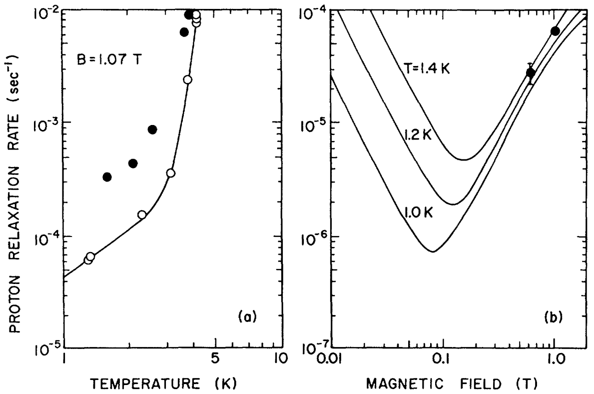

FIG. 3. (a) Proton relaxation rate vs temperature for two samples of $Y(EtSO_4)_3$:Yb, with one set of measurements compared with theoretical results for 0.02% Yb concentration. (b) Calculated proton relaxation rate vs magnetic field. The experimental point at 1.07 T is a University of Massachusetts measurement at 1.3 K; that at 0.6 T was obtained in studies at the University of California, Davis, at 1.1–1.2 K.

A possible configuration for use of the polarized target is to enhance the magnetic field of a spark-chamber facility by use of a modest Helmholtz-coil arrangement during the polarizing operation and then to stop rotation, reduce the total field, and thus capitalize on the longer relaxation time at the lower field.

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[1]C. D. Jeffries, Cryogenics 3, 41 (1963).

[2]A. Abragam, Cryogenics 3, 42 (1963).

[3]K. H. Langley and C. D. Jeffries, Phys. Rev. Lett. 13, 808 (1964), and Phys. Rev. 152, 358 (1966).

[4]J. R. McColl and C. D. Jeffries, Phys. Rev. Lett. 16, 316 (1966), and Phys. Rev. B 1, 2917 (1970).

[5]W. H. Potter, Rev. Sci. Instrum. 42, 618 (1971); W. H. Potter and H. J. Stapleton, Phys. Rev. B 5, 1729 (1972).

[6]R. L. Ballard, Ph.D. thesis, University of California, Berkeley, 1971 (unpublished).

[7]H. B. Brom and W. J. Huiskamp, Physica (Utrecht) 66, 43 (1973).

[8]C. D. Jeffries, Annu. Rev. Nucl. Sci. 14, 126 (1964).

[9]C. D. Jeffries, in *Proceedings of the International Conference on Polarized Targets and Ion Sources, Saclay, France, 1966* (La Documentation Française, Paris, France, 1967), p. 147.

[10]In addition to the work cited above, recent efforts have been directed by W. H. Potter to producing a uniformly rotating magnetic field with a stationary sample cooled to about 0.5 K. No significant polarization has been achieved as yet.

[11]J. P. Wolfe and C. D. Jeffries, Phys. Rev. B 4, 731 (1971).

[12]W. H. Potter, Rev. Sci. Instrum. 45, 1288 (1974).

[13]W. H. Potter, Phys. Rev. B 5, 1178 (1972).

Knock-Out Nucleons from Relativistic Nuclear Collisions

Steven E. Koonin[(a)]

The Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen Ø, Denmark, and The Weizmann Institute of Science, Rehovot, Israel

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A nonequilibrium single-scattering mechanism is proposed to describe the inclusive proton spectrum from relativistic heavy-ion collisions. Data from ^{20}Ne + U and ^{4}He + U collisions are shown to be consistent with a simple model of the knock-out process. Two-proton azimuthal angle correlations are suggested as a unique signature of this reaction mechanism.

