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FUTURE PROSPECTS IN N-NUCLEUS INTERACTIONS

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ABSTRACT

I examine in detail two research areas, polarization observables and antiproton-nucleus reactions, which should have near-term future impact on our understanding of the interaction of medium-energy nucleons in nuclei. More speculative future experiments employing cooled beams, double spectrometer systems, and large Q-value low momentum-transfer reactions are also discussed.

INTRODUCTION

I have been asked to tell you about future possibilities, in other words, to predict what we will be or should be doing a few years from now. Webster's definition of "predict" is, "to foretell on the basis of observation, experience, or scientific reason." I can assure you that the last item has the least to do with what I will say. It is, of course, safer not to look too far into the future so I will concentrate partly on extensions of experiments that can be done now or will soon be feasible. The remainder will be more speculative and involve a heavy dose of ideas that I have gleaned from various proposals for research[1,2] to be performed or machines to be built.[3] Although I will mention possibilities for observing exotic states of nuclear matter, one subject that I will specifically omit is hypernuclei. Not that this subject is out of place here, but it has been covered in depth at other conferences. Antiproton-nucleus interactions will, however, be discussed since this subject has direct bearing on many aspects of N-nucleus physics. Interspersed through these discussions and in the final sections, I will briefly describe some more speculative areas where the machines of the future may have some impact.

POLARIZATION OBSERVABLES IN (p,p') REACTIONS

Intermediate protons offer a distinct advantage over lower energy beams in that very efficient proton polarimeters may be built. At the high resolution spectrometer (HRS) at LAMPF, the focal-plane polarimeter[4] has a scattering efficiency of about 10% and an effective analyzing power of ~0.4 at E_p = 500 MeV. In effect, this means that nearly every reaction for which a cross section is measurable can be made to yield polarization transfer (PT) observables with a bit more effort.

Spin correlation (SC) experiments are also on the near horizon when the IUCF Cooler[3] comes on-line. The high luminosity of the circulating polarized beams in the cooler will make feasible for the first time the use of jet targets of polarized nuclei. Jet targets should also allow analysis of final nuclear polarization in many cases where more conventional targetry would not. This is an exciting area for future double-spectrometer experiments.

What might a new generation of PT and SC experiments tell us about nuclei that is difficult or impossible to get by other means? To my knowledge there has not been any general analysis of what physics SC experiments would yield. Polarization transfer, on the other hand, has been examined in detail recently[5-7] and experimental evidence suggests that these new observables may be exceptionally interesting. Without delving into the theory, I will discuss two examples that should have significant future application.

In the excitation of unnatural parity states, two spin-dependent form factors enter in the inelastic scattering (or charge exchange) process, the transverse $X_T(q)$ and longitudinal $X_L(q)$. The former is similar to that measured in magnetic electron scattering. The latter is not present in (e,e'). In the eikonal single-scattering approximation, the PT observables may be used to separate these two form factors. Specifically,

line up

$$X_L^2(q) = \sigma/4E^2\left(1 - D_{NN} + D_{SS'} - D_{LL'}\right), \qquad (1)$$

$$X_T^2(q) = \sigma/4F^2\left(1 - D_{NN} - D_{SS'} + D_{LL'}\right), \qquad (2)$$

where E and F are coefficients of the nucleon nucleon (N-N) scattering amplitude (as defined in Ref. 8), and σ is the differential cross section. The PT parameters are in the Ann Arbor Convention.[9] The subscripts N, S, and L denote normal, sideways, and longitudinal components of polarization referred to the incoming (unprimed) and outgoing (primed) momentum directions. Measurement of the PT observables are of special interest not only because they may provide new information, but because of the particular sensitivities of the above form factors to questions of great current interest in nuclear physics.

