Coalescence of Light Particles in the Reaction $^{16}O + ^{238}U$ at 315 MeV

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The production of light particles contians important information on the reaction mechanism of heavy-ion induced reactions. At relativistic energies (E/A $\gtrsim$ 200 MeV/u), the emission of composite light particles has been shown to relate to the emission of protons via the coalescence model.[1,2] We have continued our investigation of ^{16}O induced reactions on ^{238}U at 20 MeV/u and demonstrate the validity of a coalescence relation, generalized to non-relativistic energies, which takes into account the effect of Coulomb repulsion from the target nucleus. The validity of the coalescence relation at this low energy renders possible a coherent study of composite light particle production, using a single concept, over a wide range of energies from a few tens to a few thousands of MeV/u.

The experiment was performed at the 88 inch cyclotron of the Lawrence Berkeley Laboratory. A self-supporting, metallic ^{238}U target of approximately 500 μg/cm^2 areal density was bombarded with $^{16}O^{6+}$ ions of 315 MeV. Correlated fission fragments were recorded in two position sensitive solid state detectors. Coincident light particles were measured with four ΔE-E telescopes each consisting of a 400 μm surface barrier detector and a 3" thick NaI detector. These detectors were mounted in the plane defined by the two fission detectors and subtended solid angles of typically 40 msr each.

As shown in references 3, 4, and 5, the measurement of the angle between correlated fission fragments yields information about the momentum transfer to the target residue. Using this information it is possible to distinguish between fusion-like "central" and transfer-like "peripheral" collisions.[3,4,5] With this distinction we observe that, as shown in Fig. 1, the majority of light particles are produced in "central" collisions where nearly the entire momentum of the projectile is absorbed by the target residue. Consistent with this observation are the rather low average light particle multiplicities per fission event, M(p,)=0.4, M(d)=0.18 and M(t)=0.15 that are obtained by assuming azimuthally symmetric light particle angular correlations.

Energy spectra of protons measured at several angles with respect to the beam axis are shown in Fig. 2. The data can be rather well described in terms of a Maxwellian distribution at temperature T and in a rest frame that moves with a velocity V parallel to the beam axis.

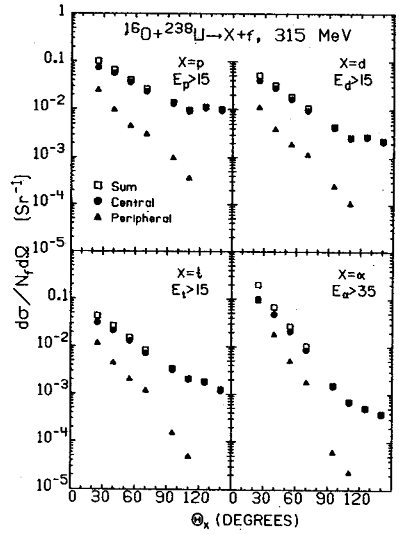

FIG. 1. Angular distribution of light particles p, d, t and α for "central" and "peripheral" collisions and their sum.

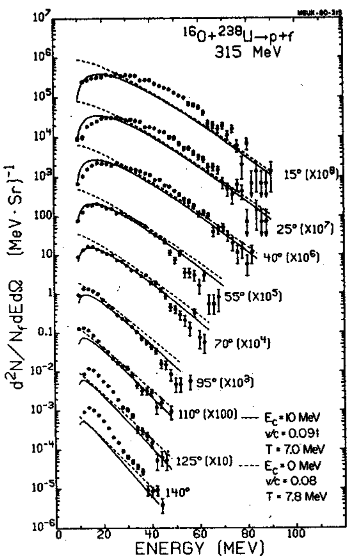

FIG. 2. Energy spectra of protons fitted according to eq. (1).

