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PROGRESS REPORT

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Theoretical and High Energy Physics

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DISCLAIMER

A Generalization of the Spherical Harmonic Gradient Formula (B. F. Bayman)

Let $\mathcal{Y}^k_m(\vec{\nabla})$ denote an operator in which x,y,z in the solid harmonic $\mathcal{Y}^k_m(\vec{r})$ are replaced by $\frac{\partial}{\partial x}$, $\frac{\partial}{\partial y}$, $\frac{\partial}{\partial z}$. If this operator acts on a scalar function $f(r)\, Y^{\ell}_{m'}(\hat{r})$, the result can be expanded in terms of vector-coupled products,

$$\mathcal{Y}^k_m(\vec{\nabla})\, f(r)\, Y^{\ell}_{m'}(\hat{r}) = \sum_L (k\ \ell\ m\ m' \mid L\ m+m')\left[\mathcal{Y}^k(\vec{\nabla})\, f(r)\, Y^{\ell}(\hat{r})\right]^L_{m+m'}$$

We show that the bracketed quantity can be written in the form

$$\left[\mathcal{Y}^k(\vec{\nabla})\, f(r)\, Y^{\ell}(\hat{r})\right]^L_M = g^L_{k\ell}(r)\; Y^L_M(\hat{r})$$

where

$$g^L_{k\ell}(r) \equiv \frac{(-2)^{\frac{L-k-\ell}{2}}}{\left(\frac{L+\ell-k}{2}\right)!\left(\frac{L+k-\ell}{2}\right)!}\sqrt{\frac{(2k+1)(2\ell+1)(k+\ell-L)!(\ell+L-k)!(L+k-\ell)!(k+\ell+L+1)!}{4\pi}}$$

$$\times\sum_{\mu=0}^{\frac{k+\ell-L}{2}} \frac{(L+\mu)!\, 2^{\mu}\, r^{L+2\mu}}{\mu!\,(2L+2\mu+1)!\left(\frac{k+\ell-L}{2}-\mu\right)!}\left(\frac{1}{r}\frac{d}{dr}\right)^{\frac{L+k-\ell}{2}+\mu}\frac{f(r)}{r^{\ell}} .$$

The familiar spherical harmonic gradient formula is the k = 1 special case of this general result. Various mutipole expansions involving angular momentum eigenstates can be derived using this expression.

Two-Neutron Transfer Reaction Mechanism with Heavy Ions at Sub-Coulomb Energies (B. F. Bayman (with M. Franey, J. Lilley and W. R. Phillips))

The ^{208}Pb(^{16}O,^{18}O)^{206}Pb reaction has been studied at the Minnesota Tandem van der Graaf at incident ^{16}O projectile energies below the Coulomb barrier. A finite-range, full-recoil, one-step DWBA calculation was performed to interpret the data. When the relative energies of the colliding and separating nuclei are below the Coulomb barrier, the optical wave functions are essentially pure Coulomb waves. This removes the ambiguity associated with the choice of the optical potentials, an abiquity which can easily introduce uncertainties of factors of five in DWBA predictions. Thus when it was found that the one-step sub-Coulomb DWBA calculation underestimated the data by an order of magnitude, this implied very strongly that multistep processes make a significant contribution to the physical transfer process.

Two types of multistep processes were investigated:

1) inelastic scattering coupled with one-step transfer, for example,
$^{208}Pb + ^{16}O \rightarrow ^{206}Pb_{2+} + ^{18}O \rightarrow ^{206}Pb_{gs} + ^{18}O$ or
$^{208}Pb + ^{16}O \rightarrow ^{208}Pb_{3-} + ^{16}O \rightarrow ^{206}Pb_{gs} + ^{18}O$. These were found to make a small contribution.

2) successive one-nucleon transfer, $^{208}Pb + ^{16}O \rightarrow ^{207}Pb + ^{17}O \rightarrow ^{206}Pb + ^{18}O$. The intermediate ^{207}Pb and ^{17}O states were taken to be closed shells plus a single hole or particle, respectively. This was found to make a very significant contribution to the transfer process. The successive one-nucleon transfer amplitude, plus the one-step amplitude, plus the non-orthogonality correction needed when two-step and one-step processes are included simultaneously, yielded a differential cross-section that agreed with the data in magnitude, energy dependence, and angular dependence.

We have thus become convinced of the importance of successive one-nucleon transfer in the two-neutron transfer reaction. Hundreds of analyses of two-neutron transfer reactions have been performed using one-step-only codes. They usually underestimate the observed cross-section, but this has usually been blamed on optical wave function uncertainties.

We now think it highly probable that important successive one-nucleon transfer components occur whenever two-nucleon transfer processes occur.

This work has been submitted for publication in Physical Review Letters.

Resonating-group method for nuclear many-body problems (Y. C. Tang (with M. LeMere and D. R. Thompson)).

A review article on the resonating-group method was written for Physics Reports C. In this article, we have covered the following topics:

(a) A discussion on the general features of the resonating-group method.

(b) The formulation of this method in nuclear bound-state, scattering, and reaction problems.

(c) A brief description of the complex-generator-coordinate technique which has recently been developed to compute matrix elements occurring in resonating-group calculations involving relatively heavy clusters.

(d) Numerical examples to illustrate the utility of the resonating-group method.

(e) Information obtained from resonating-group calculations concerning the effects of the Pauli exclusion principle in nuclear scattering and reaction processes.

(f) Possible directions for future resonating-group studies in nuclear physics.

Exchange effects in nucleus-nucleus interaction (Y. C. Tang (with M. LeMere))

The effects of antisymmetrization, represented by various nucleon-exchange terms in a resonating-group formulation, are studied in the case of nucleus-nucleus scattering. By examining the features of the effective local potentials which are constructed to yield the same Born scattering amplitudes as these exchange terms, it is found that the one-exchange and the core-exchange terms are the most important. In addition, this study shows that in all scattering systems the one-exchange term has generally a substantial influence over a wide range of energies. On the other hand, the core-exchange term is important only when the nucleon-number difference of the interacting nuclei is rather small. Based on the results of this investigation, it can also be concluded that if a local-potential model is employed to phenomenologically analyze experimental scattering results, then the effective potential in this model must, in general, have an odd-even ℓ-dependent character.

Exchange-Coulomb interaction in resonating-group calculations (Y. C. Tang (with M. LeMere))

The evaluation of the exchange-Coulomb kernel in a resonating-group calculation is generally a tedious and difficult problem. In this investigation, a simple, self-consistent procedure is proposed to approximately calculate this kernel function. By applying this procedure to $d + \alpha$, $^3He + \alpha$, and light ions plus ^{16}O systems, it is found that satisfactory results can be obtained in all these cases.

Resonating-group study of $n + {}^6Li$ and $p + {}^6Li$ systems (Y. C. Tang (with D. J. Stubeda))

Our previous resonating-group calculation on the $n + {}^6Li$ system is improved by adopting a more realistic wave function for the ^6Li cluster. In our present study, this wave function is taken to be a linear superposition of two translationally invariant shell-model functions in oscillator wells of different width parameters. By adjusting these parameters and the relative weight of the two functions, we obtain very good agreement with experimentally determined ^{6}Li form factors up to q^2 of about 7 fm^{-2}.

Work on this project is very near completion. Our plan is to examine the effects of clustering in ^{6}Li on the odd-even behavior of the effective n + ^{6}Li optical potential and to investigate whether the resonating-group method can yield results in satisfactory agreement with experimental scattering data even at higher energies of about 50 MeV/nucleon.

Effective Operators in the Shell Model (P. J. Ellis)

Motivated by the idea that collective core polarization is sufficiently strong that it must be allowed to consistently renormalize all the interactions in a given diagram, Kirson arrived at self-consistent coupled equations which include both self-screening and vertex renormalization effects (Ann. Phys. 66, 624 (1971)). We have generalized these equations to include particle-particle ladders, since it now seems clear that the G-matrix should be doubly-partitioned so that diagrams with particle-particle states of low excitation energy enter on the same footing as the other diagrams. We also remove approximately the effect of the spurious 1^- core excitation, since Ando et al. (Prog. Theor. Phys. 57, 1303, 1584 (1977)) have shown it to be significant. A computer program to carry out these calculations is close to completion. Since the amount of computer storage and time required is quite large, we have made some approximations. Firstly, we use the Tamm-Dancoff approximation (TDA) rather than the random phase approximation (RPA) since screened TDA and RPA differ rather little. Secondly, the 3 particle-2 hole vertex will not be included in the self-consistency cycle, nor will the associated B-vertex be screened. We shall use both oscillator and simulated Hartree-Fock matrix elements, the latter following our earlier work. We expect to have results shortly for the effective particle-particle and particle-hole interactions and the effective charge (with F. L. Goodin).

