tings observed in $^3H(p,n)^3He$ and $^{15}N(p,n)^{15}O$ can be understood in terms of the greater influence of the Coulomb interaction in the heavier system and differences in the extent to which the resonances which carry mixed isospin overlap. The reaction $^{11}B(p,n)^{11}C$ is similar to the reaction $^{15}N(p,n)^{15}O$ in that the splitting strengths are dominated by s- and d-wave resonances. However, the strengths are expected to be somewhat weaker in $^{11}B(p,n)^{11}C$ because the influence of the Coulomb interaction is less and the resonances are not as narrow. Perhaps the most surprising feature of the present results is that the $1^-(s_{1/2},d_{3/2})$ and $2^-(d_{3/2},d_{5/2})$ splitting strengths which dominate the reaction $^{15}N(p,n)^{15}O$ are found to be so much weaker in the reaction $^{11}B(p,n)^{11}C$. Indeed, the predicted $P-A$ differences in $^{11}B(p,n)^{11}C$ would be negligible if the spins of the target and residual nuclei were not $\frac{3}{2}$, thus permitting other strengths to contribute.

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[1]R. C. Haight, J. J. Jarmer, J. E. Simmons, J. C. Martin, and T. R. Donoghue, Phys. Rev. Lett. 28, 1587 (1972).

[2]R. L. Walter and R. C. Byrd, in Proceedings of the Conference on the (p,n) Reaction and the Nucleon-Nucleon Force, Telluride, Colorado, 29–31 March, 1979 (to be published).

[3]T. R. Donoghue, Sr., M. A. Doyle, H. W. Clark, L. J. Dries, J. L. Regner, W. Tornow, R. C. Byrd, P. W. Lisowski, and R. L. Walter, Phys. Rev. Lett. 37, 981 (1976).

[4]R. C. Byrd, Ph.D. dissertation, Duke University, 1978 (unpublished).

[5]U. Rohrer and L. Brown, Nucl. Phys. A217, 525 (1973).

[6]Sr. M. A. Doyle, H. W. Clark, K. R. Crosthwaite, L. J. Dries, J. L. Regner, and T. R. Donoghue, Bull. Am. Phys. Soc. 21, 636 (1976).

[7]U. Rohrer and L. Brown, Nucl. Phys. A261, 141 (1976).

[8]R. L. Walter and P. W. Lisowski, in *Proceedings of the International Conference of the Interaction of Neutrons with Nuclei*, edited by E. Sheldon (U. S. Energy Research and Development Administration, Washington, D. C., 1976), p. 1061.

[9]H. E. Conzett, Phys. Lett. 51B, 445 (1974).

[10]L. G. Arnold, Bull. Am. Phys. Soc. 22, 588 (1977), and unpublished.

[11]R. J. Philpott and D. Halderson, in Proceedings of the Conference on the (p,n) Reaction and the Nucleon-Nucleon Force, Telluride, Colorado, 29–31 March, 1979 (to be published).

[12]R. J. Philpott, Nucl. Phys. A289, 109 (1977).

[13]D. Halderson and R. J. Philpott, Nucl. Phys. A321, 295 (1979).

[14]D. Halderson and R. J. Philpott, to be published.

[15]G. Bertsch, J. Borysowicz, H. McManus, and W. G. Love, Nucl. Phys. A284, 399 (1977).

[16]J. C. Overley and R. R. Borchers, Nucl. Phys. 65, 156 (1965).

Energy Dependence of Charged Pions Produced at 180° in 0.8–4.89-GeV Proton-Nucleus Collisions

L. S. Schroeder, S. A. Chessin, J. V. Geaga, J. Y. Grossiord,[a]
J. W. Harris, D. L. Hendrie, R. Treuhaft, and K. Van Bibber
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 25 September 1979)

High-energy charged pions produced at 180° in 0.8–4.89-GeV proton-nucleus collisions have been studied. Both the slopes of the energy spectra and the π^-/π^+ ratios increase rapidly with primary energy up to ~ 3–4 GeV, where limiting values appear to be reached. The dependence on target mass also changes over this energy range. Unlike forward pion-production results, backward pions at these energies do not obey the scaling law suggested by Schmidt and Blankenbecler.

