BIBLIOTHEQUE
06 0000 1006

Invited paper at III. International Symposium on

Mesons and Light Nuclei

(European Conf. on Few Body Physics)

Czechoslovakia, May 27 - June 1, 1985

TRI-PP-85-28

MAY 1985

1. INTRODUCTION

2.

We want to review here radiative processes in systems of two and three nucleons. The aim is to learn about the coupling of the electromagnetic field to the two nucleon current and thus about the subnucleonic degrees of freedom, i.e. the mesonic currents, or at a different level, the quarks and gluons, from which this current is constructed. The extension to three nucleons allows us to study the embedding of the two nucleon current in the next most complicated system.

RADIATIVE REACTIONS IN TWO AND THREE NUCLEON SYSTEMS

Harold W. Fearing

TRIUMF, 4004 Wesbrook Mall, Vancouver, B. C. Canada V6T 2A3

ABSTRACT

Several of the interesting radiative processes involving few nucleon systems at medium energies are discussed, with emphasis on what is interesting about the reaction, what is currently known both theoretically and experimentally, and what should be done next. Reactions considered are proton proton bremsstrahlung, neutron proton bremsstrahlung, neutron proton radiative capture and deuteron photodisintegration, and three body processes such as $p + d + {}^3\text{He} + \gamma$.

For the most part we will limit our discussion to medium energies and will discuss processes such as proton proton and neutron proton bremsstrahlung, neutron proton radiative capture, and reactions like $p + d + {}^3\text{He} + \gamma$. Electron scattering will not be included, though it too is interesting in its own right. Other recent reviews of this general topic include Refs. 1-3.

Why are such processes interesting and important? Obviously understanding the two nucleon force is fundamental. In principle the electromagnetic interaction is one of the simplest probes of such forces. It is weak so that it may be treated only to first order and consequently double counting problems of the type inherent in pion processes are less severe here. It is also well known and simple, at least for the interaction with a single elementary particle. However the electromagnetic interaction with a multi-nucleon system is not so simple because the strong interaction is complex and the photon must couple to any charged current in the strong interaction. The overall coupling however, is constrained by current conservation, or gauge invariance, which gives relations among the various contributions and may allow the use of general simplifying results such as soft photon theorems. In addition, limiting the problem to a few nucleons may simplify it sufficiently that knowledge of the fundamental

CERN LIBRARIES, GENEVA

CM-P00067368

3.

electromagnetic couplings may actually lead to microscopic understanding of the reactions.

II. PROTON PROTON BREMSSTRAHLUNG

One of the simplest of the radiative processes is proton proton bremsstrahlung (ppv), a process which clearly must be understood if we are to understand the coupling of the photon to the two nucleon system. Traditionally ppv has been advocated as a good way to learn about off shell aspects of the nucleon nucleon force, but for a variety of reasons, both theoretical and experimental, not much has yet been learned, even though there has been quite a bit of work on the process. Now after a hiatus of several years a new ppv experiment⁴) is underway which will have much improved statistics and which will measure the analyzing power using polarized protons for essentially the first time. Thus it is appropriate to examine this problem again.

Two major theoretical approaches to ppv have been used. The first of these is the soft photon approximation (SPA), which is based on the low theorem⁵). In this approach the amplitude is expanded in powers of the photon momentum k and gauge invariance is used to fix the coefficients of the leading $O(1/k)$ and $O(1)$ terms in terms of the elastic scattering information. This approach is very simple and is easy to make gauge invariant and relativistic invariant. It contains no off shell information however, so one hopes to find places where it fails. Since other calculations indicate that off shell effects are important, it is somewhat of a surprise to find that it works rather well^{6,7}).

The other main approach is the non relativistic potential model approach. Given a potential one can obtain the ppv amplitude exactly (for a local potential at least) by evaluating the contributions from the external radiation diagrams

4.

Fig. 1a,b and permutations and from the double scattering term Fig. 1c. Such an approach involves off shell contributions directly. However, unlike the SPA, for a general potential it is difficult to make it gauge or relativistic invariant. Such calculations did fit early data, which however in retrospect were almost on shell. However the more recent TRIUMF data⁷) at 200 MeV is not well fit. In fact the SPA seems to work best here even though off shell effects are expected to be big.

A new potential model calculation along these lines has recently been undertaken by Workman and Fearing⁸). The aim was to use a modern potential and to include a number of effects which had not been combined in one calculation before. The calculation is done in momentum space by solving the Lippmann Schwinger equation for the half off shell nucleon nucleon amplitudes and combining them with propagator and vertex functions to get the ppv amplitude. The most important corrections included were the so called relativistic spin corrections which are relativistic corrections to the photon nucleon vertex. Also included were Coulomb corrections, proper frame transformations, one pion exchange for the higher partial waves, and relativistic kinematics. The calculation was done initially with the Paris potential⁹) and an extended Reid potential of Day¹⁰) and later, in collaboration with Machleidt¹¹), extended to include the Bonn potential¹²).