Well known rules exist which allow one to write down the expression for a given diagram in an uncoupled representation or m-scheme. Since one wishes to exploit the rotational invariance of the nucleon-nucleon interaction, it is then necessary to couple the fermion lines in the diagram to definite angular momenta and, if desired, isospin. This necessitates writing out the Clebsch-Gordan coefficients, recoupling them as appropriate and performing the m-summations. In most cases a large amount of Racah algebra is involved, with, of course, a significant possibility for error. We are in the process of developing a direct method for determining the angular momentum factors. We decompose a given diagram, insofar as is possible, into products of ladder diagrams (either particle-particle or particle-hole) whose angular momentum structure is simple. For this purpose it is convenient to couple the diagram to a scalar, to cut open internal lines in various ways and to cut off any one-body insertions or one-body tensor operators. The recoupling transformations involve 9-j symbols and are simple to write down. The method can be applied to effective interaction diagrams for n valence particles (n=0,1,2,...) and effective operator diagrams, needed, for example, in calculating the effective charge. It allows one to obtain expressions for the diagrams in an angular momentum coupled representation virtually by inspection (with T. T. S. Kuo, J. S. Shurpin and K. C. Tam, Stony Brook and E. Osnes, Oslo).

<u>Study of Two-Step Processes in the ^{48}Ca(p,t)^{46}Ca Reaction</u> (P. J. Ellis)

The ^{48}Ca (p,t)^{46}Ca reaction has been used to study T = 4 states in ^{46}Ca which are the analogues of the corresponding states in ^{46}K. Several transitions were observed to unnatural parity states in ^{46}Ca with cross-sections only a factor of 2-3 weaker than for the natural parity states, whereas at least a factor of 10 is expected for direct transfer. One two-step process which suggests itself here is first a(p,^{3}He) reaction to an unnatural parity state in ^{46}K (this is allowed in zero-range DWBA) followed by (^{3}He,t) charge exchange to the analogue state in ^{46}Ca. We examined this process within the framework of the coupled channel Born approximation for the lowest 2^- and 4^- T = 4 states of ^{46}Ca. For the 4^- level the shape of the angular distribution disagrees with experiment and for both levels the magntidues of the cross sections are predicted to be more than a factor of 10 smaller than the data. Thus the (p,^{3}He) (^{3}He,t) process does not make a significant contribution to this reaction. This work will be submitted for publication shortly. (with M. Strayer and M. Werby, Texas A and M).

<u>Polarization in Heavy Ion Reactions</u> (P. J. Ellis)

In previous work on spin-dependent effects in heavy ion reactions, we generalized the Strutinsky model (a simple parameterization of the S-matrix elements) to include the effects of spin and this was helpful in understanding the differential cross sections obtained in DWBA calculations. I have extended the model to heavy ion polarization phenomena, since data has started to appear. It was found possible to obtain transparent expressions for the vector polarization of the residual nucleus and ejectile in an unpolarized experiment and the vector analyzing power of a polarized beam or oriented target (all perpendicular to the reaction plane). Basically we have the familiar three terms coming from reactions on opposite sides of the target (with opposing spin orientations) and the interference. In the case of ejectile polarization, it follows from the approximate form used for the Clebsch-Gordan coefficients that the terms are weighted with $\frac{j'-\ell'}{s'}$ where $\underset{\sim}{\ell}' + \underset{\sim}{s}' = \underset{\sim}{j}'$ and ℓ' is the relative orbital angular momentum in the exit channel, s' is the ejectile spin and j' the resultant. The expressions were discussed; they imply, for instance, that the magnitude of the polarizations will exhibit oscillations out of phase with those in the differential cross section in the absence of spin-dependent optical potentials. Comparison with exact DWBA results showed that the model could describe the qualitative features of the polarization predictions. It should therefore be useful in discussing experimental data as it becomes available. (Nuclear Physics, A302, 257 (1978).

The ^{30}Si (^{16}O,^{16}O')^{30}Si* Reaction at 60 MeV (A. Dudek-Ellis and P. J. Ellis).

We have attempted to fit Minnesota data for ^{16}O + ^{30}Si elastic scattering and inelastic scattering to the lowest 2^{+} state of ^{30}Si using the coupled channels formalism. (Note that the elastic data show oscillations similar to, but weaker than, those found in the ^{16}O + ^{28}Si system). A reasonable fit was achieved using the standard macroscopic rotational model; the vibrational model gave poorer results. The magnitude of $\beta_2 R$ needed for the nuclear deformation was in reasonable agreement with the values obtained in other work, but the sign could not be determined; in the case of negative β_2 a J-dependent imaginary potential was favored An $\underset{\sim}{\ell} \cdot \underset{\sim}{I}$ spin-orbit term in the optical potential was helpful with regard to the relative phasing of the elastic and inelastic angular distributions, but made the magnitude of the oscillations too strong. Similar fits were obtained with either small or "standard" values for the imaginary diffuseness parameter. (with V. Shkolnik, J. L. Artz, D. Dehnhard and H. P. Morsch, Phys. Rev, in press).

Coupled Channels Calculations for $^{28}Si\ (^{16}O,{}^{16}O')^{28}Si^*$ (A. Dudek-Ellis)

Coupled channels calculations were performed for $^{16}O + {}^{28}Si$ elastic scattering and inelastic scattering to the lowest 2^+ level of ^{28}Si at incident energies of 45, 55 and 63 MeV. The macroscopic rotational model was used. The effect of coupling on the elastic scattering was found to be a shift in the phase of the oscillations and an increase in the back angle cross sections. Both effects were removed by reducing the real well depth V by 10-15%, so that a good fit to the elastic data was regained. Thus the rather strong energy dependence in V obtained in pure elastic calculations is unchanged. Quite an acceptable fit was obtained to the 55 MeV inelastic data without parameter searching. (with V. Shkolnik and D. Dehnhard, Phys. Rev., in press).

The Abelian Higgs Model in 1 + 1 Dimensions (H. Joos (DESY), S. Gasiorowicz and H. Suura)

The role of classical Euclidean solutions (instantons) in the path integral formulation of quantum chromodynamics is well known. It is not obvious how multiple vacua and tunneling between them manifests itself in the Hamiltonian formalism. The model was studied on a lattice by Quinn and Weinstein[1]; we approached it in the continuum limit. The following results were obtained:

(1) The classical equations of motion were studied to see whether there were extended solutions. Starting from the Lagrangian

$$\mathcal{L} = \left|\left(\partial_\mu \phi - ie A_\mu \phi\right)\right|^2 - \frac{1}{2}\lambda\left(\phi^+\phi - a^2\right)^2 - \frac{1}{4}\left(\partial_\mu A_\nu - \partial_\nu A_\mu\right)^2 \quad (1)$$

with the choice of gauge $A_0 = 0$, we make the usual Higgs ansatz

$$\phi(x) = \chi(x)\, e^{i\eta(x)} \quad (2)$$

and look for "stationary" solutions of the form

$$\begin{aligned} A_1(x) &= B(x) + E(x)t \\ \eta(x) &= \eta_0(x) + \eta_1(x)t \end{aligned} \quad (3)$$

The equations take the form

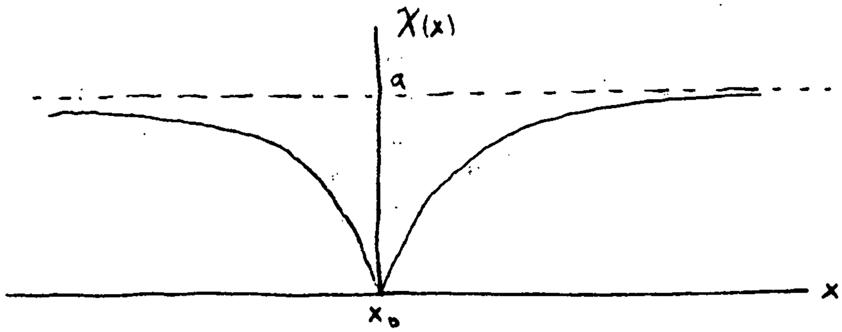
$$\partial_x E(x) = 2e\,\eta_1(x)\,\chi^2(x)$$

$$\partial_x^2 \eta_1(x) = 2e^2 \eta_1(x)\,\chi^2(x)$$

$$\partial_x^2 \chi(x) = -\eta_1^2(x)\,\chi(x) + \lambda\chi^3(x) - \lambda a^2 \chi(x)$$

for $\chi(x) \neq 0$

and have solutions that are "kink"-like except that they take the form shown below:



At the origin the phase function can be discontinuous, and it is believed to jump by a multiple of π.

