Nuclear Reactions at High Energies

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THE general features of the high energy nuclear reactions which have been observed at the Radiation Laboratory can be understood in terms of a picture which is in its main outlines quite simple, though quite different from the description appropriate at lower energies. In trying to understand what happens when a nucleus is bombarded by a high energy neutron or proton, the first consideration that comes to mind is that the collision time between the incident particle and a particle in the nucleus is short compared to the time between collisions of the particles in the nucleus. This suggests that the first step in the process can be regarded in terms of collisions between the incident particle and the individual nuclear particles. We are thus led to ask the properties of the high energy scattering between free nucleons. There are two salient points. First, the total cross section for scattering of one nucleon by another is inversely proportional to the energy of the incident particle. The mean free path of a nucleon traversing nuclear matter increases with its energy; at sufficiently high energies the nucleus begins to be transparent to the bombarding particles. Secondly, the incident particle loses only a small fraction of its energy to the struck one. The momentum transfer, which is nearly perpendicular to the direction of the incident particle, is of the order $\hbar/a$, where a is the range of nuclear forces, and does not increase with increasing energy. In case of an exchange collision, we continue to call the high energy emergent particle the incident one, even though it has changed its charge.

Since the momentum transfer, $\hbar/a$, is not large compared to the characteristic momentum, $\hbar/d$, of particles in the nucleus (with d the mean separation of nuclear particles), it is not true that the collisions made by the incident particle can be considered as collisions between free particles; interference between particles in the nucleus can be important. Such an interference effect can be expected because of the degeneracy of nuclear matter. If nuclear matter is represented as a degenerate Fermi gas, it is clear that collisions with small momentum transfers will be discouraged, since these tend to lead from an occupied state to another already occupied. An estimate of this effect indicates that as a result the mean free path of a high energy particle ($\sim$100 Mev) traversing nuclear matter will be increased over what would be expected for collisions between free particles by a factor of about 5/3. The mean kinetic energy transfer to the struck particle per collision is increased in the same ratio.

We estimate that the mean free path for a 100-Mev nucleon is about 4×10^{-13} cm, and the kinetic energy transfer to the struck particle is about 25 Mev. Since the mean free path is comparable to nuclear radii, one cannot describe what goes on in terms of formation of a compound nucleus. In fact, what happens will depend on the particular trajectory of the incident particle. If it happens to pass through the nucleus near its edge, it may make a single collision and emerge having lost only 25 Mev of its energy, possibly having changed from neutron to proton (or vice versa) as a result of an exchange collision. Or, if it strikes the center of the nucleus and has to pass through the full diameter, it may make several collisions, lose all its energy, and end its range still inside the nucleus. There are thus a variety of possibilities, ranging from the bombarding particle emerging with most of its energy intact to the loss of the entire incident energy to the nucleus.

Since the struck particles have much lower energy and shorter mean free path than the incident one, they can escape from the nucleus without further collisions only if the collision occurs near the edge of the nucleus with the struck particle heading outwards. In this case it may emerge with 15- or 20-Mev energy. Otherwise it will collide with other nuclear particles, the energy will be distributed over the nucleus, and the subsequent events can be described in terms of the usual evaporation model, the nuclear excitation energy being dissipated by successive boiling off of particles each with a few million volts of kinetic energy.

When the nucleus is bombarded with 200-Mev deuterons, or 400-Mev α-particles, the binding of the incident nucleons is important chiefly in causing a spatial correlation between them, and what goes on can be thought of in terms of a simultaneous bombardment by several individual nucleons.

The description we have given provides an explanation of several features of high energy reactions which have been observed at the Radiation Laboratory. Because of the wide distribution of excitation energies of the struck nucleus, one would expect a wide distribution of residual nuclei after the evaporation processes are complete; loss of a small number of particles should occur, as well as knocking out of many. This feature of high energy reactions has been reported by Seaborg, Perlman, and their collaborators.[1] Then we may ask about the excitation function of a particular reaction leading to a given residual nucleus. At low energies the reaction proceeds through formation of a compound nucleus. If we confine ourselves to this mechanism, the excitation function will go through a maximum when the excitation energy is most appropriate for evaporating the requisite number of particles, then will drop very rapidly as the energy gets higher because at higher excitation energy it is much more likely that more particles will evaporate. However, at high energies the mechanism of the reaction is different, because of the transparency of the nucleus; the reaction can occur through the incident particle carrying off a good fraction of its energy and giving the nucleus approximately the right excitation energy for the reaction in question. Since the probability of leaving a given excitation energy will be determined only by the mean free path, which varies slowly with the energy of the incident particle, we would expect the excitation function at high energies also to vary quite slowly. This has been confirmed in a number of cases.[2]

Finally, we should expect the transparency of nuclear matter to show up in measurements of the total cross section for absorption or scattering of the incident particle. It should be mentioned that the attenuation of the wave representing the incident particle in passing through the nucleus will give rise to diffraction scattering at small angles ($\theta \sim \hbar/Rp$, where R is the nuclear radius, p the momentum of the bombarding particle). The cross section for diffraction scattering is equal to the inelastic and absorption cross section; for good geometry attenuation measurements it just doubles the cross section. For 100-Mev neutrons, with a mean free path of 4×10^{-13} cm, one sees that for the heaviest elements one would expect a total cross section still close to $2\pi R^2$, but for light elements the cross section should drop considerably below this value. This is, in fact, true, as has been shown by experiments by Cork, McMillan, Peterson, and Sewell.

A number of more detailed calculations, based on the considerations given above, have been carried out by members of the theoretical group at this laboratory. Reasonably good agreement has been obtained with experimental results on the excitation curves and absolute cross sections of a few light element reactions, and on curves of star size *versus* frequency which have been measured by E. Gardner.[3] More detailed reports on this work will be published in the near future.

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[1] B. B. Cunningham, H. H. Hopkins, M. Lindner, D. R. Miller, P. R. O'Connor, I. Perlman, G. T. Seaborg, and R. C. Thompson, Phys. Rev. **72**, 739 (1947).

[2] W. Chupp and E. M. McMillan; R. Thornton and R. W. Senseman, to be published.

[3] Eugene Gardner, Phys. Rev. **72**, 743 (1947).