Correcting for the Coulomb repulsion from the target one obtains

$$\frac{d^2N}{d\ dE} = N_o\ (E-ZE_c)^{1/2}\ \ x\ \exp$$

$$\{\ (E-ZE_c) + E_1 - 2E_1^{1/2}\ (E-ZE_c)^{1/2}\cos\theta\ /T\} \qquad (1)$$

where E_c is the kinetic energy per charge unit gained by the Coulomb repulsion from the target, $E_1 = MV^2/2$ is the kinetic energy of a particle at rest in the moving frame, Z and M are the atomic number and mass of the emitted particle and N_o is an overall normalization constant. In eq. (1), the velocity of the target residue in the laboratory has been neglected.

The solid curves in Fig. 2 have been calculated with the parameters E_c = 10 MeV, V=0.091c and T = 7.0 MeV. The dashed curves have been calculated by neglecting the Coulomb repulsion from the target residue and using the parameters V = 0.08c and T = 7.8 MeV. Clearly, a better description of the data is obtained if the Coulomb repulsion from the target nucleus is taken into account.

The velocity of the rest frame in which the proton emission appears to be nearly isotropic closely coincides with the velocity V_N = 0.089c of the nucleon-nucleon center-of-mass frame if the slowing down of the ^{16}O nuclei in the Coulomb field of the ^{238}U target nuclei is taken into account. The temperatures observed in this rest frame are significantly larger than the temperature $T_{cn} \simeq 3$ MeV expected for the compound nucleus. If, on the other hand, one assumes the formation of a hot Fermi gas consisting of an equal number of target and projectile nucleons one obtains the value of T_N = 7.5 MeV in reasonable agreement with the experimental data. However, the large transfer of linear momentum to the target residue that is observed experimentally rules out an interpretation in terms of a hot gas of nucleons that is disconnected from the target nucleus. Rather, our data are consistent with the emission from a "hot spot" for which the thermalization of the nucleon velocities occurs first in the nucleon-nucleon center-of-mass frame and the time scale for particle emission is comparable to the time scale for energy and momentum transfer from the "hot spot" to the target nucleus.

For heavy ion collisions at relativiistic energies, the cross sections for the production of complex light particles have been shown to be related to the cross sections for proton emission by a simple coalescence model[1,2] (which has been shown to be consistent with thermal equilibrium). Assuming a stationary target nucleus in the laboratory and taking the Coulomb repulsion from the target nucleus into account one obtains

$$\frac{d^2N(Z,N)}{dE_A\, d\Omega} = \left(\frac{N_t + N_p}{Z_t + Z_p}\right)^N \frac{A^{-1}}{N!\, Z!} \left(\frac{4\pi P_o^3}{3\sqrt{2}\, m_o^{3/2}}\right)^{A-1} \frac{((E_A - ZE_c)/A)^{1/2}}{(E - E_c)^{A/2}} \left(\frac{d^2N(1,0)}{dE\, d\Omega}\right)^A, \qquad (2)$$

where $d^2N(Z,N)/dE_A d\Omega$ is the differential multiplicity of nuclei composed of Z protons and N=A-Z neutrons, P_o is the coalescence radius in momentum space, and $E_A = AE - NE_c$.

The differential particle multiplicity for a given event is not a measured quantity. In practice, one approximates this quantity by the average differential multiplicity.[1,2] For the present analysis, we use the equivalent approximation

$$\frac{d^2N(Z,N)}{dE_A\, d\Omega} = \frac{1}{N_f^o} \frac{d^2N_f(Z,N)}{dE_A\, d\Omega} \qquad (3)$$

where N_f (Z,N) is the number of light particles observed in coincidence with fission and N_f^o is the total number of fission events.