(2) The stability of the solutions to small oscillations has been studied, away from the singularity where $\chi(x) = 0$. The soliton solutions appear to be stable.

(3) The problem was also approached starting with the Hamiltonian

$$H = \int_{-\infty}^{\infty} dx \left(\frac{1}{2} E^2(x) + \pi_\phi^+ \pi_\phi + (\partial_x \phi^+ + ieA\phi^+)(\partial_x \phi - ieA\phi) + \frac{1}{2}\lambda(\phi^+\phi - a^2)^2 \right) \tag{4}$$

subject to

$$(\partial_x E(x) - \rho(x))\Psi = 0 \tag{5}$$

For states of total charge zero,

$$\int dx\, \rho(x)\Psi \equiv ie\int dx\, (\pi_\phi \phi - h.c.)\Psi = 0$$

The states $\Psi' = U^{+}\Psi$, where

$$U = \exp\left\{-i \int_{-\infty}^{\infty} dx \, A(x) \int_{0}^{x} dx' \, \rho(x')\right\}$$

satisfy $\partial_x E(x)\Psi' = 0$, so that they are characterized by a parameter ε, the value of E(x) in the state Ψ'. We also impose the condition locating the "soliton"

$$\phi(x_0)\,\Psi'_{\varepsilon} = 0$$

In terms of the Higgs variables, the Hamiltonian takes the form

$$\begin{aligned}\tilde{H} = \int_{-\infty}^{\infty} dx \Big(& \tfrac{1}{2}\left(\varepsilon + e\int_0^x dx' \, \Pi_\eta(x')\right)^2 + \tfrac{1}{2}\Pi_\eta^2(x)/\chi^2(x) \\ & + \tfrac{1}{2}\Pi_\chi^2(x) + \tfrac{1}{2}\chi^2(x)\left(\partial_x \eta(x)\right)^2 \\ & + \tfrac{1}{2}\left(\partial_x \chi(x)\right)^2 + \tfrac{1}{2}\lambda\left(\chi^2(x) - a^2\right)^2\Big)\end{aligned}$$

and the subsidiary condition is $\chi(x_0)\Psi'_{\varepsilon} = 0$. The classical solution is easily obtained, as before, and the small oscillation spectrum emerges in the Gaussian approximation. The Hamiltonian easily shows the usual massive vector meson structure in the limit that χ is "frozen" to the value $\chi_{cl.} = a$.

[1] H. Quinn and M. Weinstein, Phys. Rev. D17, 1063 (1978).

Importance of the tensor coupling in the Charmonium spectrum. (H. Suura, W. J. Wilson and Bing-Lin Young*

In the conventional treatment of the charmonium spectrum(1), all the first order relativistic corrections in the fine structure approximation, like spin-orbit, hyperfine and magnetic tensor interactions, are properly considered and taken care of. The S wave-D wave mixing should be of higher order in the fine structure constant and is therefore neglected. We found that in the bag type solutions of the relativistic wave equation with a confinement potential, proposed by Suura(2) and discussed extensively for the case of light-mass q-$\bar{q}$ systems by Geffen and Suura,(3) the S-D mixing for the triplet J=1 state (ψ) cannot be neglected, even for the heavy mass quark case, because of the boundary conditions imposed at the bag boundary. In fact we find that the S wave-D wave conventional decomposition of the relativistic amplitude is no longer appropriate, and that a new pair of amplitudes exists which satisfy coupled differential equations much easier to handle.

For the triplet ρ (or ψ) trajectory of a q-$\bar{q}$ system, we obtain a set of coupled second order differential equations for a pair of radial wave functions. The device of the pair is not unique. In references (2) and (3), a pair was chosen so that the coupling vanished in the limit of quark mass $m \rightarrow 0$. This is obviously appropriate for light mass quark systems. The differential equation involves centrifugal barrier of p-wave (average of S and D), which leads to a very natural explanation why ρ is so much heavier than π, namely, π meson (pure S wave) is pulled down by the strong attractive Coulomb potential, while ρ meson can see little of the Coulomb potential because of the centrifugal barrier. One is tempted to attribute the large $\psi - \eta_c$ splitting to the same mechanism, but before doing this one has to examine the conventional S-D decomposition which would be more appropriate for heavy mass quarks. We examined in detail a set of coupled differential equations for a pair of S and D amplitudes. Neglecting the S-D coupling which formally vanishes for infinite quark masses, we find that the S wave equation is very similar to the $^1S_0$ (η_c) equation except for small relativistic effects. The indicial relation for the decoupled equation tells that the S amplitude should vanish at the bag boundary. Because of the attractive Coulomb potential, the wave function becomes small beyond the Bohr radius which is much smaller than the bag radius, so that one could neglect the boundary condition at the bag boundary. Thus, the conventional non-relativistic treatment of the charmonium spectrum appears to be justified, and there seems to be no mechanism to lower η_c's mass relative to ψ except for a very large spin-spin interaction.

However, S-D coupling does not completely vanish near the bag boundary. In fact the indicial relation of the coupled equations tells that both the S and D amplitudes be finite at the bag boundary. Thus, the coupling produces a discontinuous change in the boundary condition, and we cannot expect that the non-relativistic S wave amplitude would be a good approximation. We believe that the boundary conditions at the bag boundary are very important. It was shown in ref. (3) that chiral symmetry breaking results from the boundary condition.

Instead of solving the coupled S-D equations with a peculiar boundary condition, we devised a new set of coupled equations for a new pair of amplitudes, which are similar to, but superior to the old ρ-equations.

The new amplitudes vanish at the bag boundary. Neglecting all the relativistic effects, we established that the new coupled equations do indeed raise ψ relative to η_c, provided there exists an attractive Coulomb-like potential of sufficient strength.

(1) E. Eichten, et al., Phys. Rev. Lett. 34, 369 (1975).

(2) H. Suura, Phys. Rev. Lett. 38, 636 (1977).

(3) D. A. Geffen and H. Suura, Phys. Rev. D16, 3305 (1977).

Semi-hadronic decays of the τ (D. A. Geffen and W. J. Wilson)

We studied the τ decay mode $\tau \rightarrow \nu_\tau \rho \pi$ and considered the possibility of discerning the elusive A_1 in the $\rho\pi$ mass spectrum. We found that the decay depends on three form factors which can, to a large extent, be determined using standard current algebra techniques. The width and the mass of the postulated A_1 remain as the only free parameters. Unfortunately, the very limited amount of data now available are unable to distinguish between a wide range of possible parametrizations, and the possibility that there is no A_1 contribution to this decay still exists. However, a quite modest increase (factor of two or three) in the precision of the experiments should provide a rather stringent test of our analysis and perhaps determine the mass and width of the A_1. The results of this work may be found in our paper, "The Search for the A_1 in $\tau \rightarrow \nu_\tau \rho \pi$ ", to be published in Physical Review D.

At the moment we are continuing our study of the decay in somewhat more detail than discussed above. In addition to the mass spectrum and the total rate, one can also consider the angular correlations of the decay particles. We find that a convenient variable is the angle between the ρ and the τ in the $\rho\pi$ rest frame. By measuring the distribution with respect to this angle certain details of our model can be tested and our analysis put on a firmer foundation.

Finally, we are also looking at other interesting semihadronic decay modes. For instance, the mode $\tau \rightarrow \nu_\tau \omega \pi$ is of some interest because (1) it has a very clean signal (the ω is a very narrow resonance), and (2) it measures the $\rho\omega\pi$ coupling. A preliminary analyses indicates that the branching ratio for this mode is only about 1% so it may be somewhat difficult to detect.

