Invited talk given at the "Symposium on Heavy-Ion Physics from 10 to 200 MeV/AMU," Brookhaven National Laboratory, July 16-20, 1979.

Nuclear Collision at $E/A \approx \tau_F$*

J. Randrup

Nuclear Science Division
Lawrence Berkeley Laboratory
Berkeley, California 94720, U.S.A.

and

NORDITA
Blegdamsvej 17
DK-2100 Copenhagen
Denmark

1. Introduction

Nuclear beams with energies between 10 and 200 MeV per nucleon are now becoming available at several laboratories around the world. This development opens up the gate to a virtually virgin field of physics which might be called intermediate-energy nuclear physics. Nuclear collisions induced by such beams create a unique environment in which a number of novel phenomena are likely to occur. The exploration of this field will therefore undoubtedly prove a very rewarding venture.

In my contribution to this Symposium I wish to limit myself to nuclear collisions where the bombarding energy per nucleon is up to the order of the Fermi kinetic energy. The discussion will be

*This work was supported by the Nuclear Science Division of the U. S. Department of Energy under contract No. W-7405-ENG-48.

qualitative rather than quantitative, with the emphasis on the basic physics of the situation. Although part of what I will present has the character of speculation, so far unsupported by experiment or elaborate calculations, I hope that it will provide some stimulation for theorists as well as experimentalists.

2. The energy ladder

Let me start out by trying to put the energy region considered into the proper perspective in relation to other energy regions of nuclear physics. As the energy of the nuclear beams is steadily raised, a number of important thresholds are being passed. In the low end of the energy scale, where the characteristic energies are of the order of a few MeV, the fine details of the nuclear structure can be studied; this is the domain of nuclear spectroscopy. With increasing energy the individual quantum states lose their significance and the detailed structure of the intrinsic nuclear system largely dissolves.

When the energy has reached a few MeV per nucleon we are in the domain of strongly damped, or deep inelastic, collisions. In this regime, where the excitation per nucleon is still small in comparison with the intrinsic single-particle energies, the important degrees of freedom are a few macroscopic variables, particularly those associated with the nuclear surface. Since the macroscopic velocities are small in comparison with typical intrinsic speeds the communication of disturbances is rather fast and the corresponding macroscopic equations of motion are approximately local in time. The coupling of the macroscopic degrees of freedom to the structureless intrinsic reservoir

damps the macroscopic motion and is a source of dynamical fluctuations in these variables.

This situation will gradually change when the energy is raised further. When the macroscopic velocities are no longer small in comparison with the intrinsic speeds the intrinsic communication will require a non-negligible time and the retardation terms must be retained in the equations of motion. At the same time, inhomogeneities are likely to occur in the nuclear interior and additional degrees of freedom are activated.

An important threshold is probably reached when the excitation energy is of the same size as the nuclear binding energy. The nuclear system has then largely lost its cohesiveness and multifragmentation becomes increasingly dominant.

When the excitation energy per nucleon increases above the Fermi kinetic energy the quantal nature of the nucleons is expected to become less important and classical models gain increasing applicability. At the same time, the one-body mean field gives way to direct two-body collisions as the main governor of the nucleonic motion.

At still higher energies it becomes possible to produce pions by direct nucleon-nucleon collisions and we then enter into the mesonic regime. The basic microscopic degrees of freedom are now no longer conserved during the collision process.

The relativistic regime is reached when the kinetic energies are of the same order as the rest masses of the participating baryons. It is then possible to excite the intrinsic states of the baryon and the entire field merges more and more with elementary-particle physics.

One is presently contemplating nuclear beams with energies which are large in comparison with the rest masses. This regime of ultra-relativistic nuclear physics is still unexplored. There are speculations that sufficiently far into this domain the hadrons may "melt" and liberate their intrinsic constituents. They might then form an extended system of quark matter. The production of such an environment would clearly have a profound bearing on our fundamental understanding of nature.