Specifically X_L emphasizes those aspects of the nuclear response sensitive to the pion field, whereas X_T is related to transverse fields as yielded for example by ρ-meson exchange. These sensitivities are clearly indicated in Fig. 1, which shows calculations of the longitudinal and transverse nuclear response functions by Alberefo et al.[10] The precise physics input into such calculation can have a dramatic affect on the predicted values of X_L and X_T. For example in Fig. 1, specific assumptions were made about the nature of short range N-N, Δ-N, and Δ-Δ correlations. Such issues are hardly resolved at present as the debate continues on the influence of Δ-h configurations in nuclei and the proximity of normal nuclear matter to the critical value for pion condensation.

It is interesting to note that the continuum response as calculated in Fig. 1 may actually be measured. There is no contribution from natural parity excitations (within the approximations indicated previously) to Eqs. (1) and (2). The most interesting application of Eqs. (1) and (2) might be in the (n,p) or (p,n) reactions, where isospin transfer, ΔT = 1, is insured. Additionally, if

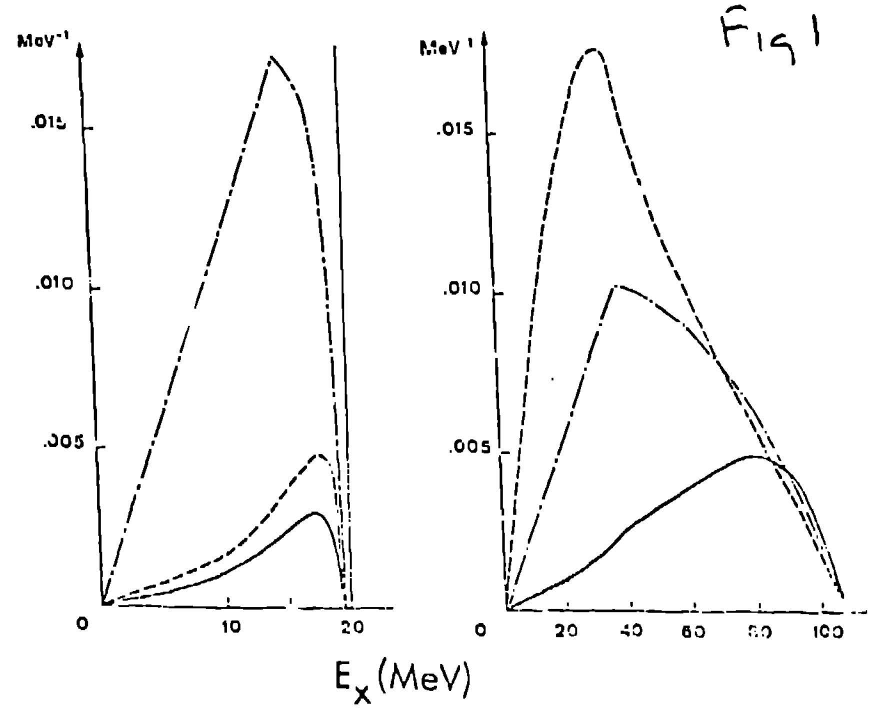

Fig. 1. Fermi gas (dot-dash), axial longitudinal (dash), and transverse response functions from Ref. 10.

sufficient precision could be attained, such an experiment might shed light on the questions of missing Gamow-Teller strength in the continuum.

Another recent application of polarization analysis, which I am confident will have significant future application, concerns the difference between the polarization (P) and analyzing power (A) in inelastic scattering (and charge exchange). For elastic scattering P = A of course due to time reversal (TR) invariance. For inelastic scattering TR does not imply P = A, however. It is easy to demonstrate that nonzero values of P-A arise from an interference between TR odd and even terms in the N-nucleus scattering amplitude.[11] The TR odd amplitides, which are ultimately related to the nonstatic parts of the N-N interaction, again offer the opportunity to measure aspects of nuclear structure not easily obtained in other experiments. At E_p = 150 MeV Carey et al.[12] have shown that P-A for the 1^+ T = 1 state in ^{12}C can be explained only by a transition density that includes a large term with orbital, spin, and total angular momentum ℓsj = 111 transfered to the nucleus. The Cohen Kurath[13] wave functions, which contain an important term of this type, are very successful in reproducing the data (Fig. 2). When the ℓsj = 111 term is removed, (P-A)(θ) remains near zero at all angles (P-A itself may still be large at diffraction minima as is seen in Fig. 2). The ℓsj = 111 term for 0^+ to 1^+ excitation is determined entirely by the combination of density-matrix elements, [illegible]) —