We report on a systematic study of the energy dependence of charged pions produced at 180° in the collisions of 0.8–4.89-GeV protons with nuclei. A principal reason for studying production of energetic pions from nuclei in the backward direction is that in free nucleon-nucleon (N-N) collisions such production is kinematically restricted. Observation of pions beyond this kinematic limit may then be evidence for exotic production mechanisms such as production from clusters.[1–5] Early experiments by Baldin *et al.*[6] using 5.14- and 7.52-GeV protons observed charged pions at 180° with energies up to four times larger than expected for free N-N collisions. They argued that simple Fermi motion could not account for this effect and stated that the dominant mechanism for producing such pions is an interaction between the incident proton and multinucleon clusters in the target nucleus, referring to this mechanism as cumulative production. A recent experiment by Perdisat, Frankel, and Frati[7] using 0.6-GeV protons observed pions at 155°, at energies beyond the N-N kinematic limit. However, they concluded that the dominant mechanism is single scattering, where the incident proton interacts with a target nucleon[8,9] producing the observed pion via the reaction $NN \to NN\pi$. Are there two different mechanisms at work, one dominating below ~1 GeV and the other above ~5 GeV? If so, how is the transition between these made as the bombarding energy is increased?

Another factor motivating our experiment was a feature discovered in Ref. 6. They found an exponential energy spectrum for the pions, with a slope parameter $T_0 \approx 60$ MeV, independent of the bombarding energy. An experiment with 28.5-GeV protons,[10] studying backward pion production from a tantalum plate located in the Brookhaven National Laboratory 80-in. bubble chamber, yielded a slope consistent with the result of Ref. 6. This suggests that a limiting value appears to have been reached. Does this persist to energies lower than ~5 GeV and where does it start to break down? Our study of the energy dependence of pion production between 1 and 5 GeV provides an answer to this question. In addition, it provides data which can be used to test the validity and range of various high-energy models[1-4] which have attempted to explain the existence of the high-energy spectrum of backward pions. Finally, our experiment provides a definitive test of a hard-scattering model[11] which was successful in explaining the scaling observed in forward pion production[12] from nuclei at energies as low as 1 GeV. This model predicts that the 180° spectra should be independent of energy, depending only on a scaling parameter.[13]

The experiment was done at the Lawrence Berkeley Laboratory Bevatron using extracted proton beams of 0.8, 1.05, 2.1, 3.5, and 4.89 GeV, with intensities $\lesssim 10^{10}$/pulse. We measured single-particle inclusive spectra of positive and negative pions produced at 180° in the collisions of protons with targets of C, Al, Cu, Sn, and Pb. At 3.5 GeV only positive pions from Cu were measured. A spectrometer consisting of a dipole followed by a quadrupole doublet was used to measure the 180° pions. Time of flight between scintillators located near the entrance of the doublet and a three-element scintillation hodoscope located beyond its exit, the magnetic rigidity (p/z) of the spectrometer, and dE/dx information from the scintillators allowed us to separate and identify pions from other particles. Average acceptance parameters for this system are $\Delta\Omega \approx 1$ msr and $\Delta p/p = \pm 6\%$ per hodoscope element, and $\theta_{\rm lab} = 180° \pm 1°$. Both transport programs and wire orbiting of the spectrometer have been used to cross-check these values. The beam intensity was measured by an ion chamber which was calibrated via the ^{11}C activation technique and checked with monitor counters. Data have been corrected for absorption in all material along the pion flight path from target to rear counters and for decay in flight. Measurements with Cherenkov counters and simple calculations indicate that the lepton contamination is typically <4%. We estimate our overall uncertainty to be 12–15%. The results presented here are for pions with kinetic energies of $\geq$100 MeV.

