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A MODEL FOR HIGH-ENERGY HEAVY-ION COLLISIONS

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August 1977

ABSTRACT

A model is developed for high-energy heavy-ion collisions that treats the variation across the overlap region of the target and projectile in the amount of energy and momentum that is deposited. The expression for calculating any observable takes the form of a sum over a series of terms, each one of which consists of a geometric, a kinematic, and a statistical factor. The geometrical factors for a number of target projectile systems are tabulated.

1. INTRODUCTION

Heavy ion collisions at high energies produce large showers of different kinds of particles. Nucleons, light nuclei and pions are observed over a wide range of energy and angle. These various products seem to be associated with three relatively distinct sources. In the more peripheral collisions substantial fragments of both the target and projectile may remain. These "spectators" may be highly excited leading to particle emission (more or less isotropic in the rest frame of the fragment) and to a distribution of final products (evaporation residues). In addition, some sort of intermediate composite may be formed from those parts of the nuclei that overlapped during the collision. Particles from this region should be distributed in velocity between the target and projectile and if each particle experiences at least two or three collisions on the average they should also be spread fairly widely in angle. (Refs. 1 & 2 provide an excellent review of the experimental results.) This part of the collision complex becomes more important with decreasing impact parameter. For central collisions where the entire projectile overlaps the target, no projectile "spectator" remains and most of the yield of the reaction is expected at intermediate energies and widely spread in angle.³⁾

The relative yields of the different products observed in this intermediate region and their energy and angular distributions can be estimated from simple geometric, kinematic, and statistical considerations. Such estimates serve to establish a "background" against which the experimental results can be compared in order to search for anomalous behavior that might be associated with new phenomena. (Ref. 4 compares a number of

different theoretical approaches to this problem with the measured data for a particular experiment. It also contains extensive references to other work in the field.)

In the following section a schematic model will be developed for predicting the distributions of products whose source seems to be the overlap region between the target and projectile. (Some of the geometrical features of this approach are similar to those employed in refs. 3,5,6.) The model itself is somewhat more general than the one used in earlier work along these lines.⁶⁾ It includes a recognition of the fact that a velocity shear exists across the overlap region that depends locally on the amount of material coming from the projectile. In addition the model is based on nuclear density distributions with diffuse (rather than sharp) surfaces.⁷⁾ A special way of summarizing the geometrical aspects of the model will be introduced that allows one to immediately assess the importance of its various features.

2. THE MODEL

In the approach described here the collision of a high energy heavy ion with a target nucleus is viewed as a totally inelastic process in the overlap region. Consequently its range of applicability is limited. It is not expected to work at very low energies where the whole target and projectile may combine and subsequently decay. At extremely high energies the target may become partially transparent to the projectile due to the falloff of the nucleon-nucleon cross section.

For any given collision the ratio of the amount of projectile matter to the amount of target matter it is aimed at varies with position in the plane normal to the beam direction. The diffuse nature of the nuclear surface region tends to smooth out these variations so that a continuous range of η (the "projectile fraction") values is expected, where

$$\eta = \frac{\text{number of particles from the projectile}}{\text{number of projectile plus target particles}} \quad (1)$$

The value of η can vary from zero (for the target spectator) smoothly through intermediate values (corresponding to the overlap region) to one (for the projectile spectator fragment). Between the target and projectile spectators (if the impact parameter is large enough for any of the projectile to survive) a distribution of material is expected, which contains a large amount of internal energy and which is drawn out into a streak by the velocity shear across the overlap region.

Figure 1 is a schematic two-dimensional representation of the model to illustrate how the nuclear density distributions are expected to evolve with time. In part (a) of the figure the material in the overlap region is seen to be moving with velocities spread uniformly between those of the target and projectile spectators. Some of the material has already "burned off" because of its high degree of internal excitation. In part (b) the process has continued, and in part (c) the hottest part of the streak has completely dissipated leaving behind the spectator fragments (that probably begin to tumble because of the angular momentum imparted) which continue to burn off particles from the excited regions on their surfaces.