Scaling Laws for Potential Models of the Quark-antiquark Interaction (J. Rosner (with C. Quigg)).

A compilation was made of several scaling formulae which exhibit the dependence of level spacings and other dimensionful quantitites upon the reduced quark mass and upon the principal quantum number for potentials of the form $V(r) \sim r^{\epsilon}$.[1)]

Threshold for production of states with New Quantum Numbers (J. Rosner (with C. Quigg)).

Explicit potential models[2)] predicted three narrow Υ levels. While details of these models were found open to question,[3)] it turned out that the number n of $^3S_1$ levels of a $Q\overline{Q}$ system (Q = heavy quark) which lie below the threshold for Zweig -- allowed decay could be estimated quite generally semiclassically. The result is $n \simeq 2(m_Q/m_c)^{1/2}$, which for $m_Q \simeq$ 5 GeV, m_c = 1.2 to 2 GeV, implies either three or four quasi-stable $^3S_1$ levels below threshold.[4)] In a logarithmic potential,[3)] this implies a threshold of around 10.6 - 10.7 GeV for production of pairs of states with new quantum numbers.

Semiclassical sum rules (J. Rosner (with C. Quigg)).

The expression $|\Psi_n(0)|^2 = (2\mu)^{3/2} E_n^{1/2} (dE_n/dn)/4\pi^2$, relating the square of the n^{th} S-wave wave function at the origin to the bound-state reduced mass n and the excitation energy E , was derived semiclassically. The relation was then used to obtain several sum rules for electron-positron annihilation[5)] and an expression for the contribution of a given flavor of heavy quark to the photon-nucleon total cross section.[6]

Inverse Scattering Problem for Quarkonium Systems (J. Rosner (with H. B. Thacker and C. Quigg)).

The inverse scattering formalism for relectionless potentials was applied to the reconstruction of confining potentials from bound-state properties. This method was extended to the case of central potentials in three dimensions, and applied to the derivation of a family of possible potentials from the $\psi(3.095)$ and $\psi'(3.684)$ levels and leptonic decay widths. Consequences for the Υ family and prospects for reducing the remaining ambiguities in the interquark potential were explored.[7]

Bounds for Leptonic Widths of Heavy Quark-antiquark Systems (J. Rosner (with H. B. Thacker and C. Quigg)).

Lower bounds on the leptonic decay widths of $\Upsilon(9.4)$ and $\Upsilon'(10.0)$ were deduced from general conditions on the interquark potential. It was shown that these could permit a distinction between the charge assignments e_Q = (-1/3, +2/3) for the new quark.[8]

Mass dependence of Schrodinger wave functions (J. Rosner (with T. Leung)).

It was noted that for power-law potentials and $V(r) \sim \ln r$ the quantity $G(r) \equiv \int_0^r dr' u_{nS}(r')[\partial u_{nS}(r')/\partial m]$ is always non-negative, meaning that at every point r in space the probability that a particle in the n^{th} S-wave state is within r increases as the reduced mass m of the bound state is increased. Work is in progress to determine the most general class of potentials for which this property holds.

Projection operators for quarks and leptons (J. Rosner (with M. Gell-Mann))

Work begun during the summer of 1977 on octonionic quantum mechanics was continued. (See 1976-77 Progress Report and 1977 Proposal.) A system of projection operators for quarks and leptons which could exhibit the pecularities of non-associative behavior[9] was searched for. Such a system was found: it consited of operators formed from products of two commuting sets of octonions, and gave two leptons and six quarks. However, the color group of this system appears to be SO(4) = SU(2) x SU(2), rather than the desired SU(3), and the search is continuing for related systems. This work is still in progress.

References

1. C. Quigg and Jonathan L. Rosner, "Scaling the Schrodinger Equation", to be published in Comments on Nuclear and Particle Physics.
2. E. Echten and K. Gottfried, Phys. Lett. 66B, 286 (1977).
3. See, e.g., C. Quigg and J. Rosner, Phys. Letters 71B, 153 (1977).
4. C. Quigg and Jonathan L. Rosner, Phys. Letters 72B, 462 (1978).
5. Cf. Glennys R. Farrar *et al.*, Phys. Lett. 71B, 115 (1977).
6. C. Quigg and Jonathan L. Rosner, Phys. Rev. D17, 2364 (1978).
7. H. B. Thacker, C. Quigg, and Jonathan L. rosner, "Inverse Scattering Problem for Quarkonium Systems: I. One-dimensional Formalism and Methodology; II. Applications to ψ and Υ Families, to be published in Phys. Rev. D18 (1978).
8. Jonathan L. Rosner, C. Quigg, and H. B. Thacker, Phys. Lett. 74B, 350 (1978).
9. Specifically, Mostow's Theorem. See F. Gursey, in Proceedings of the Charlottesville Conference on Non-Associative Algebra in Physics, March, 1977, to be published.

Semileptonic Decays of D Mesons (W. J. Wilson)

Expanding on my previous work[1] on the semileptonic decays of the D($D \rightarrow Ke\nu + x$) I have considered, in addition to the lepton spectrum, the kaon spectrum and kaon-electron correlations. If it is assumed that the principal decay mode is $D \rightarrow K^* e\nu$ then it is shown that the average values of the electron energy, the kaon energy, and the K-e invariant mass squared must, quite generally, lie within a small two-dimensional region. On the other hand, if the dominant decay mode is $D \rightarrow Ke\nu$ then the three averages must lie on a straight line which does not intersect the K^* plane. Thus, one can experimentally test in a model-independent way the notion that these two modes saturate the decay rate and also measure their relative branching ratios. These resultshave been published in reference 2.

1. W. J. Wilson, Phys. Rev. D16, 742 (1977).
2. W. J. Wilson, Phys. Rev. D17, 3032 (1978).

EXPERIMENTAL HIGH ENERGY PHYSICS (H. Courant, Y. Makdisi, M. Marshak, E. Peterson and K. Ruddick)

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SUMMARY: The primary effort of this group has been an experiment on coherent production mechanisms at Fermilab (E-272). In this experiment we have made precision measurements of the electromagnetic couplings of some vector mesons, which are crucial quantitative tests of particle symmetry models, and investigated coherent production mechanisms of the strong interaction. Analysis of an Argonne ZGS experiment on prompt lepton production has been completed yielding no anomalous results over a wide range of angles, targets and energies. Research using the polarized proton beam at Argonne has continued as has analysis of previous polarized beam data; an experiment using a polarized deuteron beam is scheduled for early Fall 1978.

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The successes of contemporary models in predicting new particles has been the major theme in elementary particle physics over the last several years. Any realistic model, however, makes quantitative as well as qualitative predictions. In particular, the SU(3) symmetry scheme implies certain relationships among the properties of various groups of particles, such as the electromagnetic couplings of vector mesons. In this particular case, there is disagreement between theory and experiment. The current experimental value for $\Gamma_{\rho\pi\gamma}$ cannot be reconciled with current theoretical concepts. This poses the dilemma that either the theory or the experiment (or both) must be wrong.

Unfortunately, the currently measured value for $\Gamma_{\rho\pi\gamma}$ is derived from an experiment with serious difficulties. Direct measurement of the decay $\rho \to \pi\gamma$ is extremely difficult due to the fact that the decay $\rho \to \pi\gamma\gamma$

is at least 1000 times more common. Missing one photon from a background event leads to an impossible confusion of the signal and the background. The Primakoff process, in which an incident pion scatters from a virtual photon in the nuclear Coulomb field and produces a rho, provides an alternative means of measuring the coupling. For an accurate result, such an experiment should be done at very high energies (to reduce the strong interaction background), on a series of different nuclear targets (to show that the scattering proceeds via the Primakoff process) and with both polarity beams (to permit elimination of possible two photon exchange effects). The use of at least two incident energies is also valuable in showing that the cross-section has the correct logarithmic dependence of the Primakoff effect. The current value of $\Gamma_{\rho\pi\gamma}$, in serious conflict with theory, comes from an experiment with none of these properties; for that reason, it has not been considered as presenting a basic problem for current particle symmetry schemes.