The inclusive proton spectra from relativistic ^{20}Ne + U and ^{4}He + U collisions have been shown to be consistent with the existence of a nuclear "fireball" at temperatures of 30–50 MeV.[1] The composite particle spectra from these collisions[2] also show equilibrium features.[3] However, a literal interpretation of the fireball picture requires equilibration to be achieved on time scales $\lesssim 10^{-22}$

sec. This seems unlikely in view of the relatively long mean free path for nucleon-nucleon interactions.[4] Microscopic descriptions of the proton data permitting the existence of nonequilibrium conditions have been attempted.[5] Although these methods reproduce the gross features of the data, significant details of the calculated cross sections are incorrect. Moreover, the large numbers of degrees of freedom in these models obscure the relationship between the microscopic dynamics and the calculated spectra. In an effort to isolate a simple reaction mechanism which provides a basis for interpreting the results of both calculation and experiment, we consider in this Letter a nonequilibrium knock-out description of the proton spectrum.

I assume that certain kinematical regions of the proton spectrum result from single scatterings of nucleons. After the interaction of a target nucleon in the overlap region of the two nuclei, both particles leave the system with no further scatterings. This knock-out mechanism describes nucleons generated in the early stages of the collision and is consequently expected to be valid for the high-energy region of the proton spectrum. Subsequent nucleon-nucleon scatterings (which I do not treat) further degrade the momenta of the projectile nucleons and result in lower-energy "thermalized" nucleons. Knock-out nucleons are expected to be most apparent in directions transverse to the beam in the nucleus-nucleus center-of-momentum system, since they are obscured in the forward (backward) direction by projectile (target) fragmentation or evaporation products.[6] The features of high kinetic energy and prominence at side angles imply that this mechanism is appropriate for nucleons with large transverse momenta. Similar models describe particle production in this kinematical region as resulting from single quark-quark scatterings in high-energy hadron-hadron collisions.[7]

Although knock-out can be investigated with any of the microscopic methods mentioned above, the essential features of this reaction mechanism are contained in a model incorporating the following simplifying assumptions:

(i) The initial momentum distribution of target nucleons, $f_T(p)$, is a Fermi sphere of radius $p_F = 268$ MeV/c. The initial momentum distribution of the beam nucleons, $f_B(p)$, is a similar Fermi sphere in the projectile rest frame. For beam energies per nucleon $E_B/A > 2p_F^2/m = 153$ MeV, where $m = 938$ MeV is the nucleon mass, the target and projectile distributions are disjoint and there is no ambiguity in satisfying the exclusion principle. Depletion of these distributions during the collision is neglected.

(ii) Interactions between target and projectile nucleons result in independent binary scatterings allowed by the exclusion principle. These scatterings are governed by the spin- and isospin-averaged free nucleon-nucleon elastic scattering cross sections. In this Letter I consider only beam energies where inelastic nucleon-nucleon scattering is unimportant or kinematically forbidden, but note that both π production[8] and modifications to the nucleon spectrum due to isobar decays may be simply included in the present scheme.

(iii) The average binding energy of the nucleons is accounted for by assuming that all scatterings occur in a potential well of depth V_0. I take $V_0 = 44$ MeV, as determined from quasielastic electron scattering on heavy nuclei.[9] Refractive effects of this potential are ignored.

With the above assumptions, the cross section for a target (T) and beam (B) to produce knock-out protons with laboratory kinetic energy E at a laboratory angle θ may be written in the factorized form

$$d^2\sigma/d\Omega\,dE = \sigma_{BT} N_{BT} \overline{Z/A}\, F(\theta, E, E_B/A). \qquad (1)$$