We first discuss the energy dependence of the slope parameter for charged pion production. Like the results of Baldin *et al.*,[6] we find that our pion spectra fall off exponentially, and have therefore parametrized the Lorentz-invariant pion cross sections by the form $Ed\sigma/dp^3 = C\exp(-T/T_0)$, where T is the pion laboratory kinetic energy. Figure 1(a) shows the dependence of T_0 on the energy of the incident proton (T_p)—for a Cu target only, as T_0 is found to depend only weakly on target mass. Trends in the data are similar for both positive and negative pions. A sharp rise is observed up to about 3 GeV, after which T_0 appears to reach a limiting value of $\approx$60 MeV. Recently, using a combination of data for various backward pion production angles, Baldin reported[14] a similar trend and suggests that it is related to the onset of limiting target fragmentation above ~3–4 GeV. The dashed curve in Fig. 1(a) is the prediction of an "effective-target" model[3,4] where the incident proton is assumed to interact in a collective fashion with the row of nucleons along its path. During the collision, this row is excited and in de-exciting emits pions in a fashion analogous to bremsstrahlung. For 180° production, the model suggests that peripheral collisions play the dominant role. The prediction of the model is seen to be in excellent agreement with our results on the energy dependence of T_0.

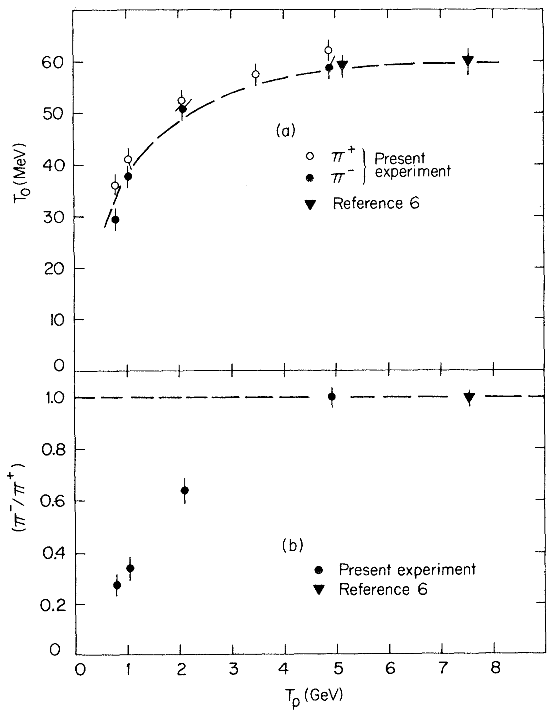

FIG. 1. Energy dependence of (a) T_0 parameter for pions, and (b) the π^-/π^+ ratio at 180° obtained by integrating each spectra up to 100 MeV for p-Cu collisions from 0.8 to 4.89 GeV. The dashed curve in both cases refers to the predictions of the "effective-target" model (Refs. 3 and 4).