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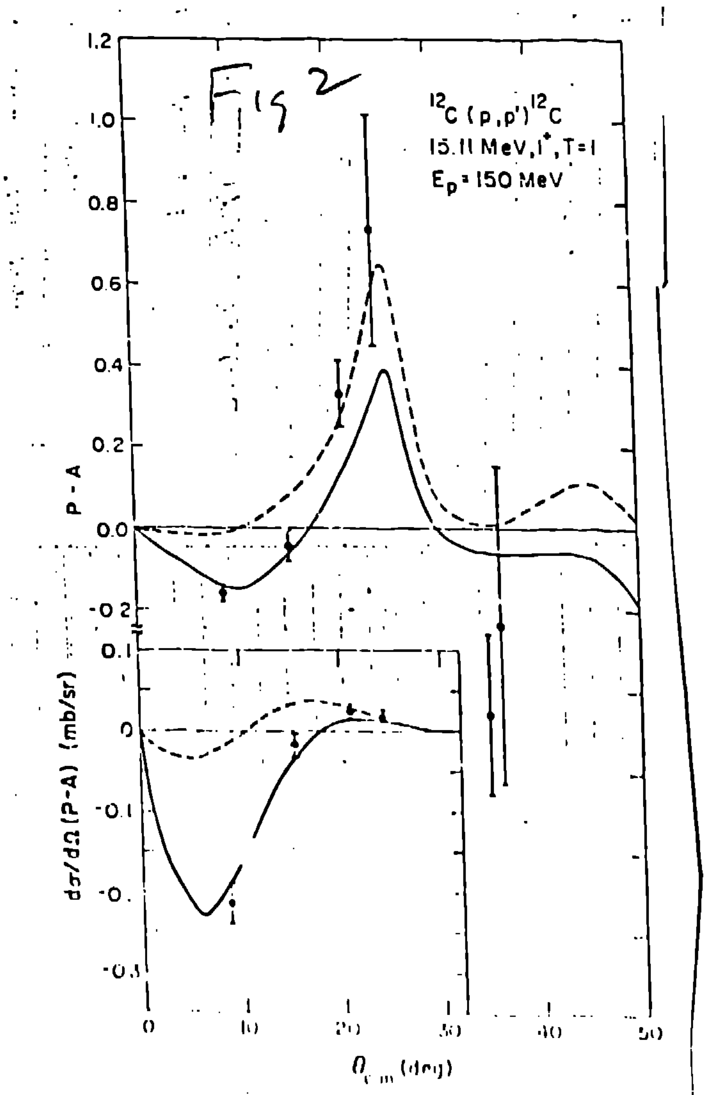

Fig. 2. P-A and (P-A)$d\sigma/d\Omega$. The solid curve is a DWIA calculation with the Cohen-Kurath wave function. The dashed curve has the 2s j = 111 term removed.

to which (e,e') is completely insensitive. It is likely that studies of P-A for other M1 states may provide unique experimental evidence concerning the effects of one particle, one hole ground-state correlations in reducing the strength of M1 transitions.

