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Two- and Few-Nucleon Systems

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From the outset I must state that the limited amount of time given to report on the contributions dealing with two- and few-nucleon systems has forced me to make a personally biased selection for which I apologise. Many of the contributions report on excellent work, both theoretical and experimental, and cover a large range of topics:

1. The nucleon-nucleon interaction and phase-shift analyses
2. The possible evidence of dibaryon resonances
3. Capture reactions to elucidate reaction dynamics
4. Determinations of the D/S state ratio ρ_D in the very-light nuclei
5. The three-nucleon systems and theoretical predictions based upon the Faddeev equations
6. Scattering of few-nucleon systems and the structure of very light nuclei

§1. Nucleon-Nucleon Scattering

New precision data for the n-p analyzing powers A_y or A_{oono} at backward angles ($\theta_{c.m.} > 120°$) at 16.9 and 25 MeV have been presented (contributions 3.4 and 3.5). These new data will have considerable impact on the phase-shift analyses as shown in Fig. 1. Note that the latest phase-shift analysis result (Arndt SP85) is included[1]. There is good agreement between this phase-shift-analysis prediction and the data. At intermediate energies forward angle n-p analyzing power data were obtained at 633, 784, 834, 934, and 985 MeV using an ionization chamber to detect the recoil protons in coincidence with the scattered neutrons. (Contribution 3.7)

At SATURNE an extensive program of measuring the spin-dependent observables in p-p and n-p scattering is under way for energies above 800 MeV. An accelerated polarized deuteron beam provides an intense polarized neutron beam. A discussion of the latest p-p results obtained at Saclay took place during the special topics section of this Symposium. These new data permit a substantial extension of the N-N phase-shift analyses towards higher energies.

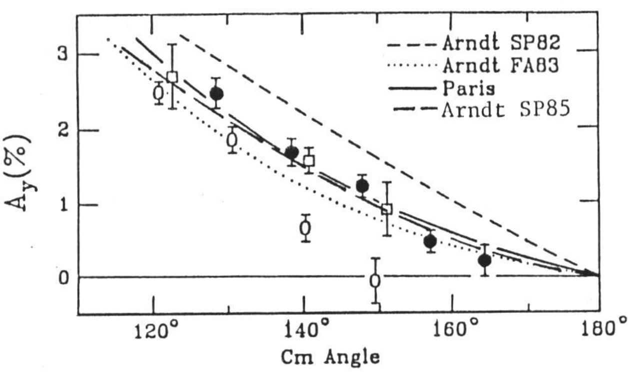

Fig. 1. Precise large-angle data (closed circles: present work; open circles and squares: previous work and theoretical predictions).

§2. Nucleon-Nucleon Bremsstrahlung

A new ppγ experiment using polarized incident protons has been performed at TRIUMF (contribution 3.14). More than $2{\times}10^5$ ppγ events were recorded, which is approximately two orders of magnitude greater than in any previous ppγ experiment. Both differential cross sections and analyzing powers were measured with backgrounds in general less than 5%. By choosing an incident energy of 280 MeV potential models of the N-N interaction should be applicable. The data are compared with predictions based upon the soft-photon approximation (which is completely determined by the N-N on-energy-shell phase shifts) and with predictions based upon the Bonn potential. A preliminary analysis of a sample of the data taken at the wider proton opening angles suggests that the calculations based upon the Bonn potential give the better description of the data (see Fig. 2). It is to be noted that this experiment presents the first direct observation of substantial off-energy-shell effects in the N-N interaction with $|\vec{p}_{off}-\vec{p}_{on}| \sim 1\text{-}2\ \mathrm{fm}^{-1}$. At present the data taken at smaller proton-proton angles are still being analyzed. Here the differences between the two theoretical predictions become much larger with ΔA_y approaching 0.4.