Some results of this calculation, for both cross section and analyzing power are shown in Fig. 2 and Fig. 3. There is still a clear difference between the potential model and SPA results, with the difference reaching a factor of two in the analyzing power at some angles. A most surprising outcome was the very similar results obtained for all the potentials used. This can be understood in retrospect by looking at the half shell functions which, it turns out, are very

similar for all these modern potentials. The results are actually sensitive to these half shell functions, as is indicated by the huge changes observed when they are set to one, but all modern potentials seem to be similar off shell as well as on shell.

Several things remain to be added to the calculation. Although the amplitude is gauge invariant as it stands there are additional gauge terms coming from nonlocalities in the potential which have never been calculated. Also only the leading term of the double scattering piece has been included so far, although if such terms have the same sign as at lower energies they will increase the cross section¹³⁾ and thus increase the discrepancy between the potential results and either SPA or the existing data.

On the experimental side the data is rather sparse, reflecting the difficulty of such experiments. There were several ppy experiments years ago, but the only modern experiment in the medium energy range is the 200 MeV experiment at TRIUMF⁷⁾. Results are shown in Fig. 4 and, as noted above, the SPA seems to fit the data better than potential models, even though off shell effects should enter for the conditions of this experiment.

A most encouraging development is a new experiment⁴⁾ at 280 MeV which is now underway at TRIUMF. The kinematic region to be covered is shown in Fig. 5 in a plot of the soft photon parameter k versus an off shell parameter Δm^2 . It covers a much wider region than previous experiments and encompasses some regions where the photon is really soft, which will give a normalization against the SPA, and some where it is quite hard, which should require off shell input. Especially interesting will be the analyzing power results which will be obtained, essentially for the first time. As seen in Fig. 3 there is sometimes a factor of two between potential and SPA results, which should easily be

distinguishable in this experiment. A sizeable fraction of the expected 100,000-200,000 bremsstrahlung events have already been recorded and preliminary results of the analysis should be available within the year.

It is interesting to speculate on the implications of possible outcomes of this experiment. If the results agree with potential model calculations for both analyzing power and cross section then the previous 200 MeV experiment⁷⁾ must have been wrong, at least in overall normalization, and presumably we understand how to calculate with a potential and have potentials which are reasonably correct both on and off shell. It then does not appear possible with present experimental techniques to distinguish between the various potentials. On the other hand, if the data still agree with the SPA then there must be something very wrong with the potential technique, or something very important left out. This would be not inconsistent with the difficulties, to be discussed below, which arise in trying to describe data for the related reaction $n + p \rightarrow d + \gamma$ using very similar potential model techniques.

In either case it would probably be useful to have additional data at somewhat lower energies, say in the 100-200 MeV range where some of the corrections to the potential model calculations may be smaller but where off-shell effects could still be significant. It might also be useful to see if there are any other accessible spin observables which might help in distinguishing among the potentials.

III. NEUTRON PROTON BREMSSTRAHLUNG

The next obvious process to consider is neutron proton bremsstrahlung (np γ). It is clearly very similar to ppy in terms of the kinematic features and in terms of the kind of information one hopes to be able to learn about the off

shell nucleon nucleon force, though of course now the $T=0$ force is accessible. However neutron proton bremsstrahlung has some very different features which make it quite interesting in its own right. Since the nucleons are now not identical, the leading term in the amplitude is not suppressed and as a result the radiation pattern is dipole rather than quadrupole. The cross section is also larger, by a factor of roughly five or so at 200 MeV, which helps offset the lower intensity of the neutron beams which are available.

The npy process is also much more sensitive to contributions from radiation from other than external legs. Meson exchange currents can be important, particularly the term involving radiation from an exchanged pion, which is not present for $pp\gamma$. In fact in the calculations of Brown and Franklin¹⁶ such contributions were comparable to those from ordinary external radiation. The double scattering contribution is also a bit more important than in $pp\gamma$, amounting to 10-25% at 200 MeV¹⁶. Thus npy is in general more sensitive to features of the two nucleon current than is $pp\gamma$.

One pays a major price however in working with neutrons. Beams are orders of magnitude less intense and detection is much harder. As a result there have been very few experiments¹⁷⁻¹⁹. However it is very encouraging that some new experiments are being considered. An experiment in the 60-70 MeV range is underway at Louvain²⁰ and one at 200 MeV is in the proposal stage at IUCF²¹.

Theoretical calculations have also been a bit sparse. There are potential model calculations of Brown and Franklin¹⁶, of Bohannon²², and of Celenza et al.²³, who however have not included one double scattering term found to be important by Brown and Franklin¹⁶. There are also specific considerations of the interaction current generated by one pion exchange^{24,25}. None of these

calculations is very recent however, or for example uses any of the modern potentials, so clearly there needs to be a great deal more theoretical work. One interesting aspect of the reaction which has not been investigated is the relevance of the the various spin observables. It would be very interesting to know if any of these observables are sufficiently more sensitive to various of the meson exchange effects here than in other possible processes to warrant the increased difficulty of experiments using neutron beams.