If the collision is completely inelastic the local values of the forward velocity v and the internal energy per particle t are given by the simple expressions:

$$\begin{aligned} v &= \eta \cdot v_{\text{beam}}, \\ t &= \eta(1-\eta) \cdot t_{\text{beam}}, \end{aligned} \quad (2)$$

where

v_{beam} = the velocity of the projectile beam,

t_{beam} = the kinetic energy per particle of the projectile beam,

and η (the "projectile fraction") is defined in eq. (1).

For higher energies the simple classical expressions eq. (2) are no longer adequate but the principle remains the same, as can be seen in figure 2. In this figure the velocity of the composite system β_c (or rather its ratio to the speed of light, $\beta = v/c$) is calculated using the

correct relativistic expression for the case where the projectile initially has 400 MeV/n kinetic energy. Its value is plotted against the projectile fraction η . In addition the internal energy per particle generated by the collision is also plotted. Note that this latter curve has been reduced by 8 MeV/n because of the binding energy of the particles that must be overcome.

In fig. 3 the distribution in the x-y plane (perpendicular to the beam direction) of various quantities of interest is shown for the specific case of $^{20}\text{Ne} \rightarrow ^{238}\text{U}$ at 400 MeV/n. The figure consists of three vertical columns corresponding to three different values of the impact parameter, $b = 2, 4$ and 6 fm. Diffuse surface density distributions are used, but the location of the equivalent sharp surfaces is indicated in part (a) (the uppermost entry in each column).

In part (b) of the figure the sum of the target and projectile density distributions is shown projected on to the x-y plane. The contour lines are at 0.05, 0.10, 0.15 and 0.20. The maximum value is also indicated. (Actually the values shown must be multiplied by 12.5 in order to obtain the densities in units of particles/fm².) Not all the contours are shown but only those that lie within the overlap region where the internal energy per particle after the collision is positive.

In part (c) of the figure the local value of η is indicated by contours at 0.1, 0.2, 0.3, etc., and the maximum values are indicated.

In part (d) the local value of β , the velocity in the z direction, is plotted with contours at 0.1, 0.2, 0.3, etc. These plots are very similar to the ones for η since β and η are nearly proportional (as can be seen in fig. 2).

0 0 0 0 4 8 0 3 8 0 4

-7-

In part (e) the local value of the internal energy (in units of MeV/n) is plotted. The contours are at 10, 20, 30, etc. MeV. The maximum possible value of 87 MeV/n (see fig. 2) is only obtained in the last figure on the right, corresponding to an impact parameter of 6 fm.

3. THE YIELD FUNCTION, $Y(\eta)$

For the actual case of a particular projectile and target combination, the geometrical aspects of the problem can be condensed into an especially simple form based on the quantity η . To see this we need only consider the origin of the functions $F_j(\underline{p})$, which are the laboratory momentum space densities (in barns) for particles of type j which are produced in the collision. These are the quantities that are measured and consequently they are the ones we address ourselves to in these model calculations. Such quantities may be calculated from the expression,

$$F_j(\underline{p}) = \int 2\pi b db \iint w_b(x,y) dx dy J_{\underline{p}' \rightarrow \underline{p}}(\beta) f_j(\underline{p}'; t) \quad (3)$$

where the first integral is over all possible values of the impact parameter b , and the second integrations are over the x - y plane normal to the beam direction. The quantity $w_b(x,y)$ (which is in units of particles/unit area) is obtained by projecting the combined target and projectile density distributions on the to the x - y plane. The quantities $f_j(\underline{p}'; t)$ are the center-of-mass-frame momentum space distributions for particles of type j that would be expected to emerge from an excited composite system of internal energy per particle t . (Normalized so as to correspond to the yield to be expected per nucleon of the original composite.)

Some appropriate model must be chosen for distributing the internal energy t among the available degrees of freedom in the composite system. For example, in appendix A the distribution in energy and angle of the

protons arising from a high energy heavy ion collision is calculated. The assumption is made there that the momentum distribution of the particles in the composite (with respect to their center of mass) is entirely random, i.e., a Maxwell distribution. Of course, this is an unnecessarily oversimplified approach, and more realistic calculations using the other aspects of the model described here are possible, where pion production is included and the yields of pions, protons, neutrons, deuterons, tritons, etc., are all predicted.^{8,10)}

In addition, it should be pointed out in passing, that nothing in the development which follows depends on an assumption that the particles have come to thermal equilibrium in their center-of-mass frame. Or, for that matter that they are even isotropically distributed in momentum. Even if a more microscopic analysis of the collision process were to indicate that an anisotropic, non-Maxwell distribution is more appropriate the same methods could be employed.