Without pretending that all the theoretical problems associated with nucleon-nucleus scattering have been solved, it is clear that much new nuclear structure physics should result in the coming years from polarization-transfer and spin-correlation experiments. To be even more speculative, there may well be an analogous application of spin observables in the excitation of nucleons when (and if) a new generation of higher energy polarized beams becomes available. As an example consider the excitation of the Δ^{++} by the reaction

$$p + p \rightarrow \Delta^{++} + n \quad .$$

What might one learn by measuring the longitudinal and transverse form factors or P-A for such a reaction? Clearly one needs theoretical input into this problem. The nuclear structure view that this reaction is $p(p,n)\Delta^{++}$ is of course incomplete. The probe and target are not distinct entities. Nevertheless, polarization observables in the excitation of nucleons would seem like a profitable ground for extension of our present and near future experimental techniques.

As a final note on polarization observables, the most intelligent applications of PT and SC techniques will require a deep understanding of the connections between the basic operators entering in nucleon scattering and those encountered in electromagnetic and semileptonic weak processes. Considerable progress has been made in laying out these connections[14] in terms of a common formalism; however, much remains to be done. It may turn out that guidance in the interpretation of exotic processes such as neutrino inelastic scattering could be provided by nucleon polarization observables.

ANTIPROTON NUCLEUS INTERACTIONS

Antiproton nucleus interactions promise numerous possibilities for new and exciting physics in the near future when the LEAR facility at CERN comes on-line. Describing with any accuracy the nature of this new physics is another matter -- considerable uncertainity exists concerning even the basic features of the $\bar{N}$-N system. Imbedding various possible scenarios for the $\bar{N}$-N interaction into nuclear matter is also not straightforward. Nevertheless with the aid of a few ideas gleaned from the theoretical literature and two experimental proposals to LEAR, I will speculate about what the future might hold.

One feature of $\bar{N}$-N system, which has a profound impact on $\bar{N}$-nucleus interactions, is the large cross section for annihilation. The dominant annihilation channel results in the production of roughly five pions. The mean pion energy is near that appropriate for the Δ_{33} resonance. That means that the pions themselves should have a short mean free path inside a nucleus. Thus if one could implant such a catastrophic event (releasing nearly 2 GeV of rest-mass energy) inside a nucleus, conditions favorable for the production of nonnormal phases of nuclear matter might well be achieved. But how does one implant a probe that itself has an extremely high probability of interacting even in the low-density matter in the nuclear surface? A group at Los Alamos has recently suggested that the properties of the $\bar{N}$-N interaction at moderate energies conspire to give antiprotons a better chance of depositing their energy in the nuclear interior than might be expected.[2,15] Extensive calculations using the intranuclear cascade model (INC) reveal that 175-MeV antiprotons have a high probability for depositing in excess of 1 GeV in a ^{238}U nucleus (Fig 3). A key feature in these calculations is a transparency conferred on the $\bar{N}$-nucleus system by the combination of a strongly energy-dependent annihilation cross section and an attractive $\bar{N}$-nucleus potential.

The Los Alamos National Laboratory group intends to use a very large, solid-angle spectrometer at LEAR in search for possible exotic effects induced by the explosion of antiprotons inside nuclei. Pion multiplicities and correlations will be employed in the initial phase of this effort. In the examination of nuclear matter under extreme conditions, the hope is that the relatively small momentum-transfer $\bar{N}$-nucleus reactions will complement relativistic heavy-ion collisions.

From the quieter side of $\bar{N}$-nucleus interaction, what might elastic or inelastic-$\bar{p}$ scattering tell us about nuclei? The Saclay-Strasbourg - Tel Aviv collaboration[1] proposes to use the SPES II spectrometer at LEAR to carry out such studies. What types of states might be strongly excited in $(\bar{p},\bar{p}')$? At present one can only speculate since few of the experiments necessary to construct the $\bar{N}$-N scattering amplitude have been performed. We are not totally in the