IV. NEUTRON-PROTON RADIATIVE CAPTURE AND DEUTERON PHOTODISINTEGRATION

Let us turn now to the remaining process involving two nucleons and a photon, namely neutron-proton radiative capture, or equivalently deuteron photodisintegration. The basic physics here is similar to that we have already considered. Here however, since we are dealing with a two, rather than three, particle final state and since we know so much about the deuteron wave function, the process is much simpler, certainly from an experimental point of view, and probably also from a theoretical point of view as well. Thus unlike the processes considered above, there are here many experiments and many theoretical calculations.

It has been known for a long time that this process contains interesting physics and that it provides a vital testing ground for our ideas of how to write down the two body electromagnetic current and how to incorporate the various corrections due to meson exchanges, isobar effects, relativistic corrections, etc. One of the first successes was the work of Risks and Brown²⁶ who showed that the inclusion of meson exchange effects (MEC) such as those shown in Figs. 6 and 7 could explain an important discrepancy in the threshold cross section. Later calculations which were attempting to explain difficulties in reproducing

the forward cross section found that a large number of other effects in addition to the MEC, such as the D state of the deuteron, different kinds of relativistic corrections, effects of the $\Delta(1236)$, and off shell aspects of the nucleon nucleon force all could also be important. Thus the process is a very rich and interesting one.

Given the multitude of effects which might be included, it may not be that surprising that the theoretical situation is still remarkably confused. Early work usually used a non relativistic potential model. Partovi's work²⁷⁾ is the classic reference. Since then there have been a number of other calculations. We will focus on just a few of them, only those most relevant to medium energies, with apologies to those authors, particularly of low energy calculations, which are not mentioned explicitly. A good survey of the present theoretical and experimental situation can be found in Ref. 28.

A number of the more recent calculations are in the spirit of Partovi, but include a number of additional effects or corrections. Examples are the work of Rustgi et al.²⁹⁾, Jaus and Woolcock³⁰⁾, Friar et al.³¹⁾, Cambi et al.³²⁾ and Hwang et al.³³⁾. For the most part these calculations start with a partial wave analysis and evaluate the matrix elements of a simple one body operator using wave functions derived from a simple nonrelativistic potential. Normally Siegert's theorem³⁴⁾ is used. This allows one to use current conservation to eliminate the current density in favor of the supposedly better known charge density. Meson exchange corrections are then added. Here one must be very careful however. There are many different definitions of MEC. Furthermore as discussed by Arenhovel³⁵⁾ many MEC can be incorporated via gauge invariance using Siegert's theorem, with the result that the residual "MEC" are small. Alternatively the MEC can be calculated explicitly as done in Ref. 36 with the

result that they are big. Several of these modern calculations improve the frame transformations used originally by Partovi²⁷⁾. A more careful consideration of the one pion exchange contribution is included in Ref. 30. D state effects have often been considered and are important, especially for the forward cross section

Some of the most important effects are relativistic corrections, in particular the spin orbit contribution to the one body electromagnetic operator. Both Friar et al.³¹⁾ and Cambi et al.³²⁾ find that this is one of the most important corrections and one which lowers the forward cross section, bringing it in better agreement with the data. The effect is partially cancelled however by the MEC coming from the one pion exchange contribution, which unfortunately depends on the choice of pseudovector or pseudoscalar coupling for the pion. There is some indication here that pseudovector is better.

There are two other modern calculations which are somewhat nonconventional, both of which are tailored for the resonance region. The first of these, by Leidemann and Arenhovel³⁷⁾ is based on a coupled channel approach in which all states involving nucleons and deltas are calculated and then joined with the photon, leading to diagrams such as those in Fig. 8a,b,c. Thus a variety of what are usually called MEC are included here. In the resonance region the isobar currents of Fig. 8b dominate.

The other non-conventional calculation, due to Lager³⁶⁾, is based on a sum of a large number of diagrams involving nucleons, deltas and pions with the photon attached to all charged lines. Nucleon rescattering in the $n-p$ state is put in only in s and p waves. The interaction can be made explicitly gauge invariant, at least at the initial level. The claim is made that this approach makes it possible to use a more realistic interaction, but that the wave functions, particularly the scattering state, are handled less well than in other

11.

calculations. Both this calculation and the previous one give qualitative, but only qualitative, fits to the cross section data in the resonance region as we will see below.

Thus there has been some progress over the past few years. There have been several new calculations extending Partovi's original work and there is some agreement on some of the important ingredients such as delta currents, some MEC, and some of the relativistic corrections. However the agreement on the result is at most qualitative as can be seen from Fig. 9 taken from Ref. 38 which shows a variety of calculations of the cross section under the same conditions. Clearly such results are not of much use in elucidating the fine details of the process. The problem seems to be that there are a number of different ways of putting in the various effects and different ways of approximating various features. Even face to face the authors do not seem to be able to sort out how their calculations differ in detail from others done in a slightly different approach. Thus it is no surprise that the data are not fitted very well.

Until recently the experimental situation was equally bad. There have been many experiments. Most of the early ones were done with bremsstrahlung beams and apparently suffered from normalization problems. Thus, particularly in the 100 - 300 MeV photon energy range there have been differences of almost a factor of two among the various experiments.