The quantity $J_{\tilde{p}' \rightarrow \tilde{p}}(\beta)$ in eq. (3) is the Jacobian transformation from the center-of-mass frame (the primed frame) to the laboratory frame. It depends only on the laboratory velocity β of the composite system.

Regardless of the actual form of the functions f_j the integrals in eq. (3) can be approximated by the expression,

$$F_j(\tilde{p}) = \sum_{i=1}^n Y(\eta_i) \cdot J_{\tilde{p}' \rightarrow \tilde{p}}[\beta(\eta_i)] \cdot f_j[\tilde{p}; t(\eta_i)] , \quad (4)$$

where

$$Y(\eta_i) = \int_{\eta_i - \frac{1}{2}\delta\eta}^{\eta_i + \frac{1}{2}\delta\eta} d\eta' \int 2\pi b db \iint dx dy w_b(x, y) \delta(\eta' - \eta_b(x, y)) . \quad (5)$$

This kind of a separation can be employed, since both the Jacobian J and the center-of-mass distribution function f depend only on η (through β and t). The η interval (from 0 $\rightarrow$ 1) can be divided into a number of equally spaced regions centered on the values η_i with a width $\delta\eta$ which is small enough so that J and f are well approximated by their values at η_i . A substantial simplification results when this procedure is used since all the geometrical aspects of the problem are contained in the "yield function" $Y(\eta)$. This function consists of a discrete set of numbers (19 in the examples given in appendix B) corresponding to the sequence of η intervals that is chosen. The values of $Y(\eta)$ (in units of cross section) can be determined, for any particular combination of target and projectile, by numerically integrating over impact parameter and over the x-y plane perpendicular to the beam.

4. DISCUSSION

The relative importance of different assumptions regarding geometrical aspects of high energy heavy ion collisions can be understood most easily by considering the resulting functions $Y(\eta)$. For example consider the much studied case of $^{20}\text{Ne} \rightarrow ^{238}\text{U}$. In figure 4 the function $Y(\eta)$ is plotted for three different models. In part (a) the nuclei have been assumed to be sharp surface spheres and the entire target and projectile contributions to the overlap region are assumed to form a single composite (the "fireball model" of ref.6) with a single value for the velocity and local internal energy. The distribution in η , which is quite narrow, is created solely by the sum over impact parameters. Part (b) shows the effect of including the dependence of η upon position in the x-y plane. Finally, part (c) shows the result for the model being proposed here, where not only is the dependence of η upon position in the x-y plane included, but the density distributions of both the target and projectile are taken to have diffuse (rather than sharp) surfaces. The implication of these differences for experimentally observable quantities can be seen in the comparison which is made in appendix A.

Another dramatic illustration of the difference between the three approaches illustrated in fig. 4 can be seen in fig. 5. In this figure the functions $Y(\eta)$ are shown for three symmetric systems. In the fireball model these distributions would all be delta-functions at $\eta=0.5$. If the variation of η in the x-y plane is included they would become rather sharply peaked distributions at $\eta=0.5$ with a width of about 0.2. When the diffuseness is also included, as it is in the cases plotted here,

the distributions spread out over the whole η interval.

In both figs. 4 and 5, and in the table of $Y(\eta)$ values given in appendix B, the values of $Y(\eta)$ for $\eta=0$ and 1 are not given. There are two reasons for this omission. The first is that both values are infinite (in principle) because they correspond to all those impact parameters where the target and projectile miss each other completely. (Strictly speaking, there are no "spectators" in this model. Since the surfaces are taken as diffuse, there is some, perhaps vanishingly small, overlap no matter how far the nuclei are separated.) Of course, some sort of cutoff could be introduced into eq. (5) that is used to calculate $Y(\eta)$. If the cutoff criterion were to depend on the dynamics, such as the velocity differential between different parts of the overlap region containing relatively small fractions of target (or projectile), then the end points of the function $Y(\eta)$ would be a function of the beam energy.