3. The mean free path

The nucleons are fermions. This generally reduces the states accessible in a collision process. At densities and excitations typical of collisions with $E/A \approx T_F$ this effect may appreciably inhibit the occurence of direct nucleon-nucleon collisons. This is well known from the lower end of the energy scale where the action of the exclusion principle largely eliminates two-body collisions, leaving the one-body mean field as the dominant governor of the nucleonic motion. Since the choice of approximations is very dependent on the nucleon mean free path it would be useful to obtain a semi-quantitative estimate of this quantity over a broad range of situations. We have made such an attempt, as will be described in the following.

Consider a uniform system of nuclear matter with a given temperature τ. The distribution of nucleons in momentum space is then given by

$$P(\vec{p}) = (1 + e^{-(\varepsilon-\varepsilon_F)/\tau})^{-1} \tag{1}$$

as a consequence of the Fermi-Dirac statistics. Here ε is the energy of the nucleon and ε_F is the Fermi energy. We now imagine that a nucleon with momentum $\vec{p}_o = m\vec{v}_o$ is moving through the system. Its motion will be degraded as a consequence of two-body collisions with the nucleons in the medium. If there were no Pauli blocking of the final states, the collision rate of the intruder nucleon would be given by

$$\nu_o = \frac{v_o}{\lambda_o} = \int \frac{d\vec{p}}{h^3} \; f(\vec{p}) \; v_{rel} \sigma_{NN} \quad , \tag{2}$$

where λ_o is the corresponding mean free path. Here σ_{NN} is the collision cross section for two nucleons in free space with the same kinematical conditions and $_{rel}$ is their relative speed.

However, the probability that a given final momentum $\vec{p}'$ is available is reduced by the factor $\bar{f}(\vec{p}') = 1 - f(\vec{p}')$. Therefore, the actual collision rate is rather

$$\nu = \frac{v_o}{\lambda}$$

$$= \int \frac{d\vec{p}}{h^3} \; f(\vec{p}) \; v_{rel} \int d\Omega \; \bar{f}(\vec{p}'_o) \; \bar{f}(\vec{p}') \; \frac{d\sigma_{NN}}{d\Omega} \tag{3}$$

where $d\sigma_{NN}/d\Omega'$ is the diffferential collision cross section for the process $|\vec{p}_o \vec{p}) \rightarrow |\vec{p}_o' \vec{p}')$.

The occurrence of the blocking factors in the collision integral gives rise to a reduction in the actual collision rate and a corresponding increase of the mean free path between collisions. The exact size of this effect depends of course on the variation of $d\sigma_{NN}/d\Omega'$ with angle and energy as well as on the distribution of nucleons in the medium. An approximate indication of the effect can be obtained by assuming that the free nucleon-nucleon collisions are isotropic and energy-independent. The mean free path is then increased by the factor

$$\eta = \frac{\int d\vec{p} f(\vec{p})\ v_{rel} \int d\Omega' \bar{f}(\vec{p}_o')\ \bar{f}(\vec{p}')}{4\pi \int d\vec{p} f(\vec{p})\ v_{rel}\ d\Omega'} \tag{4}$$

We have calculated this factor as a function of the temperature τ of the medium and for different values of the incident energy T_o of the intruder nucleon. The result is shown in Fig. 1. In general η decreases when either τ or T_o is increased. It is noteworthy that even at rather large values of these two parameters η remains appreciably above unity. For example, for a particle in the Fermi surface ($T_o = T_F$) we find $\eta = 10$ even at a temperature of $\tau \approx 10$ MeV, and at $T_o = 2T_F$ (which would correspond to a physical approach energy of $T_{beam} = T_o - T_F - B \approx 30$ MeV) we still find an η-value of around 3. Since λ_o would be around 2 fm we expect the actual mean free path $\lambda = \eta\lambda_o$ to remain at least of the order of the nuclear radius in the domain considered. The figure is useful for gaining a

quick impression of the blocking effect in a given situation. The calculated result suggests that the exclusion principle remains effective even at rather large temperatures and energies. The nucleons should therefore not be treated as classical particles.