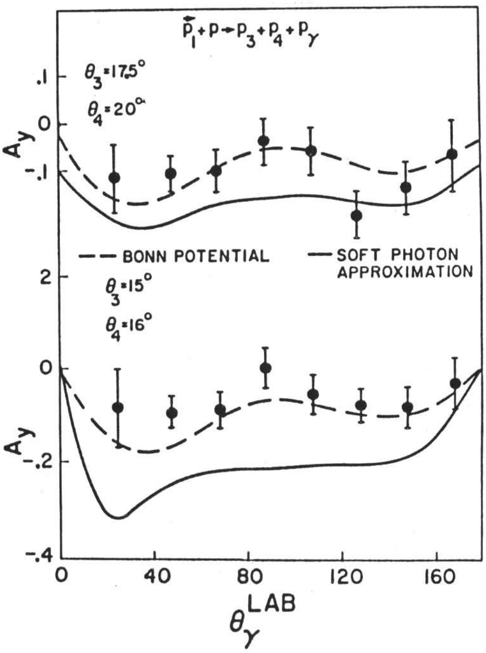

Fig. 2 Proton-proton bremsstrahlung analyzing powers for two angle pairs at 280 MeV.

§3. Radiative Capture Reactions

It is now well established that the electromagnetic interactions of the nucleons alone cannot account for the capture of neutrons by protons. The coupling of photons to virtual pions plays an important role in different energy domains: the inclusion of meson-exchange currents (MEC) is necessary to explain the thermal neutron capture cross section; at higher energies major contributions stem from isobar configurations, such as intermediate Δ's and N*s. The analyzing power A_y of the $H(\vec{n},\gamma)D$ reaction in particular is sensitive to meson exchange and other reaction mechanism effects.

At TRIUMF a program is under way of measuring the analyzing powers A_y at five energies, 180, 270, 334, 407 and 477 MeV (contribution 3.15). Results obtained at 180, 270 and 477 MeV are compared with a series of calculations made by Arenhövel and Leidermann, based on an impulse approximation concept in portion a) and b) and for coupled channels in portion c) of Fig. 3, respectively. The Reid soft-core potential was used for the underlying N-N interaction. The dashed lines are the results when only nucleonic degrees of freedom are considered. For the dashed-dotted and dashed-double dotted lines this basic approach was supplemented by meson-exchange currents and isobar configurations, respectively. The solid line represents the sum of all effects. Unfortunately higher statistics are required, in particular at 477 MeV.

In order to study D-state effects in the four-nucleon system Mellema, Wang and Haeberli made measurements of the vector and tensor analyzing powers $A_y(\theta)$ and $A_{yy}(\theta)$ in the $^2H(\vec{d},\gamma)^4He$ reaction at T_d = 10 MeV (contribution 3.48). The measured vector analyzing powers $A_y(\theta)$ and tensor analyzing power $A_{yy}(\theta)$ are shown in Fig. 4. The solid lines are Legendre polynomial least-squares fits to $\sigma(\theta)A(\theta)$ and to $\sigma(\theta)$. Both $\sigma(\theta)A_y(\theta)$ and $\sigma(\theta)A_{yy}(\theta)$ require the inclusion of odd-order terms to fit the data, which is evidence that the transition is not purely E_2. Also the vector analyzing power has substantial values comparable to the values of the tensor analyzing power. There must therefore be interference of E_2 with either E_1 or M_2 amplitudes.

§4. Dibaryon Resonances

The ETH group presented a single-energy phase-shift analysis of π-d elastic scattering data (differential cross sections σ(θ), and deuteron vector analyzing powers $iT_{11}(\theta)$ and tensor polarizations $t_{20}(\theta)$) at five energies, 117, 125, 134, 142 and 151 MeV. To fit their tensor polarizations, these authors introduce Breit-Wigner resonances to present dibaryons. The tensor polarizations t_{20} in π-d elastic scattering have now been measured at LAMPF, SIN and most recently at TRIUMF[2]. The LAMPF and TRIUMF data are essentially in agreement, while the results of the ETH group are in considerable disagreement with the other two sets of data.