The experimental ion-ion total reaction cross section is σ_{BT}.[2] N_{BT} is the impact-parameter-weighted average number of knock-out scatterings per collision, and the factor $\overline{Z/A} = \frac{1}{2}(Z_B/A_B + Z_T/A_T)$ involving the charge-to-mass ratios Z/A of the ions accounts for the fact that only protons are observed. The universal function F describes the knock-out kinematics and is given by

$$F(\theta, E, E_B/A) = \mathfrak{N}\int d\vec{p}\int d\vec{p}\,' f_T(\vec{p}) f_B(\vec{p}\,') \frac{1}{\sigma_{nn}(\vec{p}, \vec{p}\,')} \times \frac{d^2\sigma_{nn}(\vec{p}, \vec{p}\,'; \vec{k})}{d\Omega\, dE} Q(\vec{k}, \vec{k}\,'). \qquad (2)$$

Target and beam nucleons with momenta $\vec{p}, \vec{p}\,'$ scatter to final momenta $\vec{k}, \vec{k}\,' = \vec{p} + \vec{p}\,' - \vec{k}$. The momentum $\vec{k}$ is oriented to an angle θ relative to the beam direction and has a magnitude given by $(k^2 + m^2)^{1/2} - m = E + V_0$ [cf. assumption (iii) above]. The cross section for this scattering is $d^2\sigma_{nn}/d\Omega\, dE$. The total nucleon-nucleon cross section is σ_{nn}. The function $Q(k, k')$ limits the final momenta to those consistent with the exclusion principle, and the normalization constant $\mathfrak{N}$ is determined by[10]

$$\int_0^\infty dE \int d\Omega\, F(\theta, E, E_B/A) = 2, \qquad (3)$$

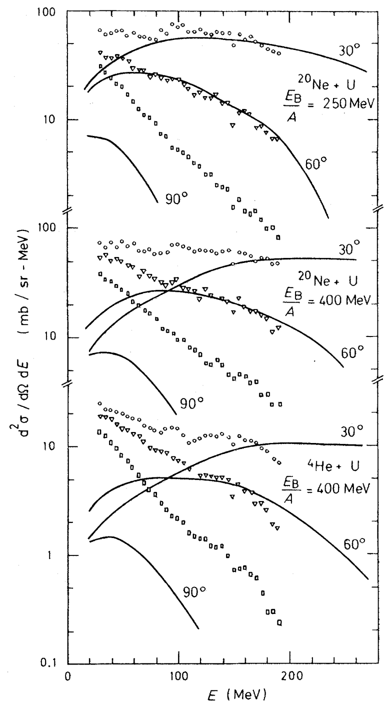

FIG. 1. Knock-out model fits (solid lines) to the inclusive proton spectra of Ref. 1. Data at various laboratory angles are denoted by ○ – 30°, ▽ – 60°, and □ – 90°.

since two knock-out nucleons are produced at each binary scattering. The integrand of Eq. (2) has been weighted to approximate the limit in which all beam nucleons in the overlap region scatter (assuming $A_B \leqslant A_T$). We confirm this fact from the data below.

We have calculated the knock-out proton spectrum from ^{20}Ne + U and ^{4}He + U collisions using Eqs. (1)–(3), with N_{BT} determined by normalization to the data. The integral (2) has been computed using Monte Carlo techniques and polynomial fits to the experimental nucleon-nucleon cross sections.[11] In Fig. 1, we compare the results with the data of Ref. (1). At $E_B/A = 250$ MeV, for $E \geqslant 80$ MeV, the flatness of the 30° spectrum is well reproduced by the knock-out model. This is in contrast to the fireball model and explains the unusually high center-of-mass velocities obtained when the proton spectra are fitted with a Maxwellian distribution.[3] The slope of the 60° data and their normalization relative to the 30° spectra are also reproduced. For angles $\theta = 90°$ and greater (not shown), the calculated spectra are far below the data, as is consistent with the kinematical regions in which the model is expected to apply. The failure at 30° for $E_B/A = 400$ MeV might be attributed to multistep processes. The fitted values of N_{BT} are 10.4 and 13.3 for the ^{20}Ne collisions at $E_B/A = 250$ and 400 MeV, respectively, and 3.8 for the ^{4}He collision. The geometrical considerations of Ref. 1 determine the impact-parameter–weighted average number of projectile nucleons in the overlap region to be 9.9 for ^{20}Ne and 2.4 for ^{4}He. Considering the 20% uncertainty in the absolute normalization of the data, I conclude that most of these nucleons undergo at least one scattering, and that the geometrical scaling in Eq. (1) is approximately satisfied. In this connection, I also note the remarkable empirical fact that at *all* angles for $E \gtrsim 100$ MeV, the $E_B/A = 400$ MeV ^{20}Ne and ^{4}He data are in the ratio 5:1. The importance of the exclusion principle may be judged by noting that 38% and 26% of the contributions to the integral in Eq. (2) are blocked at $E_B/A = 250$ and 400 MeV, respectively. All of these features are essentially unchanged if $d\sigma_{nn}/d\Omega$ is assumed to be isotropic.