4. Nuclear dynamics at moderate excitation

When the excitation energy per nucleon is small in comparison with the intrinsic kinetic energies the dynamics of the nuclear system can be discussed in terms of a few macroscopic degrees of freedom ζ, such as those associated with the shape. The remaining degrees of freedom play a rather passive role and may be described statistically in terms of a temperature τ. The temporal evolution of the macroscopic variables in governed by the Lagrange-Rayleigh equations of motion,

$$\frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{\zeta}} - \frac{\partial \mathcal{L}}{\partial \zeta} = \frac{\partial \mathcal{F}}{\partial \dot{\zeta}} \tag{5}$$

where $\mathcal{L}$ is the macroscopic lagrangian and $\mathcal{F}$ is the Rayleigh dissipation function governing the damping of the macroscopic motion due to the coupling to the intrinsic system. We have reason to expect that this damping is relatively strong, possibly dominant.[1] This expectation can be easily argued for in the low-energy limit where the nucleon mean free path is long. However, it is worth noting that at higher energies where direct two-body collisions are frequent it is still to be expected that the nucleon dynamics is strongly damped.[1]

Because the macroscopic variables are coupled to the intrinsic thermal system their dynamical evolution is not deterministic but

stochastic. A dynamical equation of the above type can therefore only be expected to describe a mean trajectory in the macroscopic coordinate space. The statistical fluctuations inherent in the thermal reservoir will given rise to stochastic excursions away from the mean trajectory. It is therefore necessary to deal with the probability distribution $P(\zeta;\ )$. The dynamics can then be discussed within the framework of transport theory. In the simplest Fokker-Planck approximation the equation of motion takes on the form

$$\frac{\partial}{\partial t} P = - \frac{\partial}{\partial \zeta} V P + \frac{\partial^2}{\partial \zeta^2} D P \tag{6}$$

Here V is the drift coefficient vector which governs the average motion of the centroid and D is the diffusion coefficient tensor which determines the accumulated dispersions in the macroscopic variables. It is these transport coefficients that characterize the dynamical properties of the nuclear system.

Let us now specialize to the collision of two nuclei A and B. When sufficiently close they may communicate by way of transferring nucleons. This mechanism appears to be an important, if not dominant, agency for the dissipation of the relative motion in the rather well-studied low-energy collisions. The transfer of an individual nucleon creates a particle-hole type excitation of the intrinsic nuclear system. It can be shown that the energy of this excition amounts to approximately $\omega = F - \vec{U}\cdot\vec{p}$ for a transfer from B to A. Here $F = \epsilon_B - \epsilon_A$ is the difference between the Fermi levels in the two

nuclei; it provides the static driving force for particle transfer. Furthermore, $\vec{U} = \vec{U}_A - \vec{U}_B$ is the relative velocity of the two nuclear regions between which the transfer takes place. Finally, $\vec{p} = \frac{1}{2} m(\vec{v}_a + \vec{v}_b)$ where $\vec{v}_a$ is the velocity of the nucleon relative to A and $\vec{v}_b$ is its velocity relative to B. Since it is the nucleons in the Fermi surface which are most readily transferred (due to the exclusion principle) we have $p \approx P_F$ and the second term $\vec{U}\cdot\vec{p}$ can be appreciable. (For example, if $\frac{1}{2} mU^2 = 2$ MeV we have $UP_F \approx 16$ MeV and if $\frac{1}{2} mU^2 = 8$ MeV we have $UP_F = 32$ MeV.) It is therefore clear that the transfer of nucleons can be very effective in damping the relative nuclear motion.