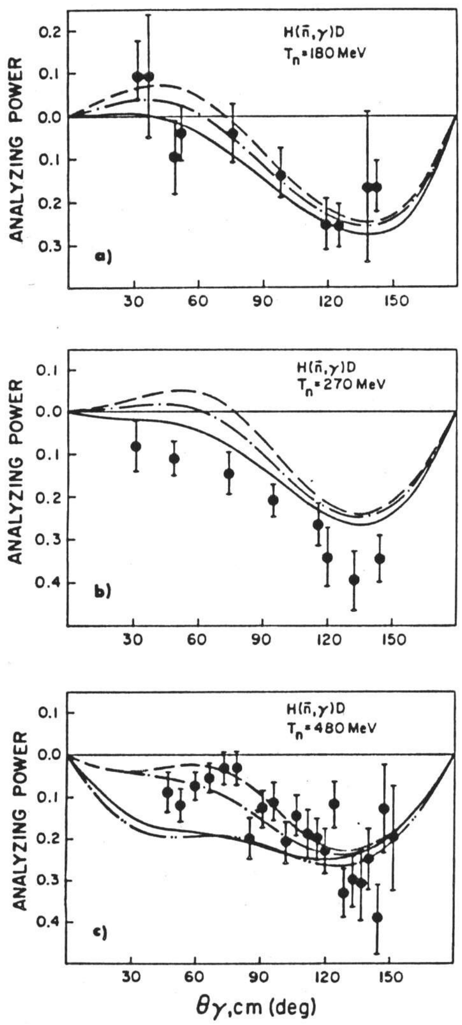

Fig. 3. Analyzing powers for the $H(\vec{n},\gamma)D$ reaction at 180, 270 and 477 MeV.

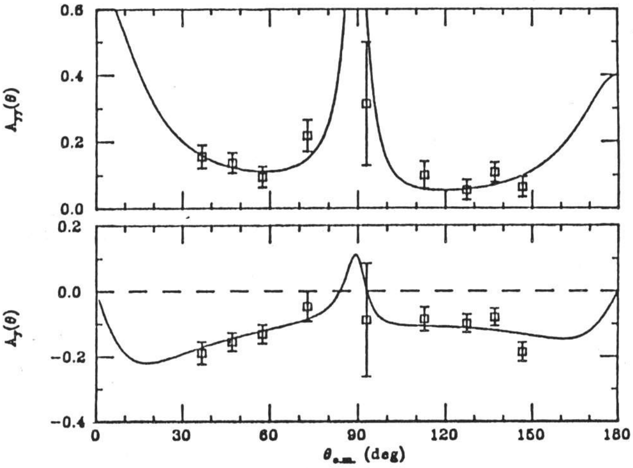

Fig. 4. Vector and tensor analyzing powers for $^2H(\vec{d},\gamma)^4He$ at 10 MeV.

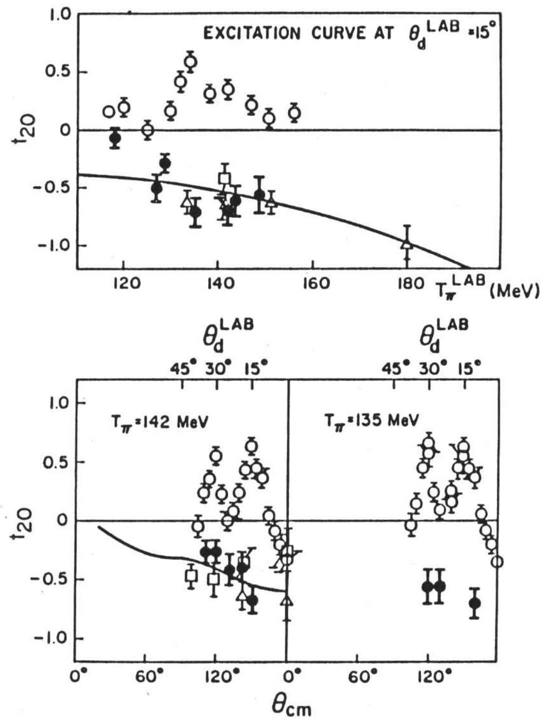

Fig. 5. Tensor polarizations t_{20} for $D(\pi^+,\pi^+)D$: open circles SIN data; squares and triangles LAMPF data; closed circles TRIUMF data. The curves are from Ref. 3.