In Fig. 3, the experimental deuteron cross section is compared to the predictions of the Coulomb modified coalescence model (open squares). For the sake of consistency with eq. (1) and Fig. 2, the Coulomb energy E_c was fixed at the value of E_c=10 MeV. The coalescence radii of P_o(d)=170 MeV/c and P_o(t)=215 MeV/c obtained by fitting the deuteron and triton spectra respectively, are in rough agreement with typical values measured for relativistic heavy ion collisions.[2]

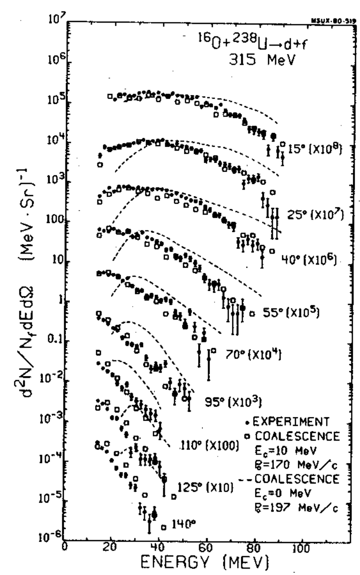

FIG. 3. Energy spectra of deuterons fitted according to eq. (3).

The Coulomb modified coalescence model is observed to give an excellent description of the relation between proton, deuteron and triton cross sections. On the other hand, the coalescence model without Coulomb corrections cannot describe this relation (see dashed lines in Fig. 3).

We are currently investigating the energy and target dependence of the coalescence radius parameter p_o. This information should help to choose between several physical models which can be written in the form of the coalescence relation with each model having a different expression for P_o.

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Energy Dependence of Central Collision from 20 to 200 MeV/nucleon

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In reactions between nuclei at projectile energies below 10 MeV/nucleon there is time for both nuclei to react and equilibrate during the reaction because the relative velocities are well below the speed of sound in nuclear matter (~.3c). At energies above 250 MeV/nucleon, the traversal time is much shorter than the nuclear relaxation time; in this case parts of nuclei are believed to be simply spectators while the interaction is localized to the overlapping volume. Transitional effects in the energy range between 10 and 250 MeV/nucleon have been showed in fragmentation of ^{16}O.[1,2] However similar investigations do not exist for heavier nuclei, A>20.

In the present experiment performed at the Low Energy Beam Line of the LBL Bevalac we investigate the transitional effects in central collisions by measuring angular distributions of emitted light particles. The spectra allow to test several models: preequilibrium excitons,[3] nuclear fireball,[4] intranuclear cascade[5-7] and the coalescence model. The coalescence model which was successfully applied down to energies as low as 20 MeV/nucleon[9] will be checked with particular interest to the coalescence radius trend as a function of the incident energy. In the first run ^{40}Ca and ^{238}U targets were bombarded with ^{40}Ar at 100 and 160 MeV/nucleon. Four telescopes have been used, two consisting of a Si ΔE detector and a 2"x3" NaI detector and two consisting of 5 Si ΔE detectors, one plastic scintillator E detector and one plastic scintillator veto detector. In the second type of telescope, the first two Si detectors are position sensitive in order to eliminate particles entering close to the edges of the counters. For particles reaching the plastic scintillator, the energy deposited therein is used only for mass and charge identification, while the total energy is obtained by using the energy loss-total energy relationship. The particle energy ranges covered are 13-200 MeV protons, 17-270 MeV deuterons, 20-315 MeV tritons, 45-685 MeV ^{3}He's and 50-700 MeV ^{4}He's. Spectra at angles between 20 to 160 degrees have been taken. Data analysis is now in progress.

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Production of Neutron-Rich Nuclides by Fragmentation of 212 MeV/u ^{48}Ca

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At low energies, heavy ion reactions have been demonstrated[1,2] to be a powerful tool for the production of new nuclides far from the center of the valley of stability. Until recently, however, little attention has been paid to the possible use of relativistic heavy ions for this purpose. In a first experiment devoted to investigate the production of new isotopes with relativistic heavy ions 14 new nuclides have been observed in projectile fragmentation reactions of ^{48}Ca at 212 MeV/u.

The experiment was performed at the Bevalac of the Lawrence Berkeley Laboratory. ^{48}Ca ions of 212 MeV/u were used to bombard an 890 mg beryllium target with a beam current of $\lesssim 10^7$ particles/sec. The projectile fragments were observed in a detector telescope consisting of twelve Si(Li) detectors, two position sensitive Si(Li) detectors and a veto scintillator placed in the focal plane of a zero degree magnetic spectrometer which had an acceptance of 0.94 msr. Further details of the experimental arrangement are described in Refs. 3 and 4.