In Fermilab E-272, (a collaboration with the University of Rochester and Fermilab) we are making a strong effort to obtain a precision measurement which is free from the systematic uncertainties in previous experiments. During Spring, 1978, we have completed measurements at 150 and 250 GeV/c, using both polarity beams at the lower energy, and four different nuclear targets. In some cases, different target thicknesses were used in order to test for absorption effects. Several thousand analyzable rho events were recorded on magnetic tape and analysis is currently underway. At the XIX International Conference on High Energy Physics at Tokyo we will report preliminary results which are in serious conflict with the SU(3) predictions.

The apparatus for E-272 consists of a high resolution charged and neutral spectrometer with a large forward acceptance. Charged particles are tracked in a multiwire proportional and drift chamber system, consisting of 110 drift and 1400 proportional channels. Positional accuracies of 200u have been obtained in the drift chamber system. Neutrals are detected in a liquid argon calorimeter, which has a positional accuracy of $\pm$ 1 mm and an energy resolution of $\frac{\Delta E}{E} = 0.12/\sqrt{E}$ FWHM. This is the first large liquid argon calorimeter to be operated in an experiment at Fermilab. Our data collection run at Fermilab includes events due to many processes other than Primakoff production of rhos. Many such processes are interesting in themselves. They include:

a) Primakoff production of various mesons and baryons. Resolution of the puzzle of the small value for $\Gamma_{\rho\pi\gamma}$ will be aided by information about the radiative width for the strange vector meson, the K*(890). The number of these events recorded is not yet clear, due to a serious background from the $\pi\pi$ decay of K's in flight. If the K* radiative width is reasonable, there should be several hundred events in our data sample. Analysis of these events is currently in progress. Higher spin mesons can also be produced by the Primakoff process; measurement of their radiative widths will indicate the nature of the relationships among members of SU(3) categories other than the vector mesons. In the preliminary analysis, we have seen evidence of the A1, A2, B and g mesons in the data sample. The rates for Primakoff production of these objects have not yet been determined. We have also observed Primakoff production of the N*(1232) and its antiparticle. Since the radiative width for this particle is known, measuring the Primakoff cross-section for the N* provides a strong validity check on both the systematics of the experiment and the use of the Primakoff process to extract particle widths.

b) Coherent strong production. Although coherent strong production in the field of the nucleus is a background to the Primakoff process, the physics bases of this mechanism are themselves interesting. These coherent phenomena proceed via ω exchange. Sufficient data have been collected (about 10^5 Al type events, for example) to permit a detailed density matrix analysis of the coherent production mechanism. Since measurements have been made at two energies, it will also be possible to study the energy dependence of the ω or Pomeron exchange process. These detailed analyses are quite complicated and will take place over the next year.

c) Meson-electron scattering. The scattering of high energy electrons provides a mechanism for probing the electromagnetic structure (form factor) of various particles. Although there have been previous experiments on this subject, there are still large uncertainties in the results. Our apparatus is ideal for the detection of meson-electron scattering. Although we do have some trigger biases, we do plan to analyze these events.

d) Neutral trigger. At an incident momentum of 250 GeV/c, we have recorded several thousand neutral trigger events. We will analyze these to make a first measurement of charge exchange scattering from nuclei at this high energy. These neutral trigger events will also permit a detailed analysis of backgrounds expected for further experiments in the M1E beam line at Fermilab (see Proposal for 1979).

Some preliminary data from E-272 are shown in Figs. 1-3. The first graph shows the π^o mass peak, which is evidence for the high position and energy accuracy obtained from the liquid argon detector. The next figure displays the reconstructed rho mass peak. In Fig. 3, we have plotted the t dependence of scattering events for several different nuclear targets. The sharp forward peak is indicative of the Primakoff effect, which is dominant in the high Z nuclei. The large t events are due to coherent ω exchange.

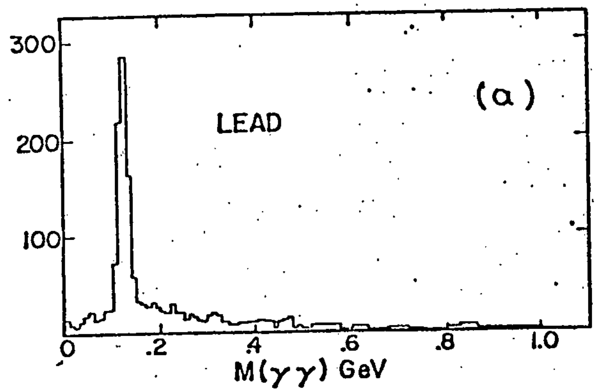


FIG. 1

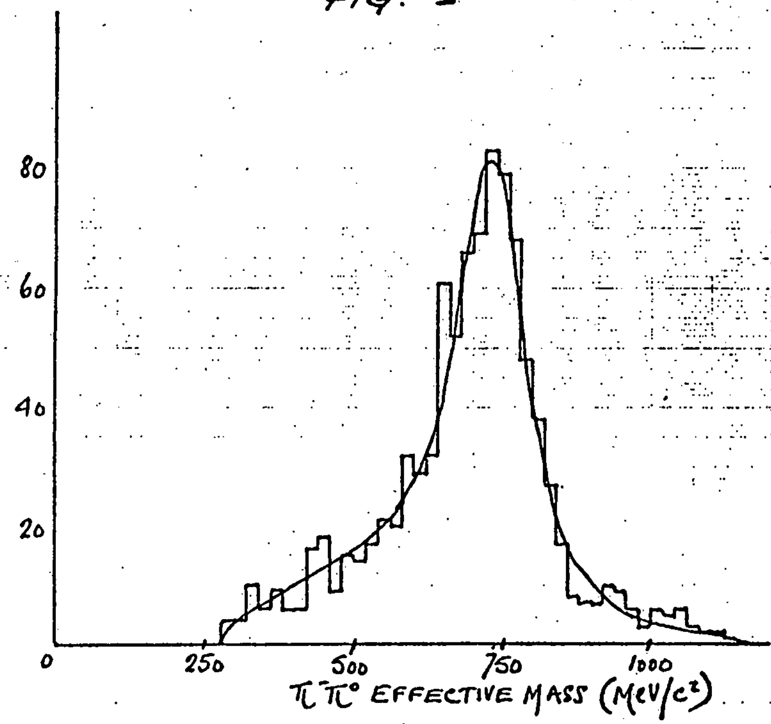


FIG. 2.

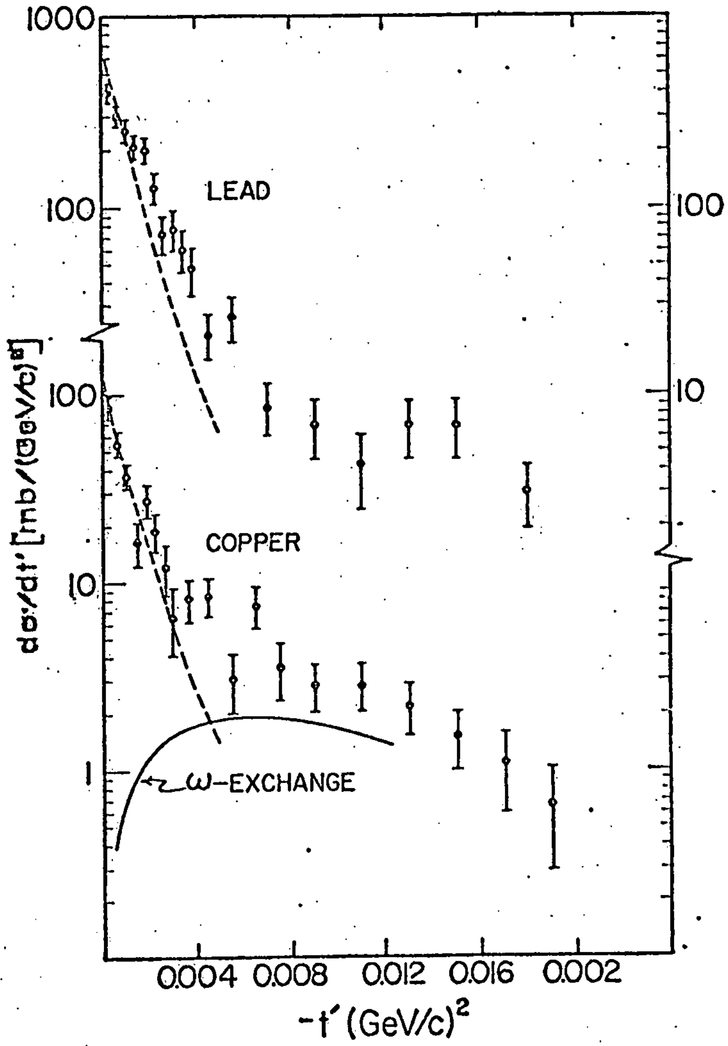


Figure 3

The analysis of an Argonne ZGS experiment on direct electron production has been completed in the past year. This experiment was important because a positive result would indicate the existence of a new mechanism for lepton production at energies as low as 10 GeV. Evidence for direct production at GeV/c at the level of e/π of 10^{-4} has been claimed in an earlier experiment at Brookhaven. In the Argonne experiment, we made measurements sensitive at the 10^{-5} level using targets at beryllium and hydrogen, incident momenta of 12, 6 and 3 GeV/c, with and without a Cherénkov counter to directly detect the pair production background. At all energies and angles and using both targets, we obtained no direct electron production except for rates consistent with known decays of vector mesons. This result is in serious conflict with the Brookhaven data $e/\ ^{0}$ ratios are shown in Figure 4.