The results of the LAMPF and TRIUMF experiments show that t_{20} is negative and smooth for all energies and angles investigated. The SIN data on the other hand show rapid variation with angle and energy in the measured tensor polarization as shown in Fig. 5. The origin of this discrepancy is not known, but the TRIUMF and LAMPF groups have pointed out that the discrepancy could have come from the determination of the unpolarized efficiency and the number of deuterons actually producing the desired reaction in the polarimeter. On the other hand the ETH group has repeated their measurements with a more elaborate polarimeter giving the same results.

The conventional three-body theory, including the work by Pöpping, Sauer and Zhang Xi-zhen presented to this conference (contribution 3.24), is in qualitative agreement with the results of TRIUMF and LAMPF. It appears, however, that most theoretical calculations overestimate π-absorption and rescattering effects. When

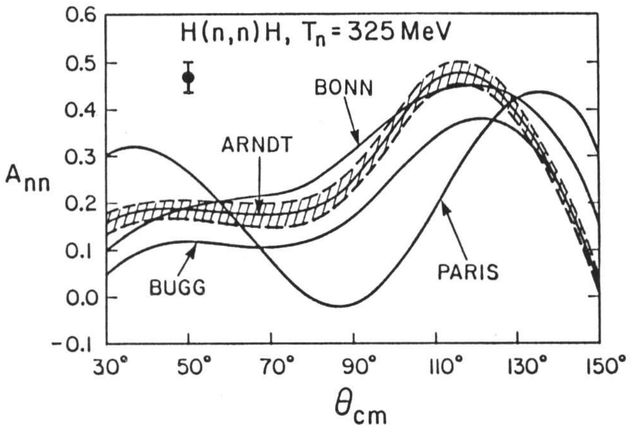

Fig. 6. Various predictions for the spin correlation parameter A_{yy} for n-p elastic scattering at 325 MeV.

these effects, through the P_{11} amplitude, are reduced or turned off, the theory is in closer agreement with experimental values for t_{20} and iT_{11}. However, introduction of dibaryon resonances is essential to explain the SIN data (see paper 3.20 of this Symposium).

In concluding my remarks on this particular topic: A lot of discussion has taken place at this Symposium on the possible evidence for dibaryon resonances. It is highly desirable though that when such evidence is presented also the criteria that were applied to the data are clearly stated.

§5. The Asymptotic D-to-S-State Ratio

A new determination of the asymptotic D-to-S-state normalization ratio ρ_D for the deuteron through sub-Coulomb stripping was obtained by Rodning and Knutson (contribution 3.35). The new result ρ_D = 0.02628±0.00047 is in good agreement with the predictions obtained from modern N-N potentials.

§6. The Three-Nucleon System

The three-nucleon system is an important testing ground for the nucleon-nucleon potential parameters used in three-body calculations based upon the Faddeev equations. These nucleon-nucleon potential parameters are obtained by fitting existing N-N scattering data, but even the modern potentials, e.g. the Paris and Bonn potentials, differ substantially in the predictions for certain observables like for instance A_{yy} or A_{oonn} for n-p elastic scattering. Figure 6 shows predictions for the observable A_{yy} in n-p elastic scattering at 325 MeV. This deficiency is in part related to the uncertainties in the deuteron D-state wave function or the tensor interaction. The three-nucleon system is the simplest system with more than two nucleons and phenomena, such as genuine three-body forces and off-shell effects, which are not observable in the interaction between two nucleons, may appear here. There is a word of caution: the three-body Faddeev calculations are first of all sensitive to the nucleon-nucleon input and thus inadequacies in this input must be removed first. Secondly, for the p-d system only an approximate treatment of the Coulomb interaction can be made at present. In this respect the n-d system is to be preferred. In addition there are questions such as the importance of relativistic effects and possible signatures of the quark structure of the nucleons. Only a multifaceted approach will solve the important questions at hand.