A second reason for not treating $Y(\eta)$ for $\eta=0$ and 1 is that it serves to call attention to the fact that the model being proposed here has as its object the calculation of those properties of high energy heavy ion collisions that cannot be associated with the target or projectile spectators. In fact the Coulomb (or nuclear) dissociation of the projectile, or the decay of a highly excited remaining piece of the target, is specifically excluded from the discussion of the model being presented here.

5. CONCLUSION

In deriving eq. (4) we accomplished the goal we set for ourselves in the introduction. This expression shows how many of the results of high energy heavy ion collisions can be approximated by a sum over a relatively small number of terms, each one of which consists of a geometrical, a kinematical, and a statistical factor. All of the geometry in this approach is contained in the function $Y(\eta)$ which can be tabulated to any target projectile combination (appendix B). The kinematic considerations are all in the Jacobian $J_{\underline{p}' \rightarrow \underline{p}}$, and all of the statistical considerations are contained in the functions f_j .

In appendix A the predictions of this approach (using a naive thermal model for f_j) are compared with experiment and the general agreement is good. The same sort of agreement (or better) is observed in calculations of composite yields (deuterons, tritons, alphas, etc.) and pion yields that are currently being undertaken.¹¹⁾ There is a tendency (which can be seen in the comparison of appendix A) for the calculated cross sections to be somewhat smaller than the measured ones, even though the shape of the energy and angular distributions agree very well. This effect may be associated with the way the geometrical considerations are handled. If the interaction region was allowed to spread during the collision and carry along adjacent material the overall cross section would be increased. This kind of spreading could be included by allowing neighboring regions to diffuse into each other (a sort of Boltzmann equation approach) or by introducing a viscosity term that would cause each region to partially drag its neighbors along (a sort of

hydrodynamic approach). In either case the factorization of eq. (4) that gives this method its appealing simplicity, would be destroyed.

The ease with which this approach can be applied, and its flexibility with regard to the incorporation of alternative forms for the functions f_j is its major strength. It is our hope that the predictions of this method will be compared with a wide range of experimental observations, and that it will be useful in helping to identify experimental results that suggest collective or otherwise anomalous effects.

ACKNOWLEDGMENTS

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APPENDICES

A. A COMPARISON WITH EXPERIMENT

As an example of how the method is to be applied, the double differential cross section ($d^2\sigma/d\Omega dE$) for proton emission will be calculated for the reactions $^{20}\text{Ne} \rightarrow ^{238}\text{U}$ at 250 and 400 MeV/n.

The yield function $Y(\eta)$ for this case is available from table 1 in appendix B and the kinematic transformation $J_{\tilde{p} \rightarrow p}$ is determined by the velocity β_i for each value of η_i . We need only to choose an appropriate form for the function $f_{\text{proton}}(\tilde{p}; t)$. Calculations similar to the one being described here are underway where the function f is relativistically correct, where pion and deuteron, triton, etc. production are included.¹¹⁾ However, for this introduction the protons will be treated as a classical ideal gas of non-interacting particles with a Maxwell distribution of velocities in the center-of-mass frame of the composite system,

$$f_{\text{proton}}(\tilde{p}; t) = \left[\eta \frac{Z_p}{A_p} + (1-\eta) \frac{Z_t}{A_t} \right] \cdot \left[\left(\frac{4}{3} \pi M t \right)^{-3/2} \exp - \left(\frac{p'^2/2M}{\frac{2}{3} t} \right) \right]. \quad (6)$$

The first term in eq. (6) is the ratio, locally, of the number of protons in the composite to the total number of nucleons, where Z and A are the charge and mass numbers of the projectile (or target). The second factor is the normalized Maxwell distribution for particles of mass M and average energy t .

The cross section we seek can be obtained by summing, as in eq. (4), over the different values of η_i (and consequently different values of β

and t) each term being weighted by $Y(\eta_i)$. The result is shown as a solid line in fig. 6. The dashed line is the result of a fireball calculation⁵⁾ where the yield function is the one shown in fig. 4a.