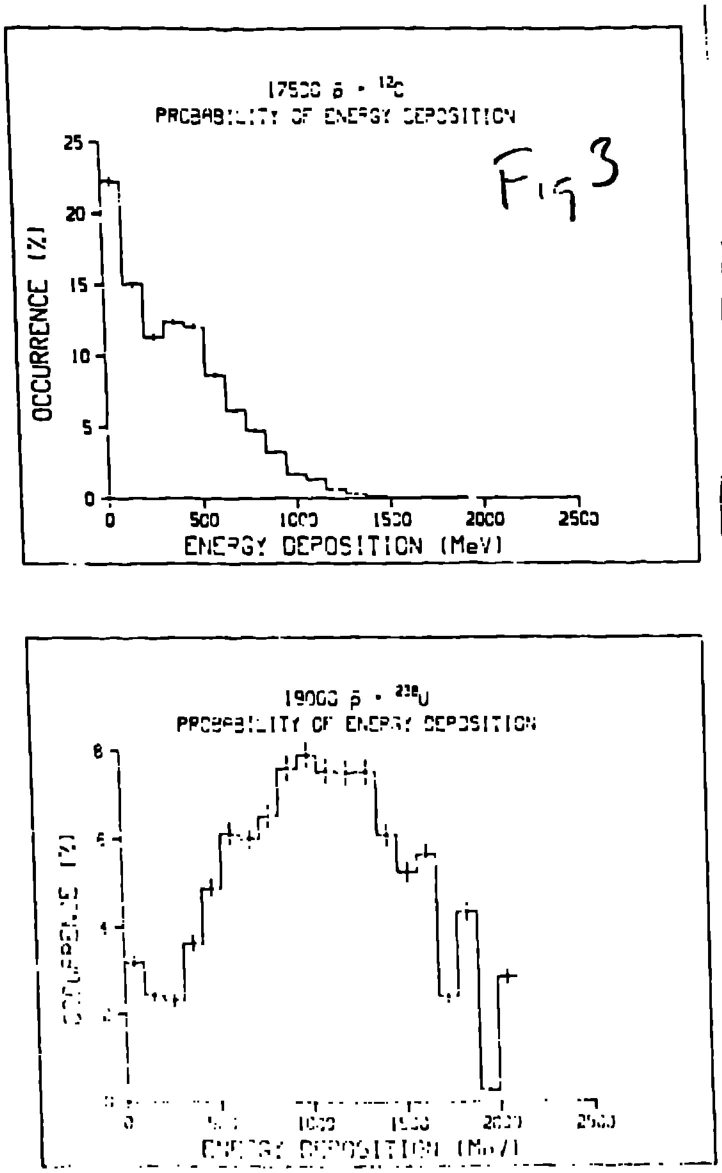

Fig. 3. Energy deposition probabilities for antiprotons from Ref. 15.

dark, however. T-channel meson exchange models of the N-N interaction may be used in conjunction with the G-parity transformation to construct the long-range real part of the $\bar{N}$-N interaction. An imaginary term is normally added to the real part to take annihilation into account phenomenologically. Several calculations along these lines have recently been published.[16-18] Among the interesting results is a strong isoscalar tensor interaction, which profoundly influences the spin observables in the $\bar{p}p$ system.[17] Such strong spin-dependences are suggestive of interesting physics for the $\bar{N}$-nucleus system.

Given a free $\bar{N}$-N interaction one is still a long way from knowing what the effective interaction will be inside a nucleus.

Medium effects, to use recent parlance, may turn out to be enormous. To some extent, however, what happens to the $\bar{N}N$ interaction may be irrelevant since Ns will most probably never make it to the nuclear interior. In the surface region "tρ" may not be a bad approximation.[19]