There are now however new data from several labs, which seem to be converging to a common value. At resonance energies and above new cross section results from Bonn⁽¹⁾ and from Tokyo⁽²⁾ agree reasonably well and apparently also agree with as yet unpublished MIT data⁽³⁾. The old Lund data⁽⁴⁾ are consistent with these at the highest energies but significantly higher than the rest below 250-300 MeV photon energy. At lower energies there have been several

12.

new measurements using neutron beams at IUCF⁽⁵⁾ and at TRIUMF⁽⁶⁾. The measurements overlap at 200 MeV neutron energy and are in good agreement there. New data from Frascati⁽⁷⁾ taken with a quasi monochromatic photon beam seems also to agree at this energy. Absolute cross sections have been measured at SIN⁽⁸⁾ also, albeit with fairly wide bins in neutron energy. Extension of the TRIUMF measurements to higher energies is underway⁽⁹⁾.

Thus the situation is improving and it makes some sense to compare with calculations, as has been done in Fig. 10. Such fits are typical of this energy region. The magnitude is about right but the shape is only qualitatively correct, with neither of the calculations of Ref. 36 or 37 really reproducing the bump seen at 90°. Most other calculations have looked at lower energies only, where the agreement between data and some of the better potential model calculations is in fact quite good, or have emphasized the forward cross section only.

The exciting development of the past couple of years has been the availability for really the first time of good data on some spin observables. In particular data from TRIUMF⁽⁵⁰⁾ now provide fairly complete angular distributions for the analyzing power using polarized neutron beams at the neutron energies 180 MeV and 270 MeV, and there are plans to extend these measurements to energies well above the pion production threshold⁽⁴⁹⁾. For the higher of the two energies there seems to be a clear discrepancy with the theory, as seen in Fig. 11. At 180 MeV the agreement is satisfactory. There is also older data⁽⁵¹⁾ on the asymmetry measured with vector polarized deuteron target for photon energies above 300 MeV. Measurements of the asymmetry using polarized photons have also been made^(52,53). Here the asymmetry at 90° as a function of energy can be fit reasonably well when MEC and isobar currents are included⁽⁵²⁾ and the angular distribution at one energy⁽⁵³⁾ agrees with a

calculation of Cambi et al.⁵⁴⁾, made using the same assumptions which give the best results for the forward cross section. At very low energies there seems to be some indication of the failure of the theory⁵⁵⁾ to fit the neutron recoil polarization data⁵⁶⁾.

There have also been new data on the forward cross section at several additional energies. Recall that this has been a longstanding puzzle, with the original Mainz⁵⁷⁾ data being significantly below the Partovi prediction, as can be seen in Fig. 12. Now new data from Louvain^{58,59)}, from IUCF⁴⁵⁾ and from TRIUMF⁴⁶⁾ all confirm the original data. The Louvain group has measured also the backward cross section at 61 MeV⁵⁹⁾, so as to be able to determine separately the a and c parameters. At this energy c turns out to be positive, in contrast to their earlier measurements at 72 MeV⁵⁸⁾, but now in agreement with most potential model calculations. There are plans⁴⁶⁾ at TRIUMF to extend the zero degree measurements to much higher energies. There are also extensive Bonn data for the backward cross section for photon energies of 180-730 MeV⁶⁰⁾.

Most of the modern calculations have focused on the forward cross section and almost anything seems to affect it. Both Friar et al.³¹⁾ and Cambi et al.³²⁾ have shown however that one of the most important corrections is the spin orbit contribution of the one body current, which is a correction of relativistic order and which moves the theory down toward the data. Unfortunately the inclusion of pion exchange contributions moves the curve back up. It is interesting in view of the apparent importance of relativistic corrections that a simple on shell soft photon approximation⁶¹⁾ fits the data fairly well, Fig. 12, since such a calculation, though crude in many respects, is both relativistic and gauge invariant.

So what should be done next? It is clear that there has been major progress in the past few years toward resolving some of the experimental discrepancies which have plagued this process. We have learned a lot about the important ingredients of the theory, but still are not able to resolve differences among the different theoretical approaches. The study of spin observables, both experimentally and theoretically seems very important as there may be sensitivities there which do not show up in the cross section. Clearly the theorists should investigate the consequences for some of the spin observables of the various effects which are supposed to be important for the zero degree cross section. Perhaps also one should look at some of the more exotic spin observables which would be possible with some of the polarized deuteron targets which are now available.

$$V. p + d \rightarrow {}^3\text{He} + \gamma$$

Let us now consider the very interesting process $p + d \rightarrow {}^3\text{He} + \gamma$. This is essentially the simplest process which allows the embedding of the two nucleon current in a more-than-two-nucleon system. Thus information about the two nucleon current obtained from the processes considered above can be used in this process to test ideas of how to embed this current in a nucleus. The wave functions necessary here are also relatively well known, as a result of extensive Faddeev calculations⁶³⁾, though there are still unresolved problems connected with the difference between ${}^3\text{He}$ and ${}^3\text{H}$ wavefunctions. At very low energies there are indications⁶⁴⁾ that various spin observables are sensitive to the small components of the three body wave function. Finally a good knowledge of this process may allow comparison with the very similar pion production process⁶⁵⁾ and thus lead to new insights concerning pion interactions with these light systems.