Combining the measurements of the magnetic rigidity with the ΔE-E measurements in the Si(Li) detectors made it possible to determine the mass and element number of the reaction products.[3] The mass resolution obtained was 0.3 amu.

The mass spectra obtained for the neutron rich isotopes of N, F, Mg, Al, Si, P, S and Cl are shown in Fig. 1. Since a multi-element detector telescope was used, particle identification could be made in several ways by choosing different ΔE-E combinations. The mass resolution was then improved by making a χ^2 cut on the mean particle identification. Also charge cuts of 0.2 units and a total kinetic-energy cut which eliminated any low energy background were made. The intensities of Fig. 1 do not correspond to relative cross sections because the spectra are summed over different settings of the spectrometer. The duration of these runs varied from 10 min. to 9 h. There is clear evidence for the particle stability of ^{22}N, ^{26}F, ^{33,34}Al, ^{37,38,39}Si, ^{40,41,42}P, ^{41,42,43,44}S, and ^{44,45}Cl with more than ten counts in each case. The observation of ^{33}Mg confirms the indications for the stability of that isotope in Ref. 1. The existence of ^{37}S, ^{40}P and ^{41,42}S confirms the measurements reported in Ref. 5.

The measured isotopic-production cross sections are given in Fig. 2. Generally, the cross sections fall smoothly with increasing neutron number although there is a pronounced odd-even effect favoring nulcides with even neutron numbers. The observed nuclide ^{22}N is predicted to be particle unstable in a modified liquid drop model whereas modified Garvey-Kelson formulations predict that ^{22}N is bound against neutron emission by 1.5 to 2 MeV. The observed

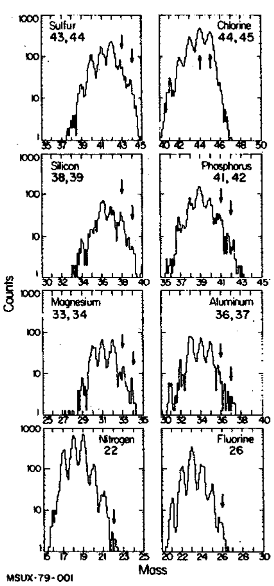

FIG. 1. Mass histograms for elements observed in the fragmentation of 212-MeV/amu ^{48}Ca by a beryllium target.

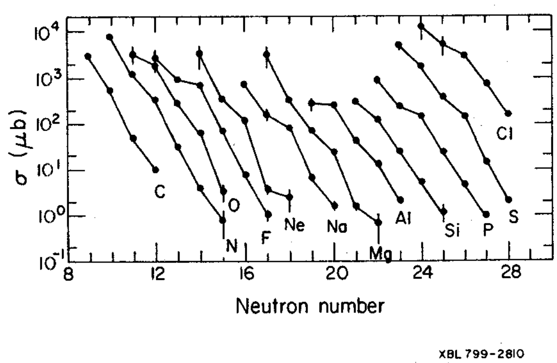

FIG. 2. Production cross sections for the elements observed in the fragmentation of 212-MeV/amu ^{48}Ca by a beryllium target. Lines are to guide the eye.

stability of ^{33}Mg which is predicted bound by only 500 keV, illustrates that simply determining whether or not an isotope is particle stable can provide quantitative tests of mass formulas.

One novel and striking feature of the yields is the rapid falloff in cross section for the oxygen isotopes, much faster than that for either nitrogen or fluorine. This is surprising since ^{24}O has been reported to be particle stable and is predicted to be so by all mass formulae. Qualitatively, an understanding of this behavior may be obtained from the predicted level schemes of these nuclei. If, as seems likely, these nuclei are formed as evaporation residues, then the number of bound states may be a more significant parameter than the binding energy in the determination of the yield. Neither ^{23}O nor ^{24}O is predicted to have any bound positive-parity states while neighboring N and F isotopes (with odd Z) are predicted to have several. Further, shell model calculations will clearly be valuable in predicting the yields of unobserved neutron rich nuclei from the observed systematics.