In a recent talk on $\bar{N}$-nucleus physics, Garreta[20] speculates that one-pion exchange (OPE) may dominate (p,p') spectra at small momentum transfer. Such states as the 15.11-MeV, 1^+,T=1 of ^{12}C would be prominent. This speculation is very plausible but it would be a mistake to conclude that the excitation of one-pion-like states is therefore uninteresting. The spin-isospin interaction for the N-N system may be written as

$$V_{\sigma\tau}(q) = V_{OPE}(q) + g_0' \quad ,$$

where g_0' is independent of q. At q = 0, $V_{OPE} \rightarrow 0$ and the cross section to pion-like states is governed by g_0'. This quantity is large as can be seen in a recent 0° (p,p') spectrum from the HRS at the Los Alamos Meson Facility (Fig. 4). The effect of short range interactions that determine g_0' may be completely different in the $\bar{N}$-N system. Finally the SPES II collaboration proposes to examine antiprotonic nuclei by using the recoilless ($\bar{p}$,p) reaction. Such nuclei might exhibit relatively long-lived states if a sufficiently strong attractive potential existed[21] for a high-spin state whose wave function was largely outside the range of the annihilation potential.

NEW SPECTROMETER TECHNIQUES

As future accelerators are constructed (at least in our dreams) it is important to ask what instrumentation is required to put the beam to maximal use. Magnetic spectrometers have been vital in medium-energy charged-particle work and will undoubtedly continue to be so in the future. They are essential not only in providing very precise momentum resolution and particle

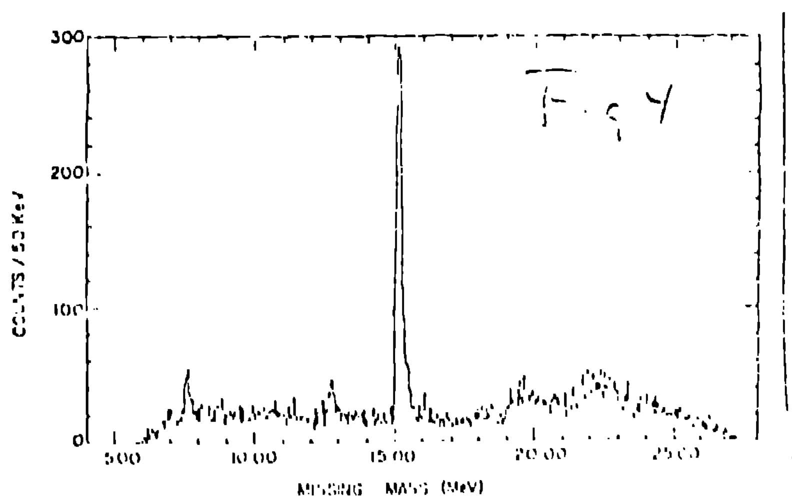

Fig. 4. Spectrum of the ^{12}C (p,p')^{12}C reaction at Ep = 497 MeV taken at zero degree.

identification, but also in the spatial separation of high-cross-section and low-cross-section reactions allowing the low background observation of the latter. The dual spectrometer system for IUCF[22] should provide much of the capability needed to use the unique properties of the electron-cooled beams. One spectrometer will have exceptional resolving power, with the promise of ∿10-keV resolution at 200 MeV. The other spectrometer, to be used in coincidence, will detect a much broader range of momenta with a sizable solid angle. It is plausible to fores e that dual spectrometer coincidence studies will assume an increasing importance in future investigations using medium-energy nucleons.

As a very speculative example of a two-spectrometer cooled-beam coincidence experiment consider the excitation of a important but weakly excited giant resonance. It is unobservable in a single experiment because of the large continuum. Once excited, however, it remembers its strong connection with the ground state and decays by gamma emission with perhaps a 10^{-4} branching ratio. Excitation o the contimuum, on the other hand does not produce the original target nucleus. In the $A(p,p')A^*$ reaction, one measures p'-A coincidences to enhance the giant resonance signal. Many other possibilities undoubtedly exist for recoil coincidence detection.

Another interesting application of spectrometers that should see even more future action is inelastic scattering at 0°. Zero-degree scattering of medium-energy protons yields momentum transfers that are extremely small (limited only by the reaction Q- value) and are hence ideal for the study of low spin states such as 0^+ and 1^+.