In a contribution to this Symposium (3.31) the Karlsruhe group shows the high degree of precision which can now be obtained in n-d scattering experiments. Measurements of the analyzing power A_y or A_{oono} at 10 energies between 18 and 50 MeV are compared with a series of Faddeev calculations made by Koike using the Graz II N-N potential. The agreement obtained although not perfect is rather satisfactory for the whole energy range under consideration (see Fig. 7). In another contribution to

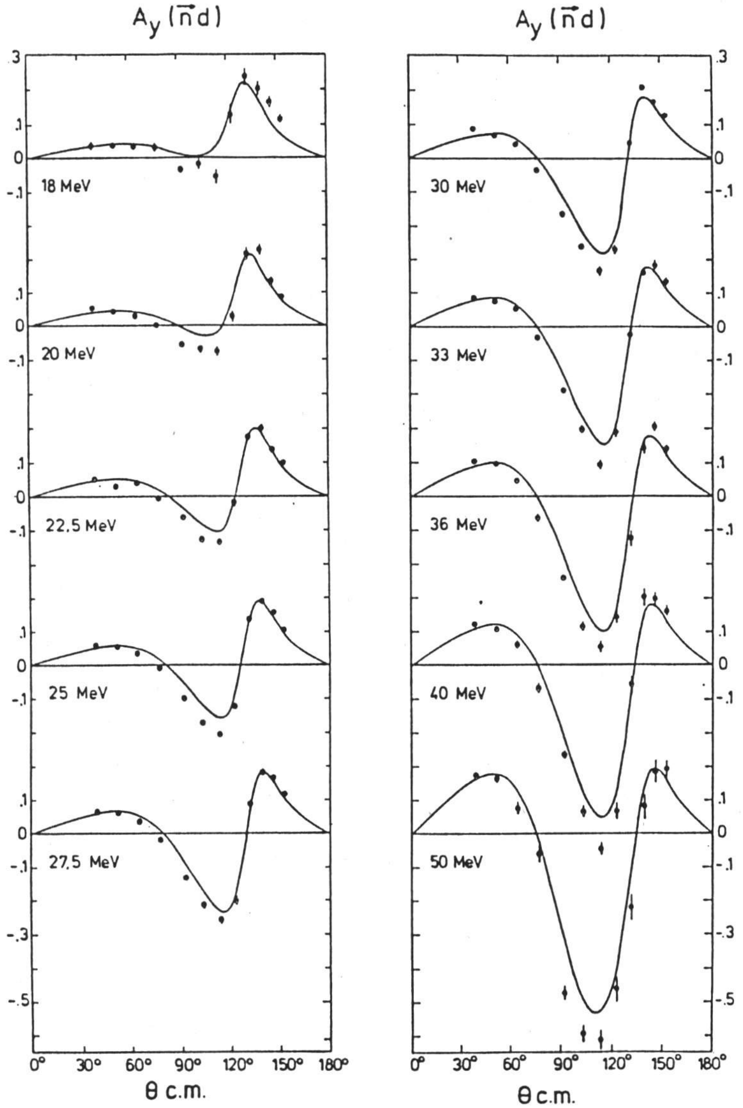

Fig. 7. Analyzing powers for $^2H(\vec{n},n)^2H$ elastic scattering at 10 energies between 18 and 50 MeV.

this Symposium (3.29) Koike et al. show the agreement that can be obtained in d-p elastic scattering at an equivalent proton energy of 28 MeV. Here Faddeev calculations using the PEST N-N interaction are presented. The agreement is quite reasonable for each of the deuteron analyzing power observables A_y, A_{yy}, A_{xz} and A_{xx}. The remaining discrepancies, in particular for the observable A_{xz}, might be related to an insufficient treatment of the higher partial waves in the calculations. To provide data which can test more unambiguously the inclusion of the Coulomb interaction in Faddeev calculations the Köln group (contribution 3.28) presented differential cross section and analyzing power data for p-d elastic scattering at 10.0 and 14.1 MeV, especially for small angles. Discrepancies with Faddeev calculations based upon the PEST interaction by Koike show the sensitivity to the Coulomb interaction at these low energies.