In Fig. 3 the production cross sections of sodium isotopes from the present work are compared to those from 205 MeV/amu ^{40}Ar + C (Ref. 3) and 28-GeV p + ^{238}U reactions.[5] The cross sections from ^{48}Ca + Be and p + ^{238}U are nearly equal whereas those from ^{40}Ar + C are substantially lower. All three reactions show the same odd-even effect which is indicative of a common final stage to the process. The increase in yield in going from ^{40}Ar to ^{48}Ca projectiles is expected, but the similarity between the yields from the latter reaction and the proton-spallation results is surprising.

In summary, fragmentation of relativistic heavy ions appears to be a practical means for the production of nuclei far from stability. The observation of these neutron-rich nuclei can be used to make quantitative tests of mass formulae. Beyond these global comparisons with mass formulae, the production cross sections appear to be sensitive to the microscopic level structure of the observed nucleus. In addition, the variations of the production cross sections indicate that, given increased beam intensities which will be available in the near future, it is practical to determine the limit of stability up to Z = 20.

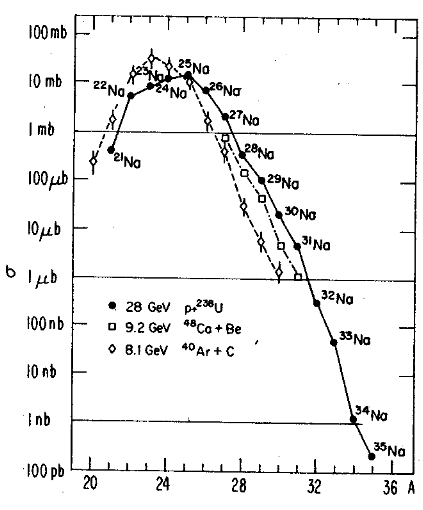

FIG. 3. Comparison of sodium production cross sections from 212-MeV/amu ^{48}Ca + Be (present work), 205-MeV/amu Ar + C (Ref. 1), and 28-GeV p + U (Ref. 3). Lines are to guide the eye.

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"Cluster Transfer" in the s-d Shell

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There has been strong interest in enhanced back-angle structures observed in heavy-ion elastic scattering. At present there are several proposed explanations for these enhancements including cluster exchange between the target and projectile. For example, in the case of $^{16}O+^{28}Si$ scattering there may be back-angle contributions to the elastic channel from the ^{12}C-transfer channel. Analyses involving exchange amplitudes have been hampered by uncertainties in the appropriate spectroscopic factors. Recent developments in SU(3) theory for light nuclei provide quantitative estimates for cluster spectroscopic factors.[1] These predictions are largely untested by comparison to direct transfer data. It was the purpose of this study to test such predictions.

The reaction $^{24}Mg(^{32}S,^{16}O)^{40}Ca$ was examined at 110 MeV. The ground state transition was found to have a first order forward-angle cross section of 100 nb/sr. This violates the first order SU(3) prediction which yields zero overlap for $^{32}S(g.s.) \to ^{16}O(g.s.)+^{16}O(g.s.)$. The detailed study of this reaction, including an excitation function and angular distribution, was undertaken in order to understand the reaction mechanism.

The data were obtained at the Tandem Van de Graaff Laboratory at Brookhaven National Laboratory. The reaction products were momentum analyzed with a Q3D magnetic spectrograph. A position sensitive ion-chamber detector of the type developed at Argonne National Lab was used in the focal plane. Targets were 100 $\mu g/cm^2$ ^{24}Mg metal targets on carbon backings. Destruction of the targets by the beam limited the beam intensity to 100 enA ≈ 10 pnA.