It is possible to derive a transport theory for nuclear collisions on the basis of the nucleon-transfer mechanism.[2] The general expressions for the transport coefficients entering into the Fokker-Planck equation (6) are given by

$$v_\zeta = \sigma \int \frac{d\vec{p}}{h^3} \frac{|v_n|}{2} \left[\bar{f}^A(\vec{p})\, f^B(\vec{p}) - f^A(\vec{p})\, \bar{f}^B(\vec{p}) \right] (\vec{p})$$

$$2D_{\zeta_1\zeta_2} = \sigma \int \frac{d\vec{p}}{h^3} \frac{|v_n|}{2} \left[\bar{f}^A f^B + f^A \bar{f}^B \right] \zeta_1(\vec{p})\, \zeta_2(\vec{p}) \qquad (7)$$

if the transfers occur over a plane contact surface of area σ. The transfer rate is taken to be proportional to v_n, the velocity component normal to the contact surface, as suggested by classical considerations. The dinuclear macroscopic variables ζ include the proton and neutron numbers of the two nucleides, their relative separation

and (radial and angular) momentum, their intrinsic angular momenta, and their intrinsic excitation. In the derivation of the above transport coefficients it is an essential assumption that the excitons created by the individual nucleon transfers are quickly dissipated into more complicated excitations so that the intrinsic nucleonic system remains in quasi-equilibrium throughout the collision; on grounds of the relatively long mean free path it is also assumed that the interior of the nucleus remains homogeneous. At relatively low energies, these assumptions are rather well justified. The theory then makes a number of general predictions about the correlations between the various observables.

But as the energy is raised those assumptions are expected to break down. The tacit assumption that the transferred nucleon is absorbed by its new host nucleus need no longer be generally valid; in the next section we shall discuss the possibility that transferred nucleons under favorable circumstances may be rejected promptly from the dinuclear complex. Furthermore, with the faster macroscopic motion the microscopic relaxation process can no longer be considered as instantaneous and the dynamical description in terms of time-local macroscopic equations of motion becomes dubious. By the same token the assumption of a quasi-equilibrated intrinsic system grows increasingly inadequate and one needs to include additional degrees of freedom describing inhomogeneities in the nuclear interior.

5. Promptly emitted particles

As mentioned earlier, it is usually a tacit assumption that a transferred nucleon is quickly assimilated in its new host. However, and this is particularly true at higher bombarding energies, the equilibration process may be aborted before completion, leading to the prompt emission of one or several particles. Such prompt ejectiles may teach us about the non-equilibrium properties of nuclei, and in particular, carry information on the early collision stage. It is therefore important to study in more detail the further fate of the transferred nucleons.

5.1 Fermi jets

The particle-hole excitation created by the transfer of a nucleon has a very special structure: it consists of a hole left behind in the down nucleus A, say, and a particle moving through the recipient nucleus B. The velocity of the intruder nucleon follows from the kinematics of the situation,

$$\vec{v}_b = \vec{v}_a + \vec{U} \tag{8}$$

Here $\vec{v}_a$ is the velocity of the nucleon as seen from A and $\vec{v}_b$ its velocity as seen from B; $\vec{U}$ is the velocity of A relative to B.

At moderately low excitation the intruder nucleon will proceed relatively uninhibited by two-body collisions, due to the action of the exclusion principle. It is then the bouncing around of the nucleon in the one-body nuclear container which provides the mecha

for bringing the nucleon into equilibrium with the other nucleons. However, under special kinematical circumstances the nuclear potential, which has only a finite height, will not be able to reflect the nucleon which may thus escape. One may appreciate that such a process is indeed energetically possible by recalling that the kinetic energy of the intruder nucleon, as seen from the host nucleus, is boosted by an amount which is of the order of UP_F. Therefore, when the relative radial nuclear velocity is sufficiently large, a transferred nucleon may be transmitted right across the recipient nucleus and emerge on the opposite side as an energetic ejectile. Since this phenomenon is a consequence of the kinematical coupling of the relative nuclear motion and the intrinsic nucleonic Fermi motion it has been called a "Fermi jet", although only one or a few nucleons can be ejected in a given collision. The Fermi jets form a subclass of Promptly Emitted Particles (so called PEPs) which refer to all light particles emitted at the early stage of a nuclear collision, whatever may be their production mechanism.