Zero-degree scattering is not only promising from the experimental point of view for maximizing the signal for $\Delta\ell = 0$ transitions, it also offers relative theoretical simplicity. Distortion effects are minimal and transition densities are closest to the "photon point".

Such studies have been in progress for about a year at the HRS at LAMPF using a specially prepared beam of 500-MeV protons. Definition of the beam is accomplished by using foil strippers instead of collimators while the ions are negative. The highly tailored H^- beam is then stripped of its electrons and transported to the target with no further collimation. This beam then passes through the spectrometer and misses all of the focal plane detectors. Inelastic scattering is detected for energy losses as small as 3 MeV. A typical 0° spectrum from 500-MeV protons on ^{12}C is shown in Fig. 4. This technique is much more difficult for heavy targets due to rescattering of Coulomb-scattered particles. Active collimators show promise of alleviating this problem for heavier systems.

HIGH-Q, LOW-q REACTIONS

Zero-degree scattering even of Fermi-Lab protons will not yield zero-momentum transfer in the region of excitation of Δ-isobar-hole configurations. Recall that it is the low q aspects of the Δ-h admixtures that are of interest in the Gamow-Teller/M1 problem.[23] Thus if we are able to examine this end of the Δ-h spectrum whose influence is so strongly exerted on the central theme of this conference, we must find another way to do it.

One method is to use the (p,d) reaction at 800 MeV.[24] The q for such conditions is near zero resulting hopefully in the production of recoilless deltas in the residual nucleus. Such an experiment was recently performed at LAMPF.[24] Deuterons with energy loss corresponding to Δ production in the $^{13}C(p,d)^{12}C^*$ reaction were observed in coincidence with decay protons from the excited nucleus. The constant excitation energy observed in the coincidence spectrum is very suggestive of the kinematics of a state in ^{12}C decaying rather than of a quasi-free $p+p \rightarrow d+\pi^+$ mechanism. Continued investigation is required before definitive statements can be made, however.

This reaction is an example of a general class of high Q-value, low-momentum-transfer reactions that are possible avenues for producing nuclear states ranging from slightly exotic (e.g., the previous example) to profoundly different. A. Goldhaber has recently suggested,[25] that colorless (in the quark sense) nuclear matter may exist in exotic configurations not at all resembling A-nucleons, but with excitation energies perhaps only a few hundred MeV above standard nucleonic matter. He speculates that high-Q-value, low-q reactions may be appropriate for exciting exotic configurations, or perhaps more likely, for producing identifiable precursors of such states.

What reaction mechanism could ever lead to the formation of such exotica? That is of course the proverbial "fly in the ointment;" indeed even for such "conventional" reactions as $^{13}C(p,d)^{12}C\Delta$ the mechanism is most appropriately described by a black box. On the positive side, in hadron-hadron interactions, no proposed reaction mechanism, however absurd, can be completely eliminated from consideration. In other words if fundamental conservation laws don't forbid it, it will probably occur with a cross section that is not ridiculous by weak-interaction standards.

Subject

SUMMARY

I have emphasized polarization observables in nucleon-nucleus physics and cross sections and correlation experiments in antinuclion-nucleus physics as the most promising areas for the near future. The more distant future is largely a matter of guess work. Aside from describing what might be accomplished with new machines and devices it is difficult to be specific. If we have learned anything relevent to the future from the near past in intermediate energy physics, it is that nuclear physicists can no longer be parochial. Much more, for example, can be learned about a given state by doing (p,p'), (e,e'), and (π,π') experiments than can be gotten from one reaction in isolation. In the future this trend needs to continue with attention given to the possible complementary aspects of hadron-scattering and weak-interaction experiments. Additionally, one of the most obvious challenges of medium-energy physics, determination of the necessity or lack thereof of quark degrees of freedom, is a central theme in high-energy heavy-ion

physics. We will learn more if we understand the nature of other approaches to the same subject.

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