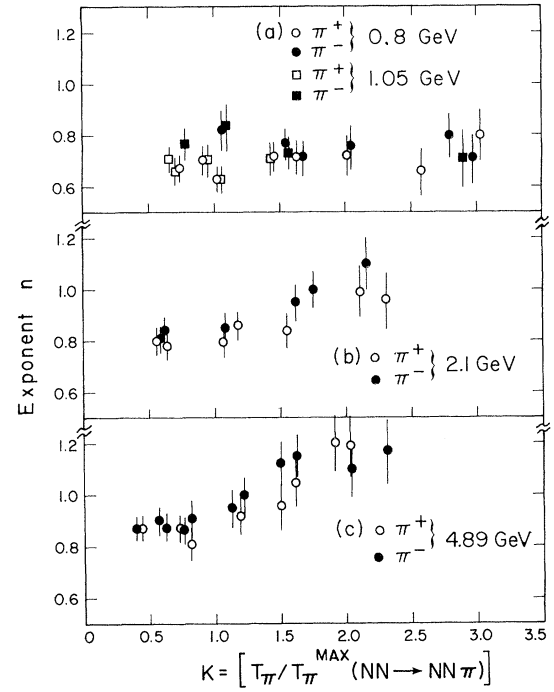

FIG. 2. A dependence for charged-pion production. The data were fitted by the form A^n; the exponent n is plotted vs the ratio K for (a) 0.8- and 1.05-GeV, (b) 2.1-GeV, and (c) 4.89-GeV protons.

However, the model consistently underestimates our pion cross sections, particularly at lower energies where it is low by about a factor of 4. Furthermore, the model does not distinguish between positive and negative pions[15] and assumes production of them to be equal. Figure 1(b) shows the ratio of the integrated cross sections for charged pions. The ratio rises sharply from the lowest energy and reaches a limiting value, again around 3–4 GeV, in disagreement with the model. Cross sections for multipion production in N-N collisions are known[16] to be increasing in the region of 1–5 GeV. The rise and subsequent flattening of both T_0 and the π^-/π^+ ratio shown in Fig. 1 could be associated with this feature. A detailed calculation, including absorption and charge-exchange effects, is required to ascertain fully the contributions of single-scattering processes in this energy region.

To study the dependence on target mass we have fitted the Lorentz invariant pion cross sections by the form $Ed\sigma/dp^3 \propto A^n$, where A is the atomic mass number of the target. Figure 2 shows a plot of the exponent n versus the ratio (K) of the pion laboratory kinetic energy to the maximum value kinematically allowed for an N-N collision. $K \geq 1$ corresponds to the cumulative production region. The data at 0.8 and 1.05 GeV are seen to be independent of K, with the cross section being $\approx$const.$\times A^{2/3}$. However, the 2.1-GeV data show an increase of n with K, and at 4.89 GeV the data exhibit the same behavior as the results of Ref. 6, rising to a value of $n = 1.0$–1.2 for $K > 1$. The variation in A dependence between 0.8 and 4.89 GeV suggests the possibility that different mechanisms are responsible for pion production over this energy range with a smooth evolution from one to the other as the energy is increased.

Next we test the prediction of the hard-scattering model of Schmidt and Blankenbecler.[11] This model predicts that the 180° negative-pion spectra should be independent of energy, depending only on the scaling parameter $x' = p_\pi^{\text{c.m.}}/(p_\pi^{\text{c.m.}})_{\max}$ in the form $(1-x')^N$. Simple counting arguments[11,17] yield $N = 6A - 5$, so that for a Cu target ($A = 63$) we expect $Ed\sigma/dp^3 \propto (1-x')^{373}$. Figure 3 shows a plot of the invariant cross section versus x' for a Cu target. Lack of scaling is clearly evident.