The Fermi-jet nucleons appear in a rather well-collimated angular region on the sides opposite to the interaction zone between the two nuclei. As time progresses, the dinuclear complex swings around and the relative motion is gradually degraded. The jets therefore appear in a narrow band in angle-energy space, a feature which should help in identifying the phenomenon experimentally. An extensive theoretical study of the Fermi jet mechanism has been carried out by Robel.[3] An independent investigation has been made by Bondorf _et al._[4,5]

5.2 Two-body collisions

Although fairly long, the nucleon mean free path can not be considered as infinite. In fact, in typical situations it is known to be of the same order as the nuclear size. This fact has an impact on the Fermi jets since the transmission of the transferred nucleons is thus obscurred. One may attempt to take account of this effect by assuming that the degradation of the nucleonic motion is dominantly due to two-body collisions. At the end of its free path the nucleon then collides with another one from the host nucleus, resulting in the creation of two quasi-free nucleons. Each of these may now propagate onward and possibly escape when reaching the surface. Such secondary ejectiles have been called two-body PEPs as opposed to the one-body Fermi-jet PEPs discussed above.[5] The angular distribution of the two-body PEPs will be distinctly different from that of the one-body PEPs: they are in general aimed more sidewards than the predominantly forward-backward directed Fermi jets. This characteristics is the combined effect of the geometrical features of the distribution of the nucleons, in coordinate and momentum space.

As an illustration we show in Fig. 2 the calculated distribution of promptly emitted neutrons from the collision of 152 MeV ^{12}C with ^{158}Gd.[5] One-body as well as two-body PEPs have been included; the total contribution of the two-body PEPs is around 30%. The bump around $\theta \approx 110^{o}$ appearing at E_n = 11 MeV results almost exclusively from the backward PEPs (i.e., those originating in the target and transmitted through the projectile, in the direction

opposite to the beam direction). The theoretical calculation is based on a statis- tical (Monte Carlo) method in which the fate of many individual nucleons are followed while the dinucleus evolves along an average dynamical trajectory (determined from an equation of the form (4)).

As the energy is increased, the two-body collisions will grow increasingly dominant and the Fermi-jet nucleons will give way to nucleons which are emitted after one or several collisions. The relative importance of the one- and two-body PEPs is illustrated in Fig. 3 for the C + Gd case.[5]

5.3 Hot spots?

When the nucleon mean free path λ is of the order of the nuclear radius R additional degrees of freedom are activated and the nuclear interior no longer remains homogeneous. Although the general expressions for the transfer of energy and momentum may still hold, it is now necessary to also consider the dynamics of the subsequent deposition of these quantities.

When $\lambda \approx R$ there is a large probability than an intruder nucleon will suffer its first collision in the front part of the recipient nucleus. If the flux of intruders is sufficiently high in comparison with the rate at which the local excitation resulting from the two-body collision is being dispersed the subsequent intruders will encounter an extra hot zone upon entering. Since the local mean free path is then diminished, they are therefore more likely to suffer an early collision. We are thus dealing with a self-amplifying process

by which the deposition of the intruders' energy in the front part of the host will produce an intransparent region: there will be a sudden phase transition where a relatively cold and transparent medium locally develops a hot and opaque zone. A hot spot has been formed.

Whether such a phenomenon will indeed occur is still an open question. After having indicated, the main line of argument in favor of it I would like to add a few words to the contrary: Although substantially reduced, the mean free path is still quite long, even at fairly high temperatures, if Fig. 1 can be trusted. Since one can hardly speak of a thermalized region with a size less than one mean free path the term "spot" appears somewhat misleading since it would occupy a sizable fraction of the nuclear volume. The size of possible temperature gradients occurring in the system is therefore severely limited and one ought to be very cautious about applying ordinary thermal-conduction theory.