The points in this figure were compiled by adding together the published proton yields from ^1H , ^2H , ^3H , ^3He , ^4He , etc.¹²⁾ If the function f we employed in eq. (6) had included provision for the formation of these other products we could simply have compared our predictions with the proton yields.⁶⁾

B. TABLE OF VALUES FOR $Y(n)$

Table 1 contains a tabulation of $Y(n)$ values for a number of different target and projectile combinations. Each column consists of nineteen entries each covering an interval of $\delta n = 0.05$. The values of n_i corresponding to the center of each of these δn intervals are located at $n_i = 0.025 + i \cdot \delta n$ as is indicated in the second column of the table. The fact that there is no entry for $n_i = 0$ or 1 has been discussed in the main part of the text.

The integrals of eq. (5) that are used to evaluate $Y(n_i)$ were done numerically using a grid point spacing of 0.2 fm for the x,y and b integrations. The diffuse density distributions were generated by folding a short range function (a Yukawa) into the equivalent sharp spherical density distribution which results in an expression for the radial distribution of density that has the form

$$\rho(r) = \rho_0 \begin{cases} \left[1 - \left(1 + \frac{R}{a} \right) e^{-R/a} \frac{\sinh(r/a)}{(r/a)} \right] & r \leq R \\ \left[\frac{R}{a} \cosh(R/a) - \sinh(R/a) \right] \frac{e^{-(r/a)}}{(r/a)} & r \geq R \end{cases} \quad (7)$$

$$\text{where } R = 1.18 A^{1/3}, \quad (8)$$

$$a = 1/\sqrt{2}$$

This procedure has the advantage that the equivalent sharp radius R is simply proportional to $A^{1/3}$ while the half-density radius of a Fermi function does not have this simple proportionality.

The other advantage is that no special normalization is required to insure that the total number of particles is correct since the volume integral of this function is independent of the diffuseness.

TABLE 1.

The yield function $Y(\eta_j)$, in barns, for various target and projectile combinations.