Another approach leading to an intermediate result for comparison with theory is an amplitude analysis of the experimental observables. As pointed out by Sperisen (contribution 3.25) complete sets of observables in p-d elastic scattering are now available at 10 MeV and at 800 MeV. At the latter energy this set comprises new data

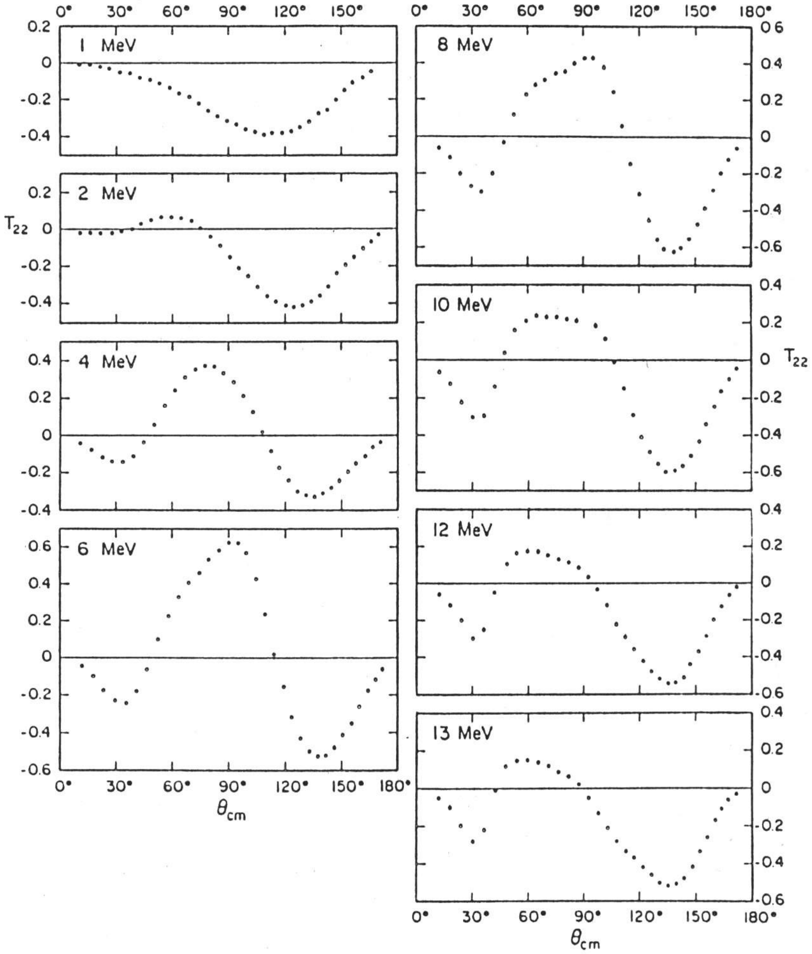

Fig. 8. The analyzing power T_{22} of the ^{3}He(d,p^{4}He reaction between 1.0 and 13.0 MeV.

on the p-d elastic scattering second- and third-order polarization observables obtained by a UCLA group (contribution 3.26).

§7. Few-Nucleon Systems with Four or More Nucleons

Precision measurements of the analyzing powers iT_{11}, T_{20}, T_{21} and T_{22} of the reaction ^{3}He($\vec{d}$,p)^{4}He between 1.0 and 13.0 MeV were made by an ETH group (contribution 3.52) (see Fig. 8). Together with similar measurements made at LANL between 12.0 and 17.0 MeV it will be possible to map out the analyzing powers over the investigated angular and energy range. This information will be helpful for deuteron polarimeters which are based on the ^{3}He(d,p)^{4}He reaction in this energy domain and which are used in π-d and e-d elastic scattering experiments.

Extensive measurements of the spin-dependent observables for p-^{3}He elastic scattering at 800 MeV have been made by a UCLA group (contribution 3.38). A sample of these data is presented in Fig. 9. Together with differential cross section and analyzing power angular distributions obtained recently at TRIUMF at 200, 300, 415 and 515 MeV a substantial amount of p-^{3}He elastic scattering data exists now for the intermediate-energy region.