Our program using the Argonne ZGS polarized beam has continued during the past year at a reduced level due to the resource requirements of Fermilab E-272 and competition for the Beam 5 line at Argonne. One experiment was completed in late 1977 to measure the analyzing power in pd backward elastic scattering and in the process $p + p \rightarrow d + \pi$ at energies near $T_p = 1$ GeV. During this same experiment (a collaboration with Argonne, UCLA, and LBL), a measurement of the analyzing power was made for pp elastic and pn quasi-elastic scattering Fig. 5. This experiment was part of a multi-year effort to make a consistent set of cross-section and analyzing power measurements for nucleon-nucleon and nucleon-light nucleus scattering at kinetic energies near 1 GeV. This region is important because the energy is high enough that no good phase shift solutions exist, but it is low enough that the simplifications of asymptopia cannot be applied. With a consistent set of measurements, it should be possible to both isolate many of NN scattering amplitudes and to check features of scattering models such as the Glauber multiple scattering model or the KMT optical potential model. The final experiment

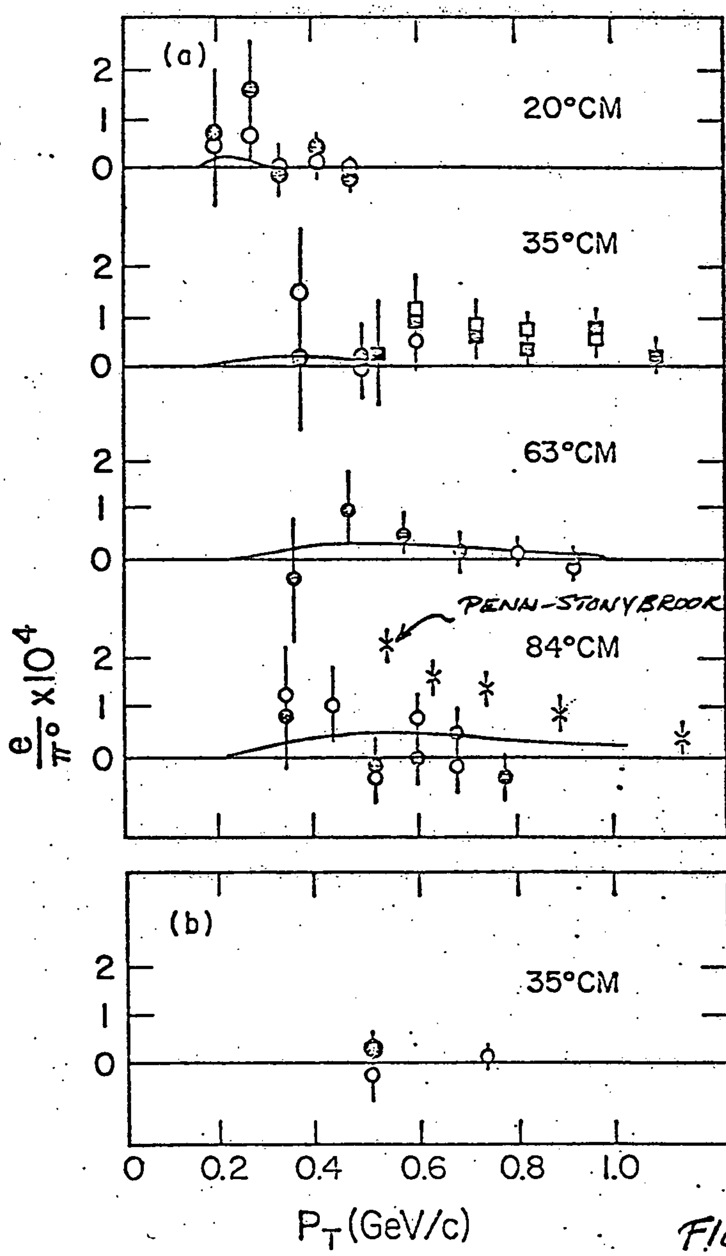
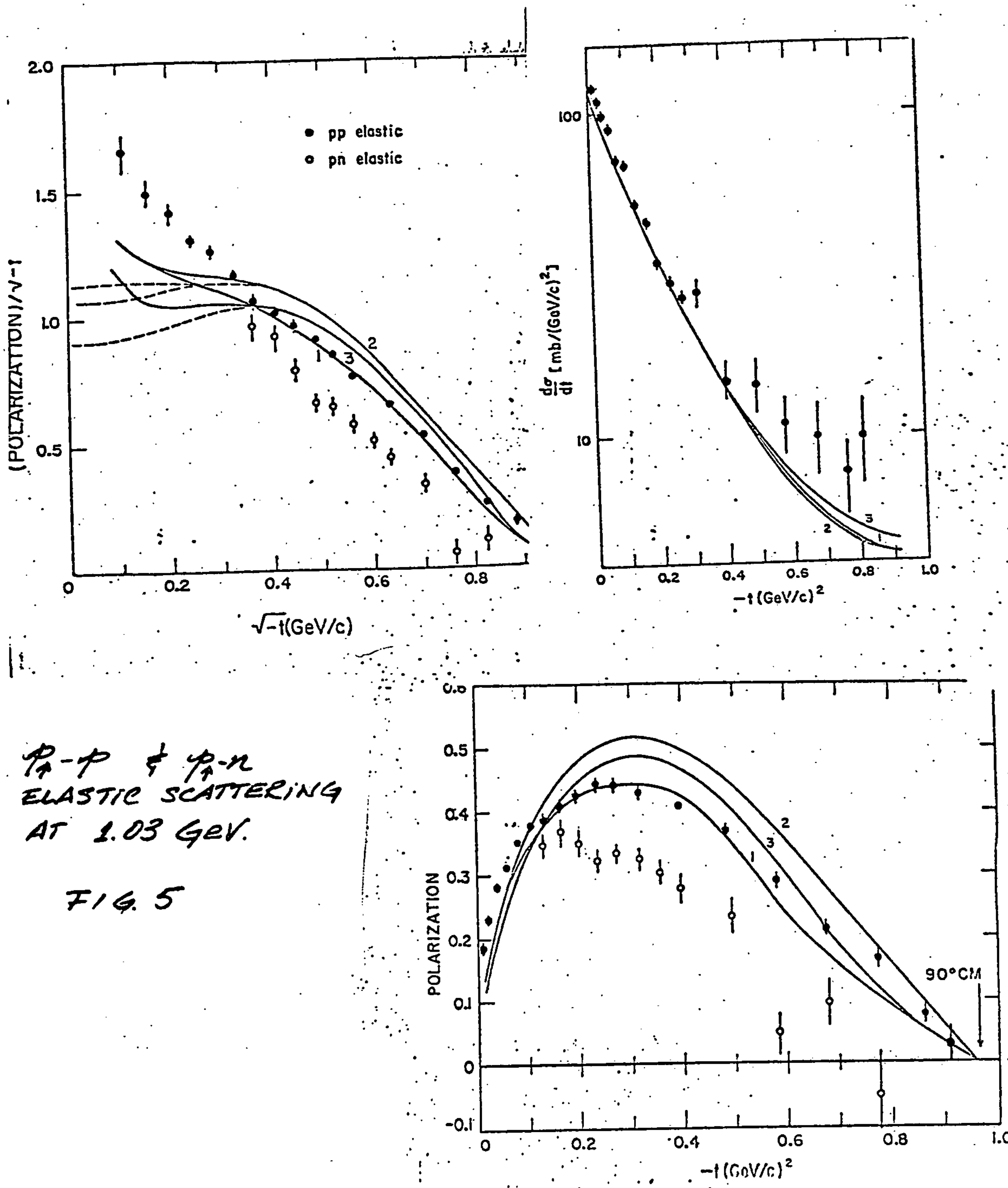


FIG 4

FIG. 4. (a) Rate of direct electron production vs momentum transfer P_T. Solid data points are for e^-, open points for e^+. Circles and squares represent data from beryllium and hydrogen targets, respectively. The crosses are the data of Ref. 4. The lines are estimates of the vector-meson contribution. (b) Production rate of single electrons or of electrons accompanied by an additional wide-angle electron.



