

Whether lesser excitations, short of a full-blown plasma, would cause significant J/ψ suppression, is a theoretical question much discussed in recent months.

The NA38 beam-dump experiment is designed specifically to look for J/ψ mesons manifested as a peak at 3.1 GeV in the invariant-mass spectrum of emerging muon pairs. Initial results from the NA38 oxygen-beam run at 200 GeV per nucleon indicate that J/ψ production is indeed suppressed by about one-third in head-on collisions.⁸ (See figure on page 19.) One estimates this suppression by comparing the observed J/ψ peak with its underlying muon-pair background in head-on and glancing collisions. Although uncertainties remain in its interpretation, the one-third suppression is thought to be quite significant, both experimentally and theoretically. "This result is perhaps the most intriguing so far," Gyulassy told us. "It's much more than we expected at this stage, when the energy densities are still quite modest, and we don't think we have a quark-gluon plasma yet."

A similar surprise comes to us from the E802 detector at Brookhaven, running with a silicon beam at 15 GeV per nucleon. In proton-proton collisions at this energy one sees about one strange K^+ meson produced for every ten or twenty π^+ . But when they collide silicon nuclei with

gold, the group finds a K^+/π^+ of $(20 \pm 5)\%$ —twice as high as the average ratio in pp collisions. The E802 detector is particularly good at distinguishing kaons from pions. If one looks only at head-on collisions, signalled by unusually large numbers of collision products, the K^+/π^+ ratio is higher still. (The K^-/π^- ratio, which is always lower, has not been observed to differ significantly between pp and heavy-ion experiments.)

This result is clearly interesting, but it is not well understood. One popular explanation goes as follows: At AGS energies, with beam and target stopping together, one is presumably seeing extraordinarily high baryon densities. Under these circumstances, up quarks and down quarks, the ordinary constituents of nucleons, are much more abundant than their antiparticles. (In a baryon-free central region at high energies, by contrast, one expects them all in roughly equal numbers.) Therefore when an $s\bar{s}$ pair of strange quarks is produced in the collision, the $\bar{s}$ strange antiquark should have a particularly easy task of finding an up quark to form a K^+ . This effect is referred to as " K^+ distillation." The observation is greeted with enthusiasm as evidence that one can reach very high baryon densities at these relatively low energies.

"These experimental runs have been a great success," comments theo-

rist Gordon Baym (University of Illinois). "These relatively light ions have achieved unprecedented energy densities over extended volumes. Our predictions and hopes for RHIC appear to be on track. Though much of the data remains to be analyzed, the experiments show that we understand heavy-ion collisions rather well."

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References

1. R. Albrecht *et al.* (WA80 collaboration), Phys. Lett. B **199**, 297 (1987).
2. A. Bamberger *et al.* Phys. Lett. B **184**, 271 (1987).
3. T. Akesson *et al.* (NA34 HELIOS collaboration), Z. Phys., to be published (1988).
4. P. L. Jain, K. Sengupta, G. Singh, Phys. Rev. Lett. **59**, 2531 (1987). G. Gerbier, W. Williams, P. B. Price, R. Guoziao, Phys. Rev. Lett. **59**, 2535 (1987).
5. T. Abbott *et al.* (E802 collaboration), Phys. Lett. B **197**, 285 (1987).
6. B. Bassalleck *et al.* (E814 collaboration), in Proc. Quark Matter '87, to be published in a special issue of Z. Phys. (1988).
7. T. Matsui, H. Satz, Phys. Lett. B **178**, 416 (1986).
8. M. C. Abreu *et al.* (NA38 collaboration) in Proc. Quark Matter '87, to be published in a special issue of Z. Phys. (1988).
9. T. Abbott *et al.* (E802 collaboration), in Proc. Quark Matter '87, to be published in a special issue of Z. Phys. (1988).

NUCLEON CORRELATIONS SEEN IN PION DOUBLE CHARGE-EXCHANGE REACTIONS

The position of one nucleon in a nucleus is assumed to affect the location of another, but such spatial correlations are hard to demonstrate. Many hoped they would appear in pion double charge-exchange reactions once the meson factories were built in the 1970s. Unfortunately, any correlations were masked by other complex interactions at the normal operating energies of the meson factories. Only recently—in new data taken at energies as low as 35 MeV—have nucleon correlations begun to surface. They show up in pion double charge exchange because these reactions necessarily involve two nucleons: The ingoing positive pion has successive charge-exchange scatterings with two neutrons in a nucleus, changing them into protons in the process. At low energies the cross sections for pion double charge-exchange transitions to certain states are larger than expected, and they are

peaked in the forward direction. Theorists have explained these features and others in terms of nucleon correlations. Their work indicates that the pion interacts with two valence nucleons outside a closed shell that are within one femtometer (about a proton radius) of each other.