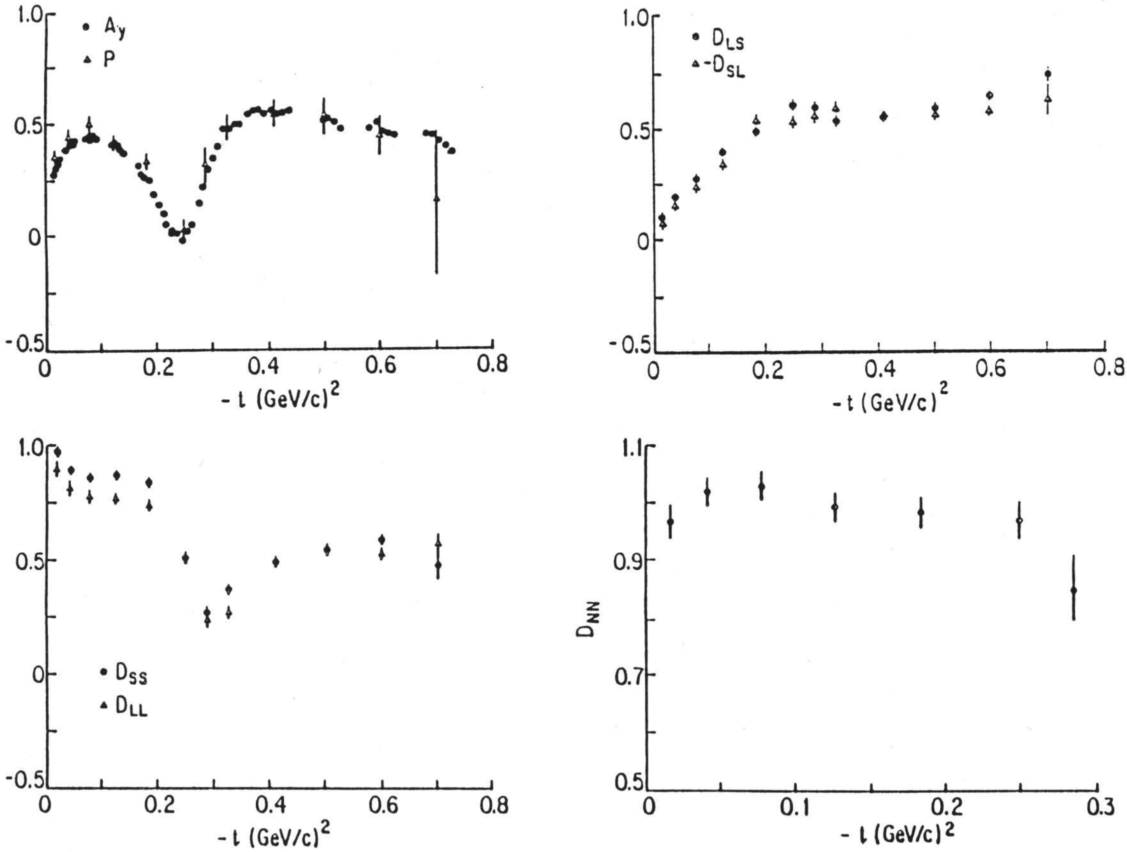

Fig. 9. Spin observables for $\vec{p}$-^{3}He elastic scattering at 800 MeV.

References

1) R. Arndt: Interactive Dial-in Program SAID, private communication.
2) Y.M. Shin: private communication.
3) H. Garcilazo: Phys. Rev. Lett. 53 (1984) 652.

DISCUSSION

SIMONIUS: Have calculations of bremsstrahlung been done in soft photon approximation for the Bonn potential, i.e., with the on shell amplitudes obtained from the Bonn potential? This is important in order to see whether the differences stem from the fact that the Bonn potential does not completely reproduce the scattering amplitude, or from the off shell behaviour.

VAN OERS: Indeed you raise an important point. The calculations are in progress and for so far I know the check you mentioned has not been made as of yet.

SLOBODRIAN: How was the soft photon calculation of nucleon-nucleus bremsstrahung carried out? There are two ways that have been used in the past, one using the average energy between initial and final states, the other using the explicit amplitudes at the initial and final energies of the bremsstrahlung transition.

VAN OERS: I am not so familiar with the details of the calculations, but to answer you: I think it is the latter approach. I suggest that one of the authors of this contribution answer your question.