A preliminary analysis of data obtained are shown in Figs. 1 and 2. Spectra were obtained at bombarding energies of 110, 140 and 160 MeV at a scattering angle of 10° (lab) for the excitation function information; the bombarding energy was held constant at 100 MeV and spectra were obtained at lab scattering angles of 10°, 12°, 14°, and 16° (17°, 25°, 30°, and 35° c.m.) for the angular distribution.

As shown in Fig. 1, the ground state cross section $\sigma_{(g.s.)}$ is strongly energy dependent, decreasing with increasing bombarding energy expontially. It is thus consistent with the assumption that the state is populated predominately by a compound nucleus evaporation mechanism. Direct transfer should display only weak energy dependence in $\sigma_{(g.s.)}$. Thus, compound

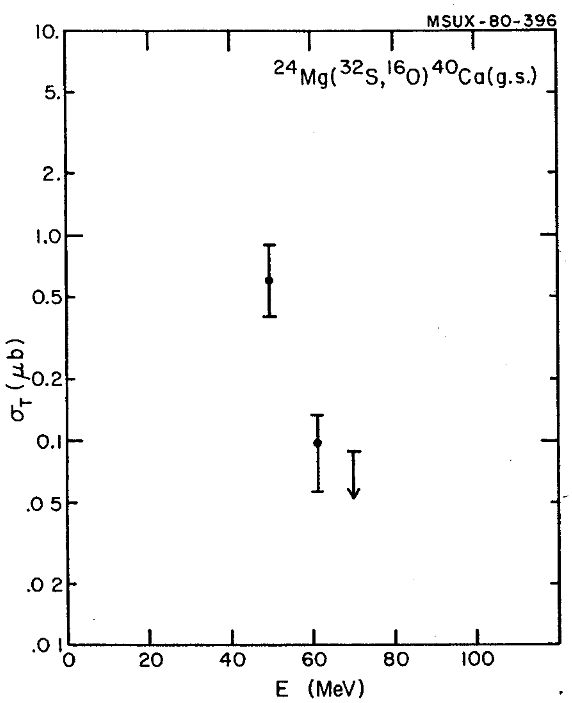

FIG. 1. Energy dependence of the ground state cross-section for the $^{24}Mg(^{32}S,^{16}O)^{40}Ca$ reaction.

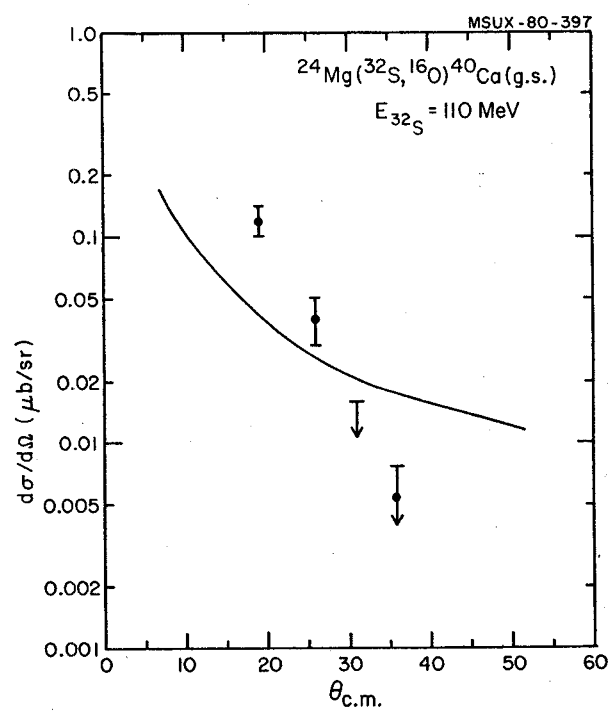

FIG. 2. Angular distribution of the ground state cross-section of the $^{24}Mg(^{32}S,^{16}O)^{40}Ca$ reaction. The solid curve is proportional to $1/\sin\theta$ and does not reproduce the trend of the data.

nucleus evaporation effects can be used to explain the discrepancy with the zero-order SU(3) prediction of $\sigma_{(g.s.)}=0$ for the $^{24}Mg(^{32}S,^{16}O)^{40}Ca$ reaction.

