabilities and the level density of the residual nucleus. In other words, α particles are mainly emitted from an energetically relaxed composite system except the possible emission occurring at the grazing angle. A similar feature is known in deeply inelastic reactions.[13]

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[1] H. C. Britt and A. R. Quinton, Phys. Rev. 124, 877 (1961).

[2] J. Galin, B. Gatty, D. Guerreau, C. Rouusset, U. C. Schlotthauer-Voos, and X. Tarrago, Phys. Rev. C 9, 1126 (1974).

[3] T. Inamura, M. Ishihara, T. Fukuda, T. Shimoda, and K. Hiruta, Phys. Lett. 68B, 51 (1977).

[4] For instance, see W. Nörenberg, J. Phys. C 5, 141 (1976).

[5] R. Weiner and M. Weström, Phys. Rev. Lett. 34, 1523 (1975), and Nucl. Phys. A286, 282 (1977).

[6] T. Nomura, K. Hiruta, T. Inamura, and M. Odera, Nucl. Phys. A217, 253 (1973).

[7] T. Ericson, Adv. Phys. 9, 425 (1960).

[8] D. C. Williams and T. D. Thomas, Nucl. Phys. 53, 577 (1964).

[9] G. Igo, Phys. Rev. 115, 1665 (1959).

[10] W. J. Knox, A. R. Quinton, and C. E. Anderson, Phys. Rev. 120, 2120 (1960).

[11] T. D. Thomas, Annu. Rev. Nucl. Sci. 18, 343 (1968), and references therein.

[12] J. Wilczynski, Phys. Lett. 40B, 37 (1972).

[13] J. Galin, J. Phys. C 5, 83 (1976).

Theoretical Correlation between Energy Dissipation, Angular Momentum Transfer, and Charge Diffusion in Deep Inelastic Reactions

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The Z dependence of the orbital angular momentum transferred into the intrinsic spins of deep-inelastic collision partners is studied. The correlation between energy loss and nucleon transfer calculated by the present method is compared with that derived by previously proposed empirical methods. The currently used empirical approaches appear to be subject to serious systematic errors.

A central problem in the analysis of deep inelastic reactions is the determination of mass, charge, and angular distributions for individual angular momentum bins.[1-3] In principle, distributions can be derived by plotting the cross section $\partial^2\sigma/\partial Z\partial E_{K,\mathrm{tot}}$ in the charge vs total kinetic energy $(Z, E_{K,\mathrm{tot}})$ plane and drawing lines on this map corresponding to constant entrance-channel angular momenta (l). The resulting distributions as a function of l bin can then shed light on quantities such as the Fokker-Planck coefficients for describing the time dependence of the charge-asymmetry degree of freedom.[1] Two different empirical prescriptions for drawing the lines of constant l have been suggested. The first prescription[1,3] calls for the lines to be drawn at constant $E_{K,\mathrm{tot}}$, parallel to the Z axis. No physical reason has been given as to why the lines of constant l in this plane should exhibit such behavior. It is certainly not correct for the lowest-l waves, where the total kinetic energy of the fragments is expected to be dominated by the Coulomb energy of two touching fragments. This prescription has been widely used, perhaps because of its simplicity. In the second infrequently used prescription,[2] the lines of constant l are drawn parallel to