6. Multifragmentation

When the beam energy per nucleon is of the same order as the Fermi kinetic energy the energy available for intrinsic excitation is comparable to the total nuclear binding energy. Hence, in principle, it would be energetically possible to totally dissemble the colliding nuclei into their nucleon constituents.

In such a situation the character of the nuclear system is profoundly altered. Rather than dealing with a dynamical situation dominated by two large nucleides, we are now faced with a competition between a large number of widely different fragmentations.

In the ordinary approach to nuclear dyanamics the system considered is described in terms of a relatively small number of marcroscopic degrees of freedom; in the exit channel these degrees of freedom describe a definite number of fragments, in various states of intrinsic excitation. Within such a framework we are now in the novel situation that the number of macroscopic variables to be dealt with is no longer an approximately conserved quantity. Quite to the contrary, macroscopic degrees of freedom can be created and destroyed in the course of the dynamical evolution as the system fluctuates back and forth between its different accessible fragmentations, ranging from a few hot or fast to many cold and slow fragments.

The theoretical methods presently in use for nuclear dynamics are inadequate for treating such a more complex phenomenon and there is a clear need for substantial formal development before a dynamical theory of such processes can be formulated.

Multifragmentation processes have already been observed experimentally. As an example Fig. 4 shows the result of 91 MeV/n C colliding with a Ag nucleus.[6] A large number of fragments are ejected. Efforts are presently underway to pursue the study of this type of collision in a forthcoming experiment at CERN. Recently it has become possible to study multifragmentation processes at lower energies by the novel streamer chamber developed in Berkeley, as K. van Bibber has already discussed.[7] Again, large parts of the initial nuclei emerge as relatively light fragments. Such pictures give a spectacular impression of the violent and complicated collision processes, the dynamics of which we must now try to understand.

7 Concluding remarks

Numerous interesting phenomena may occur in the intermediate energy region and my contribution is not intended to give a complete and balanced view of the field. I have discussed some of the basic features characterizing the new physical situation we are faced with and illustrated with a few specific phenomena which one might expect to occur. We are only just embarking on our venture into this new field and I foresee an exciting period when we try to identify the new phenomena and attempt to understand them. I expect that the journey will be exciting as well as rewarding, and feel confident that results will be established which will contribute not only to the field of nuclear physics but also to physics in general.

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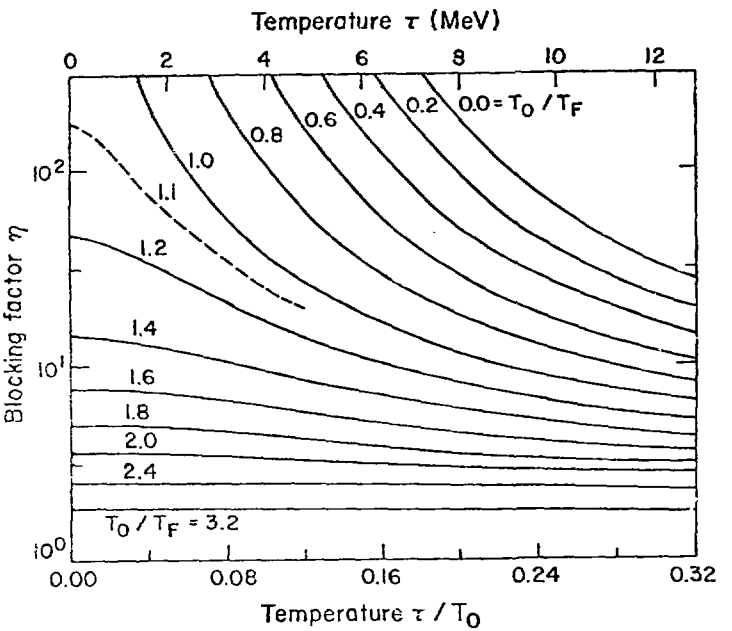

XBL 798-2467

Fig. 1. The blocking factor $\eta = \lambda/\lambda_o$ defined by Eq. (4) as a function of the temperature τ, for various values of the kinetic energy T_o of the intruder nucleon; T_F is the Fermi kinetic energy of the medium.