15.

The theoretical situation regarding this process is not particularly satisfactory. There have been a number of low energy calculations⁶⁶⁻⁶⁸) essentially all based on the matrix element of a simple non relativistic one body operator taken between nuclear states. Such an approach seems to work at very low energies, but fails when extended to medium energies as for example done by Craver et al.⁶⁸) or by Finjord⁶⁹) who in addition put in some meson exchange effects. In the medium energy region Lage⁷⁰) has made the most elaborate calculation, one based on an extensive set of diagrams, and has obtained qualitatively correct results for some energies. A phenomenological distorted wave impulse approximation approach⁶⁵) patterned after similar calculations⁷¹) of $p + d + t + \pi$ and based on the diagram of Fig. 13a also gives qualitative results for the cross section. A calculation in the same spirit but somewhat different technically in that it includes all three diagrams of Fig. 13 has been performed by Prats⁷²). After surveying the experimental situation we shall come back and see how some of these predictions agree with data.

There is by now a great deal of data on this process. It was originally suggested as a test of time reversal invariance since it is experimentally accessible in both directions, and measurements in both directions have been made. Unfortunately some of the data sets differ by a factor of two. Clearly this can not be a violation of time reversal, but must indicate problems with some of the experiments. There has been major progress in the past couple of years however and as a result there is now a set of several modern experiments which do agree with one another. In the $p-d$ direction a new experiment from IUCF has data at 100, 150, and 200 MeV⁷³). At the lower energies these data agree with older data of O'Fallon et al.⁷⁴) and Didelez et al.⁷⁵) and at 200 MeV they agree with a new TRIUMF experiment⁷⁶) which extends the available data

16.

upward with data at 200, 350, 450, and 500 MeV. Fig. 14 shows an example of some of the data as compared with some of the theoretical calculations mentioned earlier. The solid and dashed curves come from the work of Lage⁷⁰). The solid curve includes, in addition to the main Born diagrams, contributions from coupling of the photon to various meson exchange currents. Clearly such contributions are essential in this approach. The dotted curve is from the DWIA calculation of Fearing⁶⁵). It also qualitatively reproduces the shape of the angular distribution. One other modern $p-d$ experiment, that of Neikens et al.⁷⁷) gave results significantly higher than these, but a repeat experiment by the same group, as yet unpublished⁷⁸), agrees with the TRIUMF and IUCF data. In the γ -³He direction, the 1981 Bonn data⁷⁹) are significantly lower than these. However there is a new Bates experiment⁸⁰) which does give the same result as the $p-d$ experiments.

Thus the situation for the cross section is now fairly good. One must ignore some of the older experiments, which differ for reasons not understood, but one is left with a group of new experiments done in both directions which agree with each other and which provide a fairly good representation of the cross section over the whole medium energy range.

The theoretical calculations fit the data in a qualitative way, but not always in detail. One interesting situation is shown in Fig. 15, which shows the IUCF and TRIUMF data at 200 MeV. The two solid curves are from a DWIA calculation⁶⁵) based on the diagram of Fig. 13a using data for the $n + p + d + \gamma$ cross section as input. The two curves correspond to two extreme choices of subsets of the data. The dashed curve is from a calculation of Prats⁷²) including contributions of all three diagrams of Fig. 13. It reproduces a forward dip, which may be present in the data, though really based only on one

high data point. The dip can be traced to an interference between the impulse diagram Fig. 13a and the proton radiating diagram of Fig. 13b. However this latter diagram is to some extent included in the contribution of Fig. 13a when the interaction vertex for this diagram is obtained from experimental information on $n + p + d + \gamma$ as is done. Thus to include both diagrams must involve some double counting. Nevertheless this approach may fit the data better than Fig. 13a alone. It would be very interesting to have a bit more data in this region to see if the dip is really there.

One of the most exciting really new developments of the past couple of years has been the measurement of analyzing powers and other spin observables in this reaction. There is now a fairly complete set of analyzing power data ranging from 100 to 500 MeV coming from IUCF⁷³ and TRIUMF⁷⁶ as shown in Figs. 16 and 17. Essentially the only theory is that of Laget⁷⁰, as shown in Fig. 17, since the DWIA calculation⁶⁵ as presently formulated gives identically zero. When the nucleon rescattering terms are added (dashed curve) Laget's calculation reproduces the low energy data fairly well, but fails by 500 MeV. Clearly there should be more theoretical work. There has now even been one unpublished measurement of the tensor analyzing power⁸¹, so theorists should calculate all possible spin observables while they are at it.