Projectile mass number Target mass number		1 238	4 27	9 238	12 12	40 40	12 12	20 20	63 63	208 208	16 16	20 20	27 27	63 63	208 208	238 238	40 40	63 63	238 238	238 238
Index	η_j																			
1	0.05	14.80	3.71	25.88	2.23	6.78	2.36	3.87	11.31	34.37	3.40	4.51	5.91	13.25	41.01	46.58	10.55	16.24	60.69	101.74
2	0.10	4.74	1.57	12.78	1.01	3.06	1.14	1.80	5.06	15.48	1.61	2.10	2.80	6.13	18.60	21.25	5.06	7.71	28.51	50.18
3	0.15	1.22	1.07	11.31	0.70	2.01	0.76	1.20	3.49	12.88	1.06	1.42	1.88	4.12	14.42	16.91	3.39	5.46	21.42	36.31
4	0.20	0.57	0.92	5.16	0.54	1.79	0.61	0.98	3.19	14.00	0.86	1.15	1.50	3.66	15.32	18.26	2.82	4.39	21.57	31.08
5	0.25	0.35	0.94	2.39	0.48	1.82	0.51	0.82	3.40	14.78	0.77	1.03	1.46	3.79	18.19	21.86	2.66	4.27	25.12	33.63
6	0.30	0.25	0.93	1.42	0.48	2.01	0.53	0.94	3.97	8.19	0.77	1.05	1.47	4.30	19.30	20.58	2.86	5.00	31.92	40.16
7	0.35	0.22	0.59	0.97	0.43	2.20	0.56	1.05	3.97	4.71	0.84	1.19	1.76	5.25	11.06	10.96	3.20	5.99	36.28	51.00
8	0.40	0.18	0.44	0.71	0.62	1.54	0.59	1.24	2.51	2.95	0.92	1.30	2.01	5.81	6.65	6.75	3.89	7.59	22.34	70.68
9	0.45	0.14	0.34	0.60	0.77	1.06	0.77	1.35	1.80	2.15	1.20	1.70	2.54	3.81	4.57	4.77	5.34	10.14	14.82	106.00
10	0.50	0.14	0.28	0.52	0.61	0.79	0.92	1.08	1.31	1.80	1.47	2.11	2.47	2.83	3.20	3.39	6.74	7.91	11.85	147.34
11	0.55	0.13	0.23	0.49	0.51	0.75	0.77	0.86	1.11	1.34	1.20	1.70	1.76	1.96	2.61	2.64	5.34	5.57	10.15	106.00
12	0.60	0.12	0.21	0.48	0.44	0.53	0.59	0.69	0.93	1.23	0.92	1.30	1.40	1.75	2.23	2.54	3.89	4.34	12.47	70.68
13	0.65	0.10	0.23	0.46	0.37	0.56	0.56	0.63	0.77	1.38	0.84	1.19	1.26	1.55	2.27	2.31	3.20	3.41	9.75	51.00
14	0.70	0.12	0.25	0.44	0.38	0.56	0.53	0.61	0.86	1.38	0.77	1.05	1.12	1.35	2.24	2.24	2.86	3.07	6.72	40.16
15	0.75	0.12	0.25	0.50	0.40	0.65	0.51	0.62	0.93	1.45	0.77	1.03	1.13	1.48	2.29	2.28	2.66	3.07	5.36	33.63
16	0.80	0.12	0.29	0.55	0.46	0.68	0.61	0.72	1.05	1.50	0.86	1.15	1.28	1.75	2.55	2.74	2.82	3.31	5.29	31.08
17	0.85	0.15	0.33	0.68	0.61	0.84	0.76	0.89	1.40	1.73	1.06	1.42	1.57	2.14	2.87	3.09	3.39	4.11	6.05	36.31
18	0.90	0.17	0.50	0.85	0.83	1.21	1.14	1.33	1.73	2.61	1.61	2.10	2.32	2.98	4.26	4.49	5.06	5.80	8.76	50.18
19	0.95	0.22	0.94	1.45	1.84	2.47	2.36	2.72	3.62	4.87	3.40	4.51	4.85	6.00	8.28	8.73	10.55	12.05	16.89	101.74

FIGURE CAPTIONS

1. Schematic two-dimensional representation of a collision between a 250 MeV/n ^{20}Ne projectile with a ^{238}U target at an impact parameter of 8 fm. The three parts of the figure show how the system is expected to have evolved at times $t = 10, 20$ and 30 fm/c. The intensity of the shading is proportional to the degree of internal excitation generated by the collision.
2. The velocity β_c and internal energy per particle t_c of a composite system (part target and part projectile) are plotted against the projectile fraction η for the case where the initial projectile laboratory kinetic energy is 400 MeV per nucleon. The appropriate relativistic expressions were used to calculate these curves, and the t_c curve is shifted downward by 8 MeV because of the binding energy of the nuclei that must be overcome.
3. Contour plots of $\rho(x,y), \eta, \beta$ and t , for the case of $^{20}\text{Ne} \rightarrow ^{238}\text{U}$ at 400 MeV/n.
4. The yield function $Y(\eta)$ for ^{20}Ne on ^{238}U is plotted against η for three different geometrical models.
5. The yield function $Y(\eta)$ for the three symmetric cases $^{12}\text{C} \rightarrow ^{12}\text{C}$, $^{20}\text{Ne} \rightarrow ^{20}\text{Ne}$, and $^{40}\text{Ar} \rightarrow ^{40}\text{Ar}$.

6. The measured yield of protons as a function of laboratory energy and angle for the reactions $^{20}\text{Ne} \rightarrow ^{238}\text{U}$ at 250 and 400 MeV is compared with the predictions of two models. The dashed line corresponds to the fireball model and the solid line to the model being proposed here.

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$^{20}\text{Ne} \rightarrow ^{238}\text{U}$ at 250 MeV/n

$t=10$

$t=20$

$t=30$

XBL 778-1680

Fig. 1

XBL 776-1065

Fig. 2

XBL 776-1086

Fig. 3

XBL 778-1567

Fig. 4

XBL778-1568

Fig. 5

XBL 778-1566

Fig. 6

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