The simplest case of a pion double charge-exchange reaction is one in which the nucleus consists of an even number of valence neutrons outside a closed shell. The pion interaction just changes two valence neutrons to protons and leaves the nucleus otherwise unchanged. The initial and final states are members of the same isospin multiplet; the final state is the double-isobaric-analog state of the ground state. In these transitions the reaction is essentially elastic.

Experiments on carbon-14

The first pion double charge-exchange reactions to show convincing-

ly the importance of nucleon correlations were performed below 80 MeV—an energy region well away from the possible interfering effects of the strong pion-nucleon interaction known as the delta resonance. William Gibbs (Los Alamos National Laboratory) told us that single charge-exchange reactions indicate that the nucleus is rather transparent to the pion at these energies; that is, the pion essentially sees only the nucleons with which it interacts and is not strongly affected by other nuclear interactions. Thus nucleon correlations should show up most clearly and with least distortion here.

In 1984 a team of Canadian, American and Israeli physicists, working at the Tri-University Meson Facility in Vancouver, measured¹ the double charge-exchange reaction cross section on carbon-14 at 50 MeV. They used TRIUMF's time projection chamber, with its large solid angle, to



"QUARKS, NEUTRINOS, MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM!"

increase their sensitivity to low event rates, and they chose C^{14} as their target because, as a nucleus with an isospin of 1, its cross section to the double isobaric state was expected to be relatively large. Still, the measurement was somewhat of a gamble: Based on extrapolation, the cross section was expected to be about ten times less than its value of 1 microbarn per steradian measured at 80 MeV. Surprisingly, it was equal to 1 $\mu\text{b}/\text{sr}$ at 50 MeV, at the angles sampled (50° – 120°). A subsequent experiment² at LAMPF, the meson physics facility at Los Alamos, measured the cross section at 20° and determined by extrapolation that the forward cross section was about 4 $\mu\text{b}/\text{sr}$. By contrast, the single charge-exchange cross section for transitions to the isobaric analog state falls to near zero at 0° , because the elementary pion-nucleon s - and p -wave amplitudes cancel.

Gerald Miller (University of Washington) proposed that the strong forward cross section for double charge exchange at low energy might be an indication of the quark presence in the nucleus.³ In his model, two valence nucleons merge into a six-quark bag when they come close together (less than 0.95 fm). The pion interacts with the bag essentially in one step, changing two down quarks to two up quarks. This model easily explains the sharply peaked forward cross section because the angular distribu-

tion reflects the form factor for the distribution of the six-quark bag, which can be anywhere outside the nuclear core.

As intriguing as Miller's concept is, others have proposed more conventional models to explain the data. For example, Theo Karapiperis and Masahiro Kobayashi (then at the Swiss Institute for Nuclear Research) calculated the double charge-exchange cross section in a delta-hole formalism, in which they carefully correct for kinematical and medium effects in the delta resonance channel and treat the other channels in a standard distorted wave approximation.⁴ Gibbs, together with William Kaufmann (Arizona State University) and Peter Siegel (now at California State Polytechnic University, Pomona), used a shell model that included nucleon correlations to analyze the observed behavior.⁵ They found that 50 percent of the scattering amplitude arose from nucleons that were less than 1 fm apart.

We asked Miller what experimental evidence might distinguish the six-quark bag from some of these more conventional models. He replied that his theory would predict a peak in the energy dependence of the forward cross section at around 550 MeV. Preliminary data from Los Alamos do not support this prediction.

Marek Bleszynski (UCLA) and Roy Glauber (Harvard) have used a model of coherent multiple scattering to