For this process we want to comment briefly on some very nice low energy data which are really outside the energy range of this review but which nevertheless lead to some interesting information about the three body wavefunctions. It was shown long ago^{66,67} that the low energy cross section was not particularly sensitive to the D state of the ^3He wave function. More recently however King et al.^{82,83} showed that certain of the coefficients in

a Legendre polynomial expansion of the cross section are sensitive to this D state component. The tensor analyzing power is also sensitive to the D/S ratio⁶⁴). Motivated by this expectation several groups have investigated this reaction at low energies and so there is now an almost complete set of data for the various measurable spin observables. Namely there are now data for the cross section^{82,83}, for the analyzing power using polarized protons⁸², for the vector analyzing power⁸⁴ and for the tensor analyzing power⁸⁵, and from this data it has been possible to extract a value for the D/S ratio. It would be very interesting to have similar data at higher energies. Such detailed information would undoubtedly be very useful in sorting out the contributions of not only components of the wave functions but also of the various meson exchange contributions and rescattering pieces.

Thus to summarize this section, the experimental situation for the reaction $p + d + ^3\text{He} + \gamma$ is much better than it was only a couple of years ago. There is now a fairly complete set of angular distribution and analyzing power data for the whole range of energies 100-500 MeV and the agreement among the most recent experiments done in both directions is good. It still would be interesting to measure some of the more exotic spin observables however. On the theoretical side much work is needed, as the best of the calculations, at least at medium energies, reproduce the data only qualitatively.

VI. SUMMARY

We have reviewed the theoretical and experimental situation regarding radiative processes in two and three nucleon systems. There has actually been a lot of recent progress. Data sets from different experiments which agree with one another have now replaced the factor of two discrepancies of just a few years

ago for several of the processes. New data on spin observables are now available for a variety of energies. New experiments are in progress for both proton and neutron proton bremsstrahlung. The theorists have not kept up. Although there has been a lot of work, there exists no theory which

quantitatively describes all the data for either $n + p + d + \gamma$ or for $p + d + \gamma$. Thus there is still a lot to do if we are to fully understand these most basic processes.

ACKNOWLEDGEMENTS

Support in part from the Natural Sciences and Engineering Research Council of Canada is gratefully acknowledged.

REFERENCES

1. J. M. Cameron, Can. J. Phys. 62, 1019 (1984).
2. B. F. Gibson, Nucl. Phys. A416, 503c (1984).
3. H. W. Fearing, Proceedings of the IUCF Workshop on Nuclear Physics with Stored Cooled Beams, (AIP, New York, 1985) in press.
4. TRIUMF Expt. No. 208, P. Kitching, spokesman.
5. F. E. Low, Phys. Rev. 110, 974 (1958).
6. H. W. Fearing, Phys. Rev. C22, 1388 (1980); Phys. Rev. Lett. 42, 1394 (1979); Phys. Rev. C6, 1136 (1972).
7. J. G. Rogers et al., Phys. Rev. C22, 2512 (1980).
8. R. L. Workman and H. W. Fearing, Proc. of the 10th Int. Conf. on Particles and Nuclei, Heidelberg, 1984, ed. by F. Guttner et al., Book of Abstracts, Vol. 1, p C29 and to be published.
9. M. Lacombe et al., Phys. Rev. C21, 861 (1980).

10. B. D. Day, Phys. Rev. C24, 1269 (1981).
11. H. W. Fearing, R. Machleidt, and R. L. Workman, to be published.
12. K. Holinde, Phys. Rept. 68, 121 (1981); R. Machleidt, TRIUMF preprint TRI-PP-83-128 (1983).
13. V. R. Brown, Phys. Rev. 177, 1498 (1969); 66, 1110 (1972).
14. C. A. Smith et al., Phys. Rev. C22, 2287 (1980).
15. B. M. K. Nefkens et al., Phys. Rev. C19, 877 (1979).
16. V. R. Brown and J. Franklin, Phys. Rev. C8, 1706 (1973); V. R. Brown, Phys. Lett. 32B, 259 (1970).
17. F. P. Brady and J. C. Young, Phys. Rev. C2, 1579 (1970); Phys. Rev. C7, 1707 (1973).
18. M. Furić et al., Nucl. Phys. A156, 105 (1970).
19. J. A. Edgington et al., Nucl. Phys. A218, 151 (1974).
20. P. Lelieux and P. Macq, private communication.
21. H. O. Meyer, private communication.
22. G. E. Bohannon, Phys. Rev. C17, 865 (1978).
23. L. S. Celenza et al., Phys. Lett. 41B, 283 (1972).
24. G. E. Bohannon et al., Phys. Rev. C16, 284 (1977).
25. M. A. Preston and W. van Dijk, Phys. Rev. C19, 1693 (1979).
26. D. O. Riska and G. E. Brown, Phys. Lett. 38B, 193 (1972).
27. F. Parçovi, Annals of Physics 27, 79 (1964).
28. For a recent review see Proceedings of the Workshop on Radiative Processes in Few Nucleon Systems, TRIUMF, Vancouver, Canada published in Can. J. Phys. 62, 1019-1128 (1984).
29. M. L. Ruestgl et al., Can. J. Phys. 62, 1064 (1984).
30. W. Jaus and W. S. Woolcock, Nucl. Phys. A431, 669 (1984).