Considering the simplicity of our model, knock-out appears to be a viable alternative to the fireball in certain kinematical regions. The radically different equilibrium assumptions of these two pictures then make a determination of the correct reaction mechanism imperative. One definitive test of the knock-out picture is the presence of proton-proton azimuthal angle correlations. We consider the correlation function[12]

$$C(\varphi) = \frac{2\pi}{\sigma_{BT}} \frac{d^2\sigma}{d\varphi_1 d\varphi_2} - \frac{\langle n \rangle^2}{2\pi}. \qquad (4)$$

Here $d^2\sigma/d\varphi_1 d\varphi_2$ is the differential cross section for producing a coincident proton pair with azimuthal angles φ_1 and φ_2 relative to the beam direction. It is a function of the relative angle $\varphi = \varphi_1 - \varphi_2$, which I take to range from 0 to 2π. The proton multiplicity is n and $\langle \ldots \rangle$ denotes average over all collisions. The integral of $C(\varphi)$ from 0 to 2π is $C_0 = \langle n(n-1)\rangle - \langle n \rangle^2$.

For completely uncorrelated proton emission, as is assumed in the fireball model, $C(\varphi) = C_0/2\pi$ is independent of φ. In contrast, pairs of knock-out protons are strongly correlated at $\varphi = \pi$. This can be seen in Fig. 2, where I show $[C(\varphi) - (C_0 - \overline{Z/A})/2\pi](\overline{Z/A})$ for the simple model presented above. The nonnegligible size of the Fermi momentum relative to the beam momentum makes the back-to-back correlation less than perfect and results in a peak of width $\sim\pi/3$ at $\varphi = \pi$. It is then apparent that this peak should narrow with increasing E_B/A.

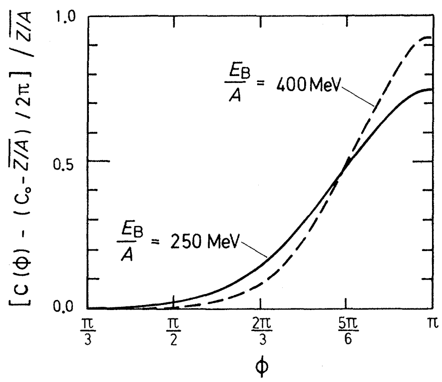

FIG. 2. Two-proton azimuthal correlation functions as calculated in the knock-out model. The curves are symmetric about $\varphi = \pi$ and vanish for $\varphi < \frac{1}{3}\pi$ and $\varphi > \frac{5}{3}\pi$.