$\vec{p}$-p & $\vec{p}$-n
ELASTIC SCATTERING
AT 1.03 GeV.

FIG. 5

Solid lines are predictions of existing phase shift solutions with Coulomb interference.

in these series is scheduled for October, 1978. It will use a vector and tensor polarized deuteron beam to study the spin structure of pd scattering. Superconducting solenoids in the beam line will permit several orientations of the deuteron spin in order to obtain the largest possible amount of information about the spin amplitudes.

Analysis of data from two earlier polarized beam experiments has been completed during the past year. Data from the first measurement of the analyzing power for large angle, high energy pn elastic scattering are shown in Fig. 6 . At 2, 3 and 6 GeV/c, there is a consistent pattern in which the pn data parallel the pp data, but at a considerably smaller absolute magnitude, throughout the forward hemisphere. It is clear from these data that 6 GeV/c is still quite far from the asymptotic region where pp and pn analyzing powers should be equal. Fig. 7 shows the results of a measurement of the depolarization parameter for pp elastic and inelastic scattering. These data permit the investigation of the parity of the object exchanged in the scattering process. Elastic scattering, which is mostly normal parity exchange, has a depolarization parameter near unity. The strongly negative D observed in N*(1232) production is evidence that this object is produced mostly through abnormal parity (such as pion) exchange.

Table 1 contains the status of all currently active experiments.

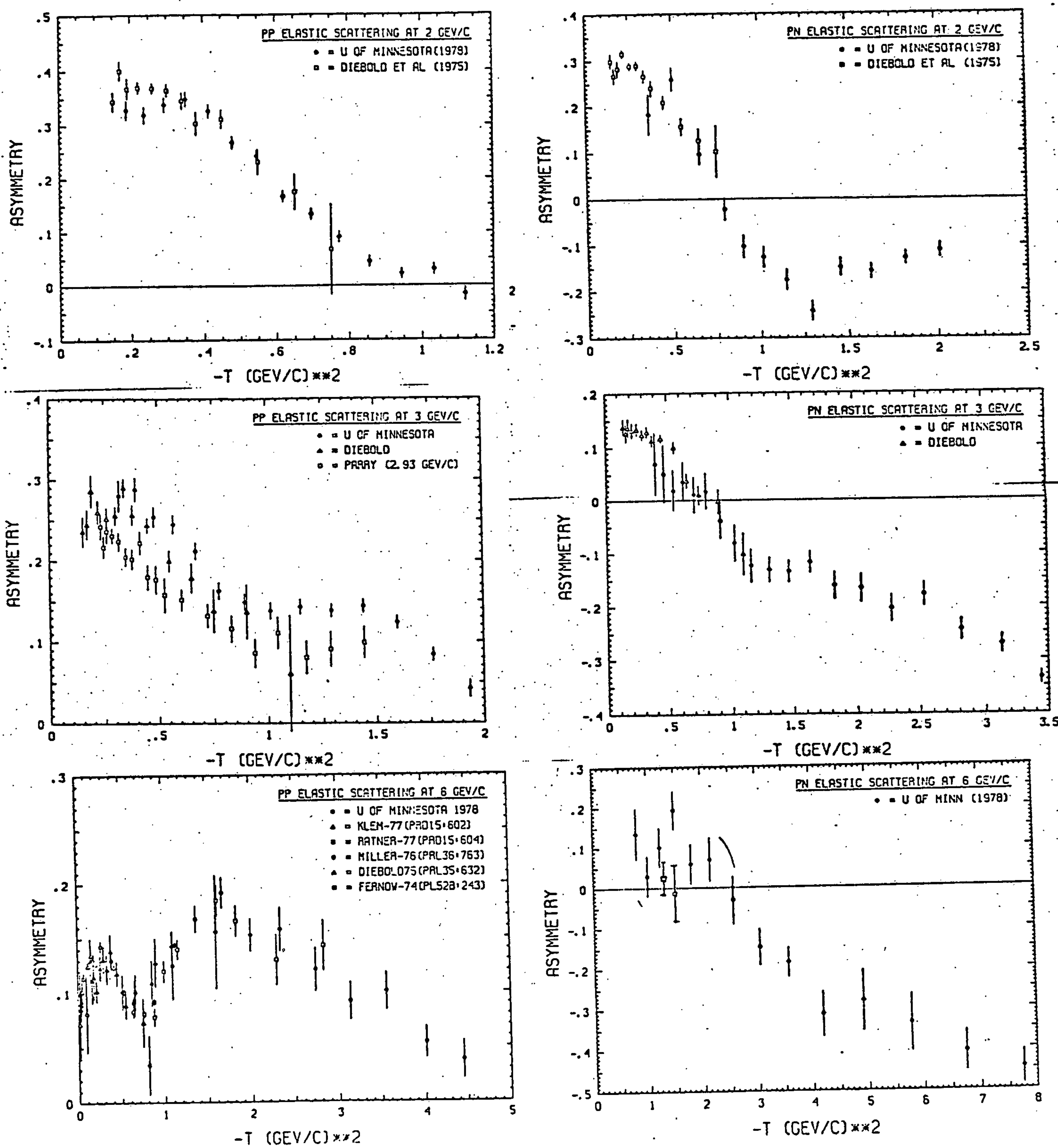
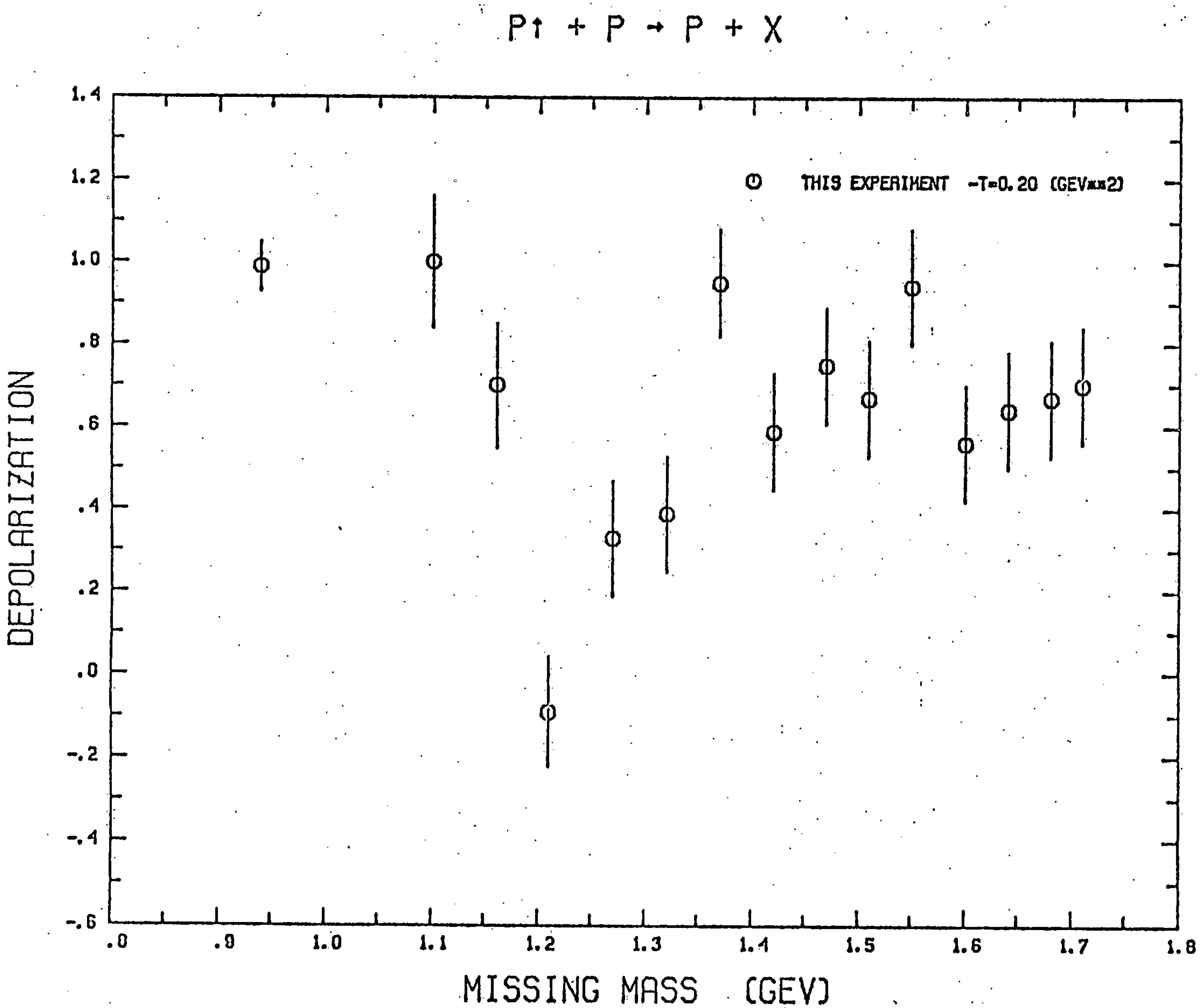