The angular distribution data (Fig. 2) provide additional information. If the ground state were populated by an evaporation mechanism, from an equilibrated system, then one would expect $\frac{d\sigma}{d\Omega}(\theta)\propto\frac{1}{\sin\theta}$. However, we observe that $\frac{d\sigma}{d\Omega}(\theta)\propto\left(\frac{1}{\sin\theta}\right)^4$ is in closer agreement with the data. Unfortunately, the data do not indicate what the nonequilbirium process is. It is interesting to note that particles as heavy as ^{16}O are emitted from the compound system since it requires preexistence of the cluster in the surface of the compound nucleus. One could alternatively explain the ^{16}O nuclei as resulting from incomplete union or by coalescence from the large number of lighter emitted particles. However, both processes do not populate discrete energy levels but lead to a continuum. In this study we have limited ourselves to the study of ^{16}O ejectiles corresponding to the ^{40}Ca ground state and thus to a binary final state; incomplete fusion or coalescence are therefore not sources of these ^{16}O nuclei.

In conclusion, we find that our data are not in conflict with the SU(3) prediction. The SU(3) predictions plus our results do not support cluster exchange as explanation for back-angle elastic scattering structures. The $^{24}Mg(^{32}S,^{16}O)$ ^{40}Ca ground state cross section can be explained by compound nucleus evaporation which are consistent with the observed strong energy dependence of the cross section. The next step would be to study such reactions as $^{24}Mg(^{32}S,^{20}Ne)^{36}Ar$ which are predicted to have measureable direct transfer cross sections. The cross sections are likely to be small, however (1 μb/sr).

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Pion Production by Heavy Ions

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The project to study subthreshold pion production in heavy ion collisions has been extended this year in three separate directions to answer questions raised by the first data set. These original data were discussed in the last annual report and a recent publication.[1] The project continues to be a collaboration primarily with the LBL groups of Rasmussen and Crowe.

The questions raised by the data are as follows: I) How does the large Coulomb effect on π^-/π^+ ratios at 0° at the projectile velocity depend on the atomic mass of beam and target? What is its angular dependence? II) Do Coulomb effects manifest themselves at 90° c.m. and account for other observed anomalies? III) What is the mechanism for the surprisingly high cross section below E/A=150 MeV? To attempt to answer these questions, the apparatus was modified by adding a pair of wire chambers and an array of eleven plastic scintillators as is shown in Fig. 1. The apparatus continues to consist of a large gap magnet used as a spectrograph, but the detection system was changed to provide a continuous focal plane and a resolution of about 1%. Very important additions are the angle measuring capability of the new wire chambers (both θ and ψ) and the ability to rotate the entire spectrometer about the target out to more than 50° lab. This permits a complete continuous angular distribution well beyond 90° in the cm of the nucleon-nucleon system.

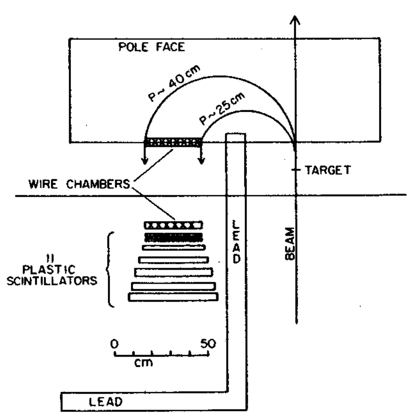

FIG. 1. Present experimental configuration for pion production experiments.

I. The Coulomb Peak at 0°

One year ago the data on the Coulomb anomaly at 0° consisted mainly of a strong π^-/π^+ enhancement which seemed to be located at 55 MeV pion energy and E/A=390 MeV. This peak is now understood as a Coulomb effect due to the projectile-like residue, as postulated in the published report.[1] A thorough treatment in the framework of the fireball model[2] gave a very good explanation of all the features of the Coulomb effect. This treatment also explained the absence of a large Coulomb effect at the fireball velocity. The expansion of the hot nuclear matter in the fireball reduces the enhancement to about a factor of three at the fireball velocity.