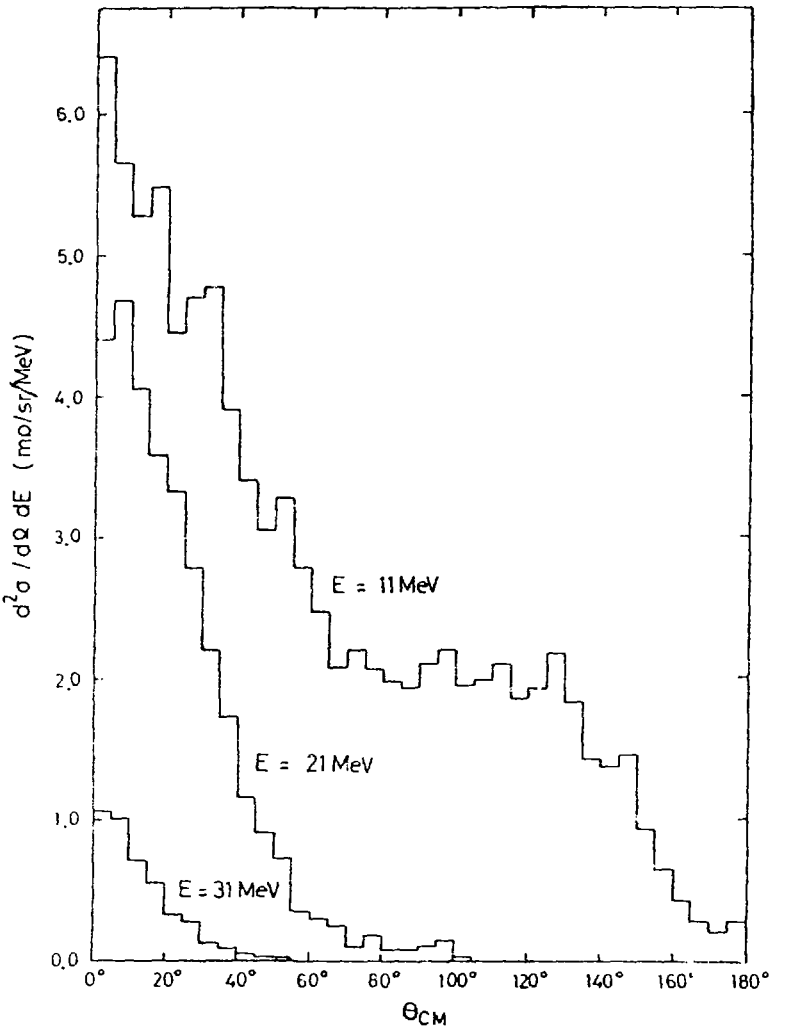

Fig. 2. The angular distribution of promptly emitted neutrons in the 152 MeV ^{12}C + ^{158}Gd collision, for selected cm energies.[5]