31. J. L. Friar et al., Phys. Rev. C30, 441 (1984); C31, 287 (1985).
32. A. Cambi et al., J. Phys. G10, L11 (1984) and references cited therein.
33. W.-Y. P. Hwang et al., Annals of Physics 149, 335 (1983); W.-Y. P. Hwang, Can. J. Phys. 62, 1072 (1984).
34. A. J. F. Siegert, Phys. Rev. 52, 787 (1937); J. L. Friar and S. Fallieros, Phys. Rev. C29, 1645 (1984).
35. H. Arenhovel, Z. Phys. A302, 25 (1981).
36. J. M. Laget, Nucl. Phys. A312, 265 (1978); Can. J. Phys. 62, 1046 (1984).
37. W. Leidemann and H. Arenhovel, Can. J. Phys. 62, 1036 (1984); Phys. Lett. 139B, 22 (1984); Nuovo Cimento 76A, 256 (1983).
38. H. O. Meyer, Can. J. Phys. 62, 1109 (1984).
39. M. L. Rustgi et al., Phys. Rev. C29, 785 (1984).
40. E. L. Lonon and H. Feshbach, Ann. Phys. 48, 94 (1968).
41. J. Arends et al., Nucl. Phys. A412, 509 (1984).
42. K. Baba et al., Phys. Rev. C28, 286 (1983); Phys. Rev. Lett. 48, 729 (1982).
43. B. L. Craft, Ph.D. thesis, MIT, Cambridge, Mass., 1982 and to be published.
44. P. Dugan et al., Z. Phys. A280, 341 (1977); A276, 55 (1976).
45. H. O. Meyer et al., Phys. Rev. Lett. 52, 1759 (1984); Phys. Rev. C31 309 (1985).
46. J. M. Cameron, private communication.
47. E. De Sanctis et al., Phys. Rev. Lett. 54, 1639 (1985).
48. G. Nicklas et al., Phys. Lett. 141B, 170 (1984).
49. D. A. Hutcheon, Can. J. Phys. 62, 1114 (1984).
50. J. M. Cameron et al., Phys. Lett. 137B, 315 (1984).

51. T. Ishii et al., Phys. Lett. 110B, 441 (1982); see also K. Althoff et al., Proc. of the 10th Int. Conf. on Particles and Nuclei, Heidelberg, 1984, ed. by F. Guttner et al., Book of Abstracts, Vol. 1, p. A15.
52. W. Del Bianco et al., Phys. Rev. Lett. 47, 1118 (1981).
53. V. G. Gorbenco et al., Nucl. Phys. A381, 330 (1982).
54. A. Cambi et al., Proceedings of the Workshop on Perspectives in Nuclear Physics at Intermediate Energies, Trieste, 1983, to be published.
55. M. L. Rustgi et al., Phys. Rev. Lett. 50, 236 (1983); Phys. Rev. C29, 1580 (1984).
56. R. J. Holt et al., Phys. Rev. Lett. 50, 577 (1983).
57. R. J. Hughes et al., Nucl. Phys. A267, 329 (1976).
58. J. F. Gilot et al., Phys. Rev. Lett. 47, 304 (1981).
59. A. Ninane et al., Can. J. Phys. 62, 1104 (1984).
60. K. H. Althoff et al., Z. Phys. C21, 149 (1983).
61. H. W. Fearing, Proceedings of the International Conference on Few Body Problems in Physics, Karlsruhe, ed. by B. Zeitnitz, Vol. II, p. 99 (Elsevier, 1984) and to be published.
62. J. Govaerts et al., Nucl. Phys. A368, 409 (1981).
63. See e.g. J. L. Friar et al., Phys. Rev. C25, 1616 (1982).
64. A. Arriaga and F. D. Santos, Phys. Rev. C29, 1945 (1984).
65. H. W. Fearing, Proceedings of the IX International Conf. on the Few Body Problem, Eugene, Oregon, 1980, vol. 1, p. 39; Abstracts of contributed papers to the IX International Conf. on High Energy Physics and Nuclear Structure, (Versailles, 1981) p. 198 and to be published.
66. B. F. Gibson and D. R. Lehman, Phys. Rev. C11, 29 (1975).
67. S. Aufleger and D. Drechsel, Nucl. Phys. A364, 81 (1981).
68. B. A. Craver et al., Nucl. Phys. A276, 237 (1977).