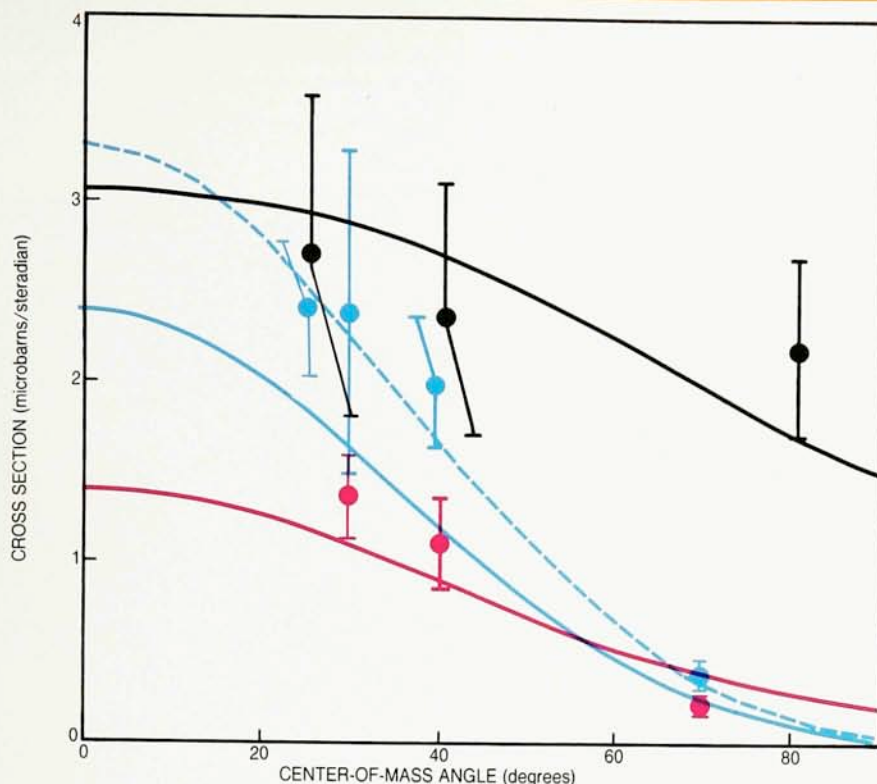
analyze the double charge-exchange reaction. In discussing the C^{14} data, they argued that the weakness of the interactions of the pion with the nucleus at low energy justifies a second-order impulse approximation that neglects pion absorption and elastic multiple scattering.⁶ By writing an expression for the double charge-exchange cross section explicitly in terms of two variables—the centroid of two nucleons and the distance between them—Bleszynski and Glauber show that the magnitude and shape of the differential cross sections can be quite responsive to the position correlations of the two neutrons. Glauber told us that the strong pair correlations of the two valence neutrons is caused by the angular momentum constraints present in the shell model. Helmut Baer (Los Alamos), a major participant in some of the double charge-exchange experiments, feels that the approach of Glauber and Bleszynski has made the phenomenon easier to visualize and has helped focus attention on the role of nucleon correlations.

Measurements of the double charge-exchange transition to double-isobaric-analog states at 50 MeV in two other nuclei—oxygen-18 and magnesium-26—show that the cross sections have about the same magnitude and angular distributions as those for C^{14} . All three have isobaric spins of 1. These data suggest that the double charge-exchange reaction is fairly independent of atomic mass number.

Puzzle of the calcium isotopes

Many reasoned that calcium-42, which also has an isobaric spin of 1, should have about the same cross section as the other isotopes that had been measured.

However, if the unexpectedly large double charge-exchange cross sections at low energy can be attributed to pairs of nucleons, then Ca^{48} , with eight valence neutrons, should have a cross section that is bigger than that for Ca^{42} by a factor of 28—equal to the number of pairs of excess neutrons. The Ca^{48} cross section was measured by a group of experimenters at LAMPF, including Baer, Michael Leitch, Robert Burman, Martin Cooper, Anzhi Cui, Bruce Dropesky, Greg Giesler, Farokh Irom, Christopher Morris (all of Los Alamos), James Knudson, Joseph Comfort (both of Arizona State), Dennis Wright (Virginia Polytechnic Institute) and Ronald Gilman (University of Pennsylvania).⁷ They were unable to sort out the double-isobaric-analog final state from the other final states at 50 MeV, but they did mea-



Pion double charge-exchange cross sections⁷⁻⁹ are shown for three calcium isotopes: Ca^{42} (blue circles), Ca^{44} (red) and Ca^{48} (black). Experimenters expected the cross section for Ca^{48} to be more than ten times greater than what was eventually measured. Data are compared with recent theoretical predictions¹⁰ (solid lines in corresponding colors), which take account of nucleon correlations. Blue dotted line shows the Ca^{42} cross section from a calculation that includes more than one angular momentum shell.

sure the cross section for a transition to this state at 35 MeV. They found that it was about the same as those for C^{14} , O^{18} and Mg^{26} and that it had a rather flat angular distribution. Subsequent measurements on Ca^{42} and Ca^{44} showed that the ratio of cross sections of the three calcium isotopes is 1:0.6:1.1 instead of 1:6:28, as expected on the basis of excess neutron pairs.^{8,9}