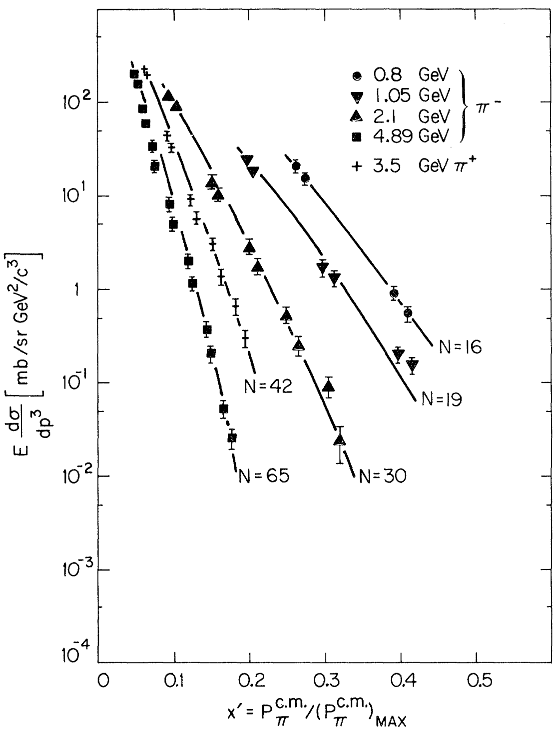

FIG. 3. Lorentz-invariant cross section vs x' for π^- production at 180° by 0.8-, 1.05-, 2.1-, and 4.89-GeV protons and π^+ production at 180° by 3.5-GeV protons on a Cu target.

However, we note that each spectrum can be represented by the form $(1-x')^N$, but for values of N much smaller than predicted. These values, shown as the solid lines through the data in Fig. 3, increase with energy. The model assumes that the proton interacts collectively with the whole nucleus, a condition necessarily satisfied only near $x'=1$. Landau and Gyulassy[17] have recently modified this model by assuming that the interaction occurs with a nucleon or nucleon cluster, rather than the entire nucleus. Their model[17] predicts an energy dependence which agrees with the trend shown in Fig. 3. The individual clusters are assumed to have internal motion, an exponential distribution providing the best fits to data. They are able to reproduce the data using clusters containing one to four nucleons, but with no single choice being preferred. As constructed, the model only predicts the shape of the backward pion cross section.

The rapid changes which are seen in 180° pion production when traversing the region of 1–5 GeV and higher may be indicative of a transition from dominance of a single nucleon-nucleon scattering mechanism to one where nucleon clusters play an ever increasing role. To isolate the production mechanism further, experiments are required which will measure additional observables such as associated multiplicities and two-particle correlations. However, it is clear that by measuring the production of pions in kinematic regions beyond those available in free N-N collisions, such as at 180° and high energies, one is probing the short-range behavior of nucleons in nuclei. This behavior might manifest itself as large Fermi momenta or nucleon clusters.

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[a]Present address: Institut de Physique Nucléaire de Lyon, Lyon, France.

[1]V. V. Burov, V. K. Lukyanov, and A. I. Titov, Phys. Lett. 67B, 46 (1977).

[2]M. I. Gorenstein and G. M. Zinovjev, Phys. Lett. 67B, 100 (1977).

[3]Meng Ta-chung, in *Proceedings of the Symposium on Relativistic Heavy Ion Collisions, 1978*, edited by R. Bock and R. Stock (Gesellschaft für Schwerionenforchung, Darmstadt, W. Germany, 1978).

[4]H. B. Mathis and Meng Ta-chung, Phys. Rev. C 18, 952 (1978).

[5]L. L. Frankfurt and M. I. Strikman, Phys. Lett. 83B, 407 (1979).

[6]A. M. Baldin, N. Giordenescu, V. N. Zubarev, L. K. Ivanova, N. S. Moroz, A. A. Povtoreiko, V. B. Radomanov, and V. S. Stavinskii, Yad. Fiz. 20, 1201 (1975) [Sov. J. Nucl. Phys. 20, 629 (1976)].

[7]C. F. Perdrisat, S. Frankel, and W. Frati, Phys. Rev. C 18, 1764 (1978).

[8]R. D. Amado and R. M. Woloshyn, Phys. Rev. Lett. 36, 1435 (1976).

[9]S. Frankel, Phys. Rev. Lett. 38, 1338 (1977).

[10]T. Hayashiro, O. Kusumoto, G. Fujioka, H. Fukushima, and T. Hara, Lett. Nuovo Cimento 16, 71 (1976).

[11]I. A. Schmidt and R. Blankenbecler, Phys. Rev. D 15, 3321 (1977).

[12]J. Papp, J. Jaros, L. Schroeder, J. Staples, H. Steiner, A. Wagner, and J. Wiss, Phys. Rev. Lett. 34, 601 (1975).