69. J. Flinford, Nucl. Phys. A274, 495 (1976).
70. J. M. Laget, Symposium on Delta-Nucleus Dynamics, Argonne 1983, ed. by T. H. S. Lee, ANL-PHY-81-1 Conf-830588, p. 329 and to be published.
71. H. W. Fearing, Phys. Rev. C16, 313 (1977); C11, 1210 (1975); C11, 1493 (1975).
72. F. Prats, Phys. Lett. 88B, 23 (1979).
73. M. A. Pickar et al., IUCF Annual Report, Indiana University, Bloomington, Ind., p. 72 (1983).
74. N. M. O'Fallon et al., Phys. Rev. C5, 1926 (1972).
75. J. P. Didelez et al., Nucl. Phys. A143, 602 (1970).
76. J. M. Cameron et al., Nucl. Phys. A424, 549 (1984); R. Abegg et al., Phys. Lett. 118B, 55 (1982).
77. B. M. K. Nefkens et al., Phys. Rev. Lett. 45, 168 (1980).
78. B. H. Silverman, Ph.D. Thesis, UCLA, 1983.
79. H. J. Gaassen et al., Z. Phys. A303, 35 (1981).
80. D. I. Sober et al., Phys. Rev. C28, 2234 (1983); W. J. Briscoe et al., Phys. Rev. Lett. 49, 187 (1982).
81. M. Hugl et al., IUCF Annual Report, Indiana University, Bloomington, Ind., p. 60 (1983).
82. S. E. King et al., Phys. Rev. Lett. 51, 877 (1983); Phys. Rev. C30, 21 (1984).
83. M. Anghinolfi et al., Nucl. Phys. A410, 173 (1983).
84. S. E. King et al., Phys. Rev. C30, 1335 (1984).
85. M. C. Vetterli et al., Phys. Rev. Lett. 54, 1129 (1985).

FIGURE CAPTIONS

- Fig. 1: Some contributions to ppy in a local potential model: (a) and (b) external radiation; (c) double scattering.
- Fig. 2: Cross section for ppy at 280 MeV incident energy, with final protons each at 10° relative to the incident beam, in the potential model of Ref. 8 and in the SPA approach of Ref. 6.
- Fig. 3: Analyzing power for ppy under the same conditions as in Fig. 2.
- Fig. 4: Comparison of potential model⁸ and SPA⁶ calculations with 200 MeV data of Ref. 7.
- Fig. 5: Kinematic region investigated in some available ppy experiments, plotted versus the soft photon parameter k/T and an off shell parameter ΔW^2 , which is essentially the average difference between the square of the four momentum of the off shell nucleon and of its mass in units of the nucleon mass. The experiments are: 42 MeV¹⁴), 200 MeV⁷), 280 MeV⁴), and 730 MeV¹⁵).
- Fig. 6: One pion exchange part of the MEC contribution to the two body current in $n + p + n + p + \gamma$ or $n + p + d + \gamma$.
- Fig. 7: Pair current contribution to the MEC for $n + p + n + p + \gamma$ or $n + p + d + \gamma$.
- Fig. 8: Some types of two body currents included in the coupled channel approach of Ref. 37: (a) some of the MEC; (b) currents involving isobars; (c) MEC involving isobars.
- Fig. 9: A summary, taken from Meyer³⁸) of various attempts to calculate the cross section for $\gamma + d + n + p$ at 200 MeV. The labels correspond to: R³⁹), A³⁷), P²⁷), L⁴⁰), C³²), S³⁹), H³³).

Fig. 10: Comparison (from Ref. 37) of the cross section for $\gamma + d + n + p$ as calculated by Leidemann and Arenhovel³⁷ (dashed curve: impulse approximation, solid curve: coupled channel calculation) and by Laget³⁶ (dot dashed curve) with the data of Ref. 41.

Fig. 11: Analyzing power for $n + p + d + \gamma$ at 270 MeV from TRIUMF experiment⁵⁰. Curves are from Partovi²⁷ (solid line) and Leidemann and Arenhovel³⁷ (dashed line).

Fig. 12: 0° cross section for $\gamma + d + n + p$ showing the data of Hughes et al.⁵⁷, Meyer et al.⁴⁵, Gilot et al.⁵⁸, and Ninane et al.⁵⁹.

Dashed curve is from Partovi²⁷, solid curve is a full SPA calculation⁶¹, and long dashed curve is an approximation to it⁶².

Fig. 13: (a) Distorted wave impulse approximation model for $p + d + {}^3\text{He} + \gamma$ used in Ref. 65. (b), (c) Additional diagrams included in Ref. 72.

Fig. 14: Cross section data from Ref. 76 for $p + d + {}^3\text{He} + \gamma$ at 200 MeV and 500 MeV. Dotted curve is the DWIA calculation of Ref. 65. Solid and dashed-dotted curves are calculations of Ref. 70 with and without MEC respectively.

Fig. 15: Results for $p + d + {}^3\text{He} + \gamma$: Solid curves - DWIA calculation of Ref. 65 for two extreme choices of the $n + p + d + \gamma$ data. Dotted curve - calculation of Ref. 72. Data are from Refs. 73 and 76.

Fig. 16: Analyzing power for $p + d + {}^3\text{He} + \gamma$ taken from Refs. 38 and 73. Solid squares are IUCF data^{38,73} and open triangles are TRIUMF data⁷⁶].

Fig. 17: Analyzing power for $p + d + {}^3\text{He} + \gamma$ at 200 MeV and 500 MeV taken from Ref. 76. Calculations are due to Laget⁷⁰ with (dashed curve) and without (solid curve) nucleon rescattering.

Fig. 1

Fig. 2

Fig. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG. 10

FIG. 11

Fig. 12

Fig. 15

Fig. 16

Fig. 14

Fig. 17