A set of runs was performed in July 1979 to study the Coulomb peak in more detail. The most dramatic effect was observed for ^{12}C targets and heavy projectiles as is shown in Fig. 2. The Coulomb peak exists at all energies measured, both above and below threshold. Its width in momentum is about the same in the direction perpendicular to the beam as it is in the beam direction.

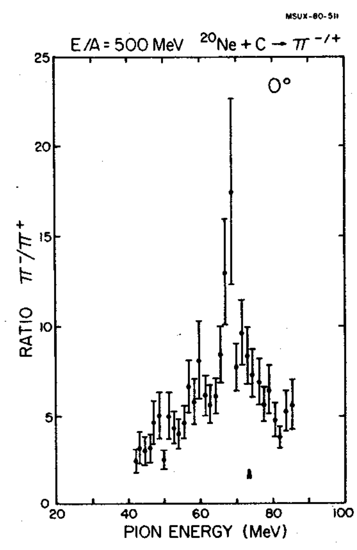

FIG. 2. Ratio of π^-/π^+ for Ne + C collisions at E/A 500 MeV. The arrow is at the beam velocity.

II. Coulomb effects at 90° c.m.

In recent papers by Wolf et al.[3] an enhancement was observed in the π^+ spectra at 90° c.m.

This enhancement was thought to be a collective effect since it is not seen in the elementary N-N cross section. It has been proposed however that the effect may also be due to the Coulomb field of the reaction participants.[4] The experiment had been performed with π^+ particles only since particle detectors were employed without magnetic analysis. The idea that the effect was due to the Coulomb field can be easily checked by a π^+-π^- comparison. Consequently a run at E/A = 1.05 GeV/A at 90° c.m. was made with Ar on KCl. A Coulomb effect was observed, but it was only the supression of π^+ with respect to π^- for pions moving slowly with respect to the fragments. The data are still under analysis but seem to indicate that Coulomb effects cannot explain the difference between the nuclear and the nucleon-nucleon collisions. However since the effect itself is not large, the data need to be analyzed and looked at very carefully before any conclusions can be reached.

III. Mechanism for subthreshold pion production

As can be seen in Fig. 3, the energy dependence of pion production at 0° is very strong

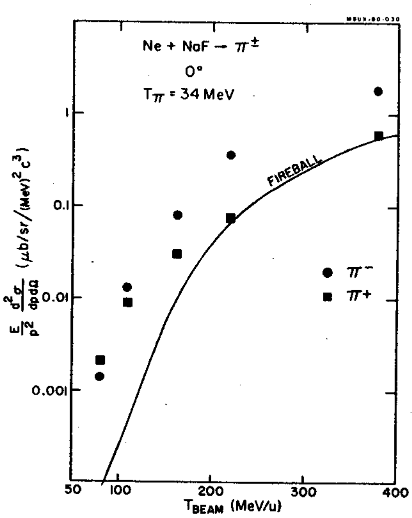

FIG. 3. Energy dependence of pion production at 0° and T_π = 34 MeV. The curve was calculated according to the formulas of ref. 5.

below the free nucleon-nucleon threshold (E/A= 290 MeV). A fireball or thermal calculation[5] fails to account for the cross section at the lower energies, and the first collision model[6] gives an even smaller cross section. The problem in these calculations is that both neglect significant processes which should contribute to the pion production. In the case of the thermal model, some additional composite particle production could increase the pion production cross section (by raising the temperature). In the case of the first collision model, a sharp edged Fermi distribution was used. Both of these theories are being worked on at present, but in the absence of angular distribution data the results cannot be conclusive. Consequenlty a complete angular distribution of Ne+NaF was taken at E/A = 125 MeV in June 1980. Whether the cross section is isotropic or forward peaked in a pion-energy dependent way will help to distinguish between different models for the reaction mechanism.

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