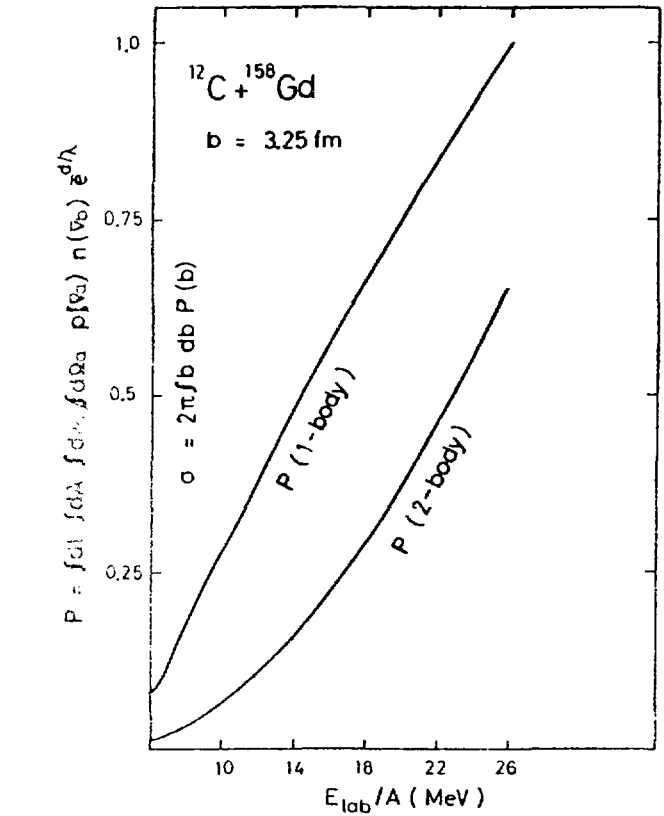

Fig. 3. The energy dependence of the contribution from oneand two-body PEPs in the C + Gd case for one selected impact parameter b = 3.25 fm.[5]

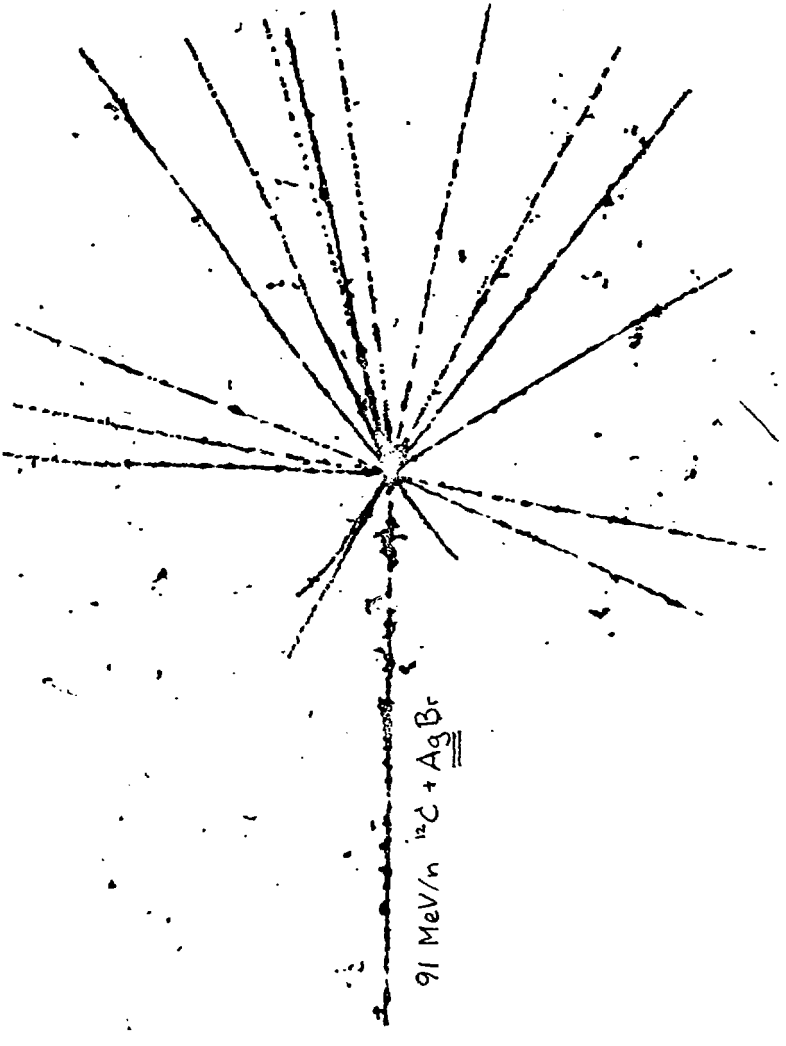

Fig. 4. The result of a 91 MeV/n ^{12}C nucleus colliding with a AgBr emulsion (B. Jacobsson, priv. comm.).