PP ELASTIC SCATTERING AT 2 GEV/C
• = U OF MINNESOTA(1979)
□ = DIEBOLD ET AL (1975)
ASYMMETRY
-T (GEV/C)**2
PN ELASTIC SCATTERING AT 2 GEV/C
• = U OF MINNESOTA(1978)
■ = DIEBOLD ET AL (1975)
PP ELASTIC SCATTERING AT 3 GEV/C
• = U OF MINNESOTA
▲ = DIEBOLD
□ = PARRY (2.93 GEV/C)
PN ELASTIC SCATTERING AT 3 GEV/C
• = U OF MINNESOTA
▲ = DIEBOLD
PP ELASTIC SCATTERING AT 6 GEV/C
• = U OF MINNESOTA 1978
▲ = KLEM-77 (PRD15:602)
■ = RATNER-77 (PRD15:604)
• = MILLER-76 (PRL36:763)
▲ = DIEBOLD75 (PRL35:632)
■ = FERNOV-74 (PL52B:243)
PN ELASTIC SCATTERING AT 6 GEV/C
• = U OF MINN (1978)

FIGURE 6



P↑ + P → P + X
THIS EXPERIMENT -T=0.20 (GEV**2)
DEPOLARIZATION
MISSING MASS (GEV)

FIGURE 7

Table 1. Currently Active Experiments

Experiment No.	Title	Activity this year	Current Status
Argonne E365	Elastic scattering	Analysis and publication	Published
Argonne E407	Depolarization	Analysis completed	Thesis, results to be published
Argonne E411	$P\text{-}He^4$ scattering	Publication	Final publication submitted.
Argonne E415	Direct Electron production	Analysis completed	Published
Argonne E418	pn polarization at 2, 3, 6 GeV/c	Analysis completed	To be published
Argonne E437	Low energy polarization	Data collection and analysis and publication	Submitted for publication
FERMILAB E272	Coherent production	Construction, installation, data collection and analysis	Analysis continues, preliminary results reported in Tokyo

Publications Previously Reported

COO-1764-299 "Odd-even behavior in the n + ^{6}Li system", D. J. Stubeda and Y. C. Tang, J. Phys. Soc. Japan (Suppl) 44, 236 (1978).

COO-1764-30 "Resonating-group calculations in light systems", Y. C. Tang, Fizika (Suppl. 3) 9, 91 (1977).

COO-1764-302 "Resonating-group study of the n + ^{6}Li system", D. J. Stubeda, M. LeMere, and Y. C. Tang, Phys. Rev. C17, 447 (1978).

COO-1764-309 "Lepton spectrum in the semileptonic weak decays of charmed mesons", W. J. Wilson, Phys. Rev. D16, 742 (1977).

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COO-1764-331 "Resonating-group method for nuclear many-body problems" Y. C. Tang, M. LeMere and D. R. Thompson, will appear in Physics Reports C.

COO-1764-332 "Odd-even ℓ-dependence of effective internuclear potential", M. LeMere and Y. C. Tang, will appear in the Proceedings of the 3rd International Conference on clustering aspects in nuclear structure and nuclear reactions, Winnipeg, Manitoba, Canada 1978.

COO-1764-333 "Exchange effects in nucleus-nucleus interaction", M. LeMere and Y. C. Tang, submitted to Phys. Rev. C.

COO-1764-334 "Exchange Coulomb interaction in resonating-group calculations", M. LeMere and Y. C. Tang, submitted to Phys. Rev. C.

COO-1764-335 "Search for Direct Electron Production in p-p and p-Be Collisions at 12 GeV/c", Makdisi, et al., Phys. Rev. Lett. Aug. 1978, pg. 367.

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COO-1764-337 "Pion Dissociation in the nuclear Coulomb field", D. Berg, et al., submitted for the XIX International Conf. on High Energy Physics, Tokyo, 23-31 August 1978, Marshak, Makdisi, et al.

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COO-1764-339 "On Polarization in Heavy Ion Reactions", P. J. Ellis, Nucl. Phys. A302, 257 (1978).

COO-1764-340 "Study of the $^{30}Si(^{16}O^{16}O')^{30}Si^*$ Reaction at 60 MeV", A. Dudek-Ellis, P. J. Ellis, *et al.*, Phys. Rev., in press.

COO-1764-341 "Coupled Channels Calculations for $^{28}Si + ^{16}O$ and the Energy-dependence of the Optical Potential", A. Dudek-Ellis *et al.*, Phys. Rev., in press.

COO-1764-342 PROGRESS REPORT - 1977-1978

COO-1764-343 "Inverse Scattering Problem for Quarkonium Systems, I. One-dimensional Formalism and Methodology" by Thacker, Quigg and J. Rosner, Fermilab-Pub-77/108-THY.

COO-1764-344 "Inverse Scattering Problem for Quarkonium Systems, II. Applications to ψ and Υ Families" by Thacker, Quigg and J. Rosner, Fermilab-Pub-77/109 THY.

COO-1764-345 "Determining the Fifth Quark's Charge: The Role of Υ Leptonic Widths" by Thacker, Quigg and J. Rosner - Fermilab-Pub-77/19-THY.

COO-1764-346 "Counting Narrow Levels of Quarkonium" by Quigg and Rosner, Physics Letters 72B, no. 4, p. 462 (1978).

COO-1764-347 "Semiclassical sum rules" by Quigg and Rosner, Phys. Rev. D17, 9 (1978) 2364.

COO-1764-348 "Kaon-electron correlations in the semileptonic decays of D mesons" by W. J. Wilson, Phys. Rev. D17, 11, 3032 (1978).

COO-1764-349 "The Search for the A_1 in $\tau \to \nu_\tau \rho \pi$ " by Wilson and Geffen, submitted for publication.

COO-1764-350	"Spin-Dependent Effects in Heavy Ion Reactions I and II", Proceedings of the Intern. Conf. on Nucl. Structure, Tokyo, Sept. 5-10, 1977, Bayman, Dudek-Ellis and P. Ellis.
COO-1764-351	"Spectroscopy with the $^{45}Sc(\alpha,p)^{48}Ti$ reaction at 26 MeV", B. Bayman, A. Evinay (with C. Ellegaard, J. Garret and O. Hansen), submitted for publication.
COO-1764-352	"Two-neutron transfer reaction mechanism with heavy ions at sub-Coulomb energies", B. Bayman (with M. Franey, J. Lilley and W. Phillips) submitted for publication.