The knock-out peak in $C(\varphi)$ could be enhanced in an experiment by requiring one or both of the detected protons to be emitted with high energy at a forward angle, where the knock-out process should dominate the spectrum (Fig. 1). However, three factors may result in an experimental correlation which is weaker than that shown in Fig. 2. First, shadowing by the surrounding nuclear matter may block one member of the knock-out pair, although the relatively large values of N_{BT} found above indicate that in certain kinematic regions most knock-out protons manage to escape. Second, refraction by the nuclear mean field may weaken the correlation. This effect will become smaller as the proton energy increases. Finally, for processes such as the fireball or evaporation which involve equilibrated systems, overall momentum conservation forces a kinematic excess in $C(\varphi)$ in the range $\pi/2 \leq \varphi \leq 3\pi/2$. However, to the extent that the recoil from proton emission is absorbed by many nucleons, this excess is expected to be a broad rise in the backward hemisphere, in contrast to the narrow peaks of Fig. 2. Some or all of these three features are included in current microscopic calculations. A detailed study of $C(\varphi)$ in these models therefore seems worthwhile.

The experimental identification of knock-out processes would provide several possibilities for improving our understanding of relativistic nuclear collisions. Knock-out protons are indicative of a highly nonequilibrium situation and must be taken into account in any attempt to determine equilibrium features from the experimental data. In addition, because knock-out nucleons can be generated deep within the interaction region, their subsequent escape might serve to probe the condition of the surrounding nuclear matter. A sudden decrease in the knock-out component with increasing bombarding energy might signal the onset of the critical opalescence phenomenon predicted by π-condensation theories.[13] Finally, the knock-out mechanism is characteristic of only the first step in the equilibration process. The use of microscopic calculations to establish specific spectral features associated with nucleons undergoing two or more collisions would aid in determining further details of relativistic collision dynamics from the experimental data.

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[(a)]Permanent address: Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, Calif. 91109.

[1]G. D. Westfall, J. Gosset, P. J. Johansen, A. M. Poskanzer, W. G. Meyer, H. H. Gutbrod, A. Sandoval, and R. Stock, Phys. Rev. Lett. 37, 1202 (1976).

[2]H. H. Gutbrod, A. Sandoval, P. J. Johansen, A. M. Poskanzer, J. Gosset, W. G. Meyer, G. D. Westfall, and R. Stock, Phys. Rev. Lett. 37, 667 (1976).

[3]R. Bond, P. J. Johansen, S. E. Koonin, and S. Garpman, to be published.

[4]M. I. Sobel, P. J. Siemens, J. P. Bondorf, and H. A. Bethe, Nucl. Phys. A251, 502 (1975).

[5]A. A. Amsden, J. N. Ginocchio, F. H. Harlow, J. R. Nix, M. Danos, E. C. Halbert, and R. K. Smith, Jr., Phys. Rev. Lett. 38, 1055 (1977), and references cited therein.

[6]Knock-out nucleons remain somewhat forward peaked in this frame since the nucleon-nucleon center-of-momentum frame generally appears to be moving forward in this system.

[7]D. Sivers, S. Brodsky, and R. Blankenbecler, Phys. Rep. 23C, 1 (1976).

[8]G. F. Bertsch, Phys. Rev. C 15, 713 (1977).

[9]E. J. Moniz, I. Sick, R. R. Whitney, J. R. Ficenec, R. D. Kephart, and W. P. Trower, Phys. Rev. Lett. 26, 445 (1971).

[10]For large V_0, Eq. (3) must be modified to account for scatterings which result in one nucleon with insufficient energy to escape the potential well. However, since V_0 is only slightly larger than the Fermi energy, the little phase space available for such events amounts to a negligible correction.

[11]K. Chen, Z. Fraenkel, G. Friedlander, J. R. Grover, and J. M. Miller, Phys. Rev. 166, 949 (1968).

[12]J. D. Jackson, in *Phenomenology of Particles at High Energies*, edited by R. L. Crawford and R. Jennings (Academic, London, 1974), p. 97.

[13]M. Gyulassy, V. Ruck, and W. Greiner, in *Proceedings of the Fourth Conference on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria, 1976,* edited by W. D. Meyers (Institut für Kernphysik, Technische Hochschule Darmstadt, West Germany, 1976), p. 115.

