BREMSSTRAHLUNG AND RADIATIVE PROCESSES
AT MEDIUM ENERGIES

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ABSTRACT

Some general features of the electromagnetic interaction are discussed, features which make it useful as a probe of nuclear and few body systems. Then some specific reactions are reviewed, including $pp \rightarrow pp\gamma$, $np \rightarrow np\gamma$, $pd \rightarrow {}^3\text{He}\gamma$, $dd \rightarrow {}^4\text{He}\gamma$, and $A(p,\gamma)A+1$, with the aim of focusing on some of the interesting physics which perhaps could be investigated via such reactions at a medium energy proton facility with stored cooled beam as is being developed at IUCF.

I. INTRODUCTION

We want to discuss radiative processes at medium energies with particular emphasis on some of those nucleon initiated reactions which involve interesting and exciting physics and which at the same time may exploit some of the novel features of the proton cooler being built at IUCF. An immediate reaction to this aim might be that electrons rather than protons are the primary electromagnetic probes relevant for medium energy nuclear physics studies. It is true that much has been learned using electrons and we can anticipate learning a lot more with ongoing improvements of existing machines and with the development of high intensity, high duty factor machines. However there are also a number of proton or light ion induced electromagnetic processes which promise interesting physics and perhaps different kinds of information than that available from electron scattering.

To begin, we want to talk about some of the general features of the electromagnetic interaction used as a probe of hadronic systems. We then look at some specific radiative processes including proton-proton bremsstrahlung, some neutron induced processes such as $np \rightarrow np\gamma$ and $np \rightarrow d\gamma$, some simple few body reactions such as $pd \rightarrow {}^3\text{He}\gamma$ and $dd \rightarrow {}^4\text{He}\gamma$ and finally the (p,γ) reaction on "real" nuclei. In each case we want to ask why the reaction is interesting, what is already known both theoretically and experimentally, what are some of the important theoretical ingredients, and if possible what could be measured to give additional insight.

It is hard for a theorist to fully appreciate the technical advances which have gone into the development of a machine such as the cooler. However there are some anticipated features which may make possible entirely new kinds of experiments. In particular we note the possibility of polarized atomic beam targets of a variety of nuclei, the possibility of measuring recoil nuclei, the good energy resolution, and the general cleanliness of the beam and lack of background, all of which could be used to advantage for some of these radiative processes.

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II. GENERAL FEATURES OF ELECTROMAGNETIC PROCESSES

The electromagnetic interaction has several features which make it very useful as a probe of hadronic systems. In the first place it is "weak". Thus it can almost always be treated just to first order. One does not have to worry, for the photon, about the uncertainties introduced by distortion effects which are crucial for reactions induced by, say, protons or pions. One also does not have to worry about the double counting problems which enter in purely strong processes as for example in (p,π) where the basic reaction mechanism involves deltas and pion rescattering effects very closely entwined with the rescattering interactions or distortion of both proton and pion as they traverse the nucleus. The electromagnetic interaction is also "known" so that the photon becomes in principle a useful probe of the less well known strong interactions.

However, the electromagnetic interaction, while known, is also "complicated". This is not because the primary interaction itself is complicated. The coupling of a photon to a free elementary particle is in fact very simple. Its form is determined by general principles and there is usually a great deal of experimental information available to pin down form factors. The interaction becomes complicated because the hadronic interaction being probed is complicated, involving nucleons and clouds of pions or other mesons being exchanged, or at another level many quarks and gluons. The photons must couple to each charged particle. Thus even fairly simple microscopic descriptions of a strong process will lead to many contributions when a photon is coupled to all charges. We see this for example in the relatively complicated meson exchange correction calculations necessary for even simple systems or in the many diagrams required in diagrammatic approaches to simple (p,γ) processes.

Another feature of the electromagnetic interaction is that it couples to a "conserved current". This is both a blessing and a curse. Current conservation allows one to use very general relations which often combine a lot of unknown and complicated physics into a simple result. The classic example of this is the