Elizabeth Bleszynski (UCLA) has recently joined Glauber and Marek Bleszynski to calculate¹⁰ the differential cross sections for the three calcium isotopes, which compare favorably with the measurements (see the figure above). Adding extra neutrons to the valence shell considerably flattens the angular distributions. It also causes the probability distribution of nucleon pairs to be much less sharply peaked at distances below 1 fm, as these theorists show. In the picture they develop, the angular distribution contributed by any neutron pair is roughly equal to the form factor for the distribution of its centroid. For the closely spaced pair in Ca^{42} , the centroid, whose distribution is essentially that of the neutrons themselves, can extend to large radii. Thus the

form factor is sharply peaked. In the case of Ca^{48} , the exclusion principle requires the nucleons to be farther apart; hence their centroids are concentrated at small radii and the form factor is broader.

Gibbs, with Naftali Auerbach and Eliazar Piasetzky (both of Tel Aviv University), have analyzed the dependence of the amplitude of the pion double charge-exchange reaction on the number of valence neutrons in a given shell.¹¹ They find that the amplitude for an entire shell can be written as the sum of only two terms, multiplied by the square root of the number of pairs of excess nucleons. The first term is present even in the absence of nucleon correlations, whereas the next term represents the influence of short-range interactions. If the double charge exchange proceeds exclusively via the intermediate analog state, only the first of these terms would appear. The second term results when calculations include a sum over all other intermediate states. (When the pion collides with one of two correlated nucleons, it can change the state of both. The subsequent pion collision can change them both back again. Thus the

intermediate state is not necessarily the analog one.)

The second term contributes with full strength only to the cross section for Ca^{42} , where it accounts for the forward angle scattering. The interference between the first and second terms in the case of Ca^{48} explains why that cross section is relatively small and flat. Gibbs, Auerbach, Kaufmann and Joseph Ginocchio (Los Alamos) have since performed more detailed shell model calculations to show that these two terms agree with those extracted from experimental data.

Now that this fairly limited class of reactions has demonstrated the influence of nucleon correlations, investigators are turning to other nuclei. For example, Ginocchio has generalized the approach of his Los Alamos colleagues to calculate double charge-exchange cross sections for nuclei with both protons and neutrons in the valence shell.

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References

1. I. Navon, M. J. Leitch, D. A. Bryman, T. Numao, P. Schlatter, G. Azuelos, R. Poutissou, R. A. Burnham, M. Hasinoff, J. M. Poutissou, J. A. Macdonald, J. E. Spuller, C. K. Hargrove, H. Mes, M. Blecher, K. Gotow, M. Moinester, H. Baer, *Phys. Rev. Lett.* **52**, 105 (1984).
2. M. J. Leitch, E. Piasetzky, H. W. Baer, J. D. Bowman, R. L. Burman, B. J. Dreesky, G. A. Rebka Jr., J. N. Knudson, J. R. Comfort, V. A. Pinnick, D. H. Wright, S. A. Wood, *Phys. Rev. Lett.* **54**, 1482 (1985).
3. G. Miller, *Phys. Rev. Lett.* **53**, 2008 (1984).
4. T. Karapiperis, M. Kobayashi, *Phys. Rev. Lett.* **54**, 1230 (1985).
5. W. R. Gibbs, W. B. Kaufmann, P. B. Siegel, *Proc. of the Pion Double Charge-Exchange Workshop*, LAMPF, Los Alamos National Laboratory, Los Alamos, N. M., 10-12 January 1985.
6. M. Bleszynski, R. Glauber, *Phys. Rev. C* **37**, 681 (1987).
7. H. W. Baer, M. J. Leitch, R. L. Burman, M. D. Cooper, A. Z. Cui, B. J. Dreesky, G. C. Geisler, F. Irom, C. L. Morris, J. N. Knudson, J. R. Comfort, D. H. Wright, R. Gilman, *Phys. Rev. C* **35**, 1425 (1987).
8. Z. Weinfeld, E. Piasetzky, H. W. Baer, R. L. Burman, M. J. Leitch, C. L. Morris, D. H. Wright, S. H. Rokni, J. R. Comfort, *Phys. Rev. C* **37**, 902 (1988).
9. K. K. Seth, *Nucl. Phys. A* **478**, 591C (1988).
10. R. Glauber, E. Bleszynski, M. Bleszynski, to be publ. in *Phys. Rev. Lett.*
11. N. Auerbach, W. R. Gibbs, E. Piasetzky, *Phys. Rev. Lett.* **59**, 1076 (1987).