Determination of γ Softness in $^{192,194,196}Pt$ from Coulomb Excitation with ^{136}Xe Projectiles

I. Y. Lee, D. Cline,[(a)] P. A. Butler, R. M. Diamond, J. O. Newton,[(b)] R. S. Simon,[(c)] and F. S. Stephens
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 13 June 1977)

The $^{192,194,196}Pt$ nuclei were Coulomb excited with ^{136}Xe projectiles. Strong excitation of the ground-state band (up to spin 10^+) and the "γ" band (up to spin 8^+) were observed. Excitation of the upper members of the γ band is shown to be sensitive to the γ softness. The observed Coulomb-excitation yields imply $B(E2)$ values which follow the rigid-triaxial-rotor relation. This contradicts current calculations which predict considerable γ softness.

The collective properties of nuclei in the Os, Pt, and Hg region have been the subject of many recent experimental and theoretical studies. These nuclei are in the shape-transitional region between the well-deformed rare-earth nuclei and double-closed-shell ^{208}Pb, and several different collective models have been used to account for the properties of their lowest-lying states. These models range from the triaxially deformed rigid rotor,[1] through various rotation-vibration models about triaxial[2] or axial shapes,[3] to the γ-unstable (shape-unstable) model.[4] Collective-model calculations with the complete Bohr Hamiltonian have been performed by Kumar and Baranger using potential-energy surfaces and inertial parameters calculated within the pairing-plus-quadrupole model.[5] They predict a prolate to oblate shape transition in the Os–Pt region. In addition, they predict shallow deformation potentials, especially soft to γ vibrations. Calculations using the deformed-oscillator model and the Strutinsky normalization procedure also give shallow potentials.[6]

The experimental evidence for nonaxial collective motion in these nuclei is quite convincing.[7-10] The static electric quadrupole moments of the lowest 2^+ states strongly suggest a gradual prolate to oblate shape transition, that is, from a ground state $\gamma \simeq 20°$ in ^{186}Os to $\gamma \simeq 35°$ in ^{198}Pt. An analysis of unique parity spectra in adjacent odd-A nuclei within the rigid triaxial rotor plus particle model[11] implies similar values for the triaxial deformation parameter γ. The location of the collective second 2^+ state below the first 4^+ state in these doubly even nuclei is in agreement with triaxial deformation. The average values of the deformation parameters $\langle\beta^2\rangle$ and $\langle\beta^3\cos 3\gamma\rangle$ appear to be well defined by the experimental data but the spread about these average values, that is, the softness is essentially undetermined.[12] The only evidence on the softness comes from the surprising constancy of the γ values extracted from the unique parity spectra in adjacent odd-A nuclei, which suggests rather stable triaxial shapes. However, the level energies are not a very good probe of the nuclear shape; they are rather insensitive to softness and are sensitive to the inertial parameters (whose γ dependence is usually taken to correspond to irrotational flow) in addition to other effects such as Coriolis antipairing. In contrast, the $E2$ matrix elements are a more direct measure of quadrupole deformation of the nuclear charge distribution. For a nucleus having γ value around $30°$ there are three sets of comparably large $B(E2)$ values. They are the $I \to I-2$ transitions in the ground band, the $I' \to I'-2$ transitions in the γ band, and the $I' \to I$ transitions between the bands. The higher spin members of the last two sets are sensitive to the γ softness as are the transitions to the $0'$ double-γ vibrational state.[12] The goal of the present work was to determine the γ softness of the Pt nuclei from measurement of these $E2$ transition strengths by heavy-ion Coulomb excitation.

The Pt iostopes were Coulomb excited using a ^{136}Xe beam from the SuperHILAC of the Lawrence Berkeley Laboratory. The targets consist of $\sim 1\text{-mg/cm}^2$ self-supporting rolled metallic foils of isotopically enriched $^{192}Pt(57.3\%)$, $^{194}Pt(97.4\%)$, and $^{196}Pt(97.5\%)$. Three silicon detectors were used to detect scattered Xe ions at