[13]R. P. Feynman, Phys. Rev. Lett. 23, 1415 (1969).

[14]A. M. Baldin, in *Proceedings of the Nineteenth International Conference on High Energy Physics, Tokyo, Japan, 1978*, edited by G. Takeda, S. Homma, M. Kawaguchi, and H. Miyazawa (Physical Society of

Japan, Tokyo, 1979), p. 455.
[15]E. Moeller and Meng Ta-chung, private communication.
[16]See, for example, the compilation of $NN \to NN + m\pi$ cross sections in Lawrence Radiation Laboratory Report No. UCLR-20000NN, 1970 (unpublished).
[17]R. H. Landau and M. Gyulassy, Phys. Rev. C 19, 149 (1979).

Selective Excitation of Multiple-Quantum Coherence in Nuclear Magnetic Resonance

W. S. Warren, S. Sinton, D. P. Weitekamp, and A. Pines
University of California, Berkeley, California 94720

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Wideband *selective* n-quantum excitation in the NMR of coupled spins is demonstrated for the first time. By a combination of multiple pulse averaging and phase shifts φ a pure n-quantum excitation operator can be produced ($n = 2\pi/\varphi$). This allows enhancement of normally weak n-quantum transitions. Selective excitation of the zero- and four-quantum transitions in benzene illustrates this approach. Extensions to selective absorption of only groups of n photons in other regimes of spectroscopy are straightforward, in principle.

It has recently been shown that the Zeeman-quantum-number selection rule ($\Delta M = 1$) of conventional Fourier-transform NMR can be overcome, thus permitting the observation of multiple-quantum ($\Delta M = n$) coherences.[1-4] Because the number of transitions decreases as ΔM increases, multiple-quantum spectra are normally easy to interpret, whereas the normal single-quantum spectrum may be intractable. Figure 1 illustrates this point with the n-quantum spectra of oriented benzene. Unfortunately, there is a large decrease in intensity which becomes exponentially more severe as n increases, limiting the size of molecules and number of quanta amenable to this approach. Clearly, it would be extremely valuable if we were able to selectively excite only certain orders of n-quantum coherences. This would have implications also in optical multiphoton pumping[5] by the selective absorption of only groups of n quanta. This has been considered virtually impossible in general, so that, to date, aside from even-odd–order selection due to symmetry of the bilinear spin operators,[6] no general method of exciting only se-

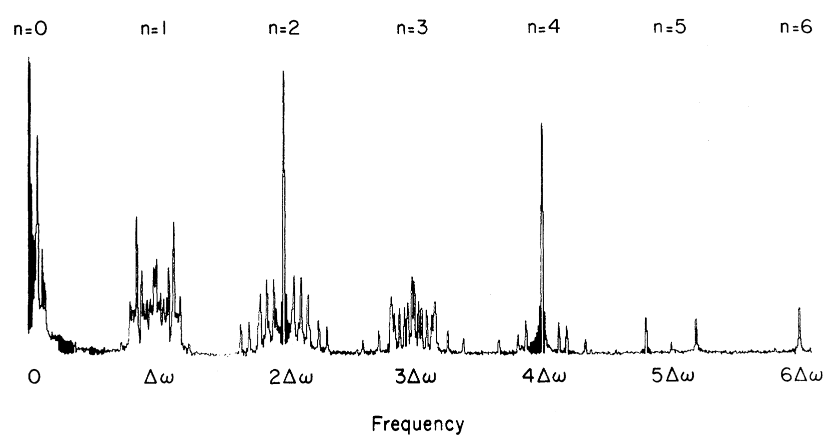

FIG. 1. Multiple-quantum NMR echo spectra of benzene oriented in a liquid crystalline solvent obtained with wideband nonselective excitation and with extensive time and ensemble averaging to observe weak four-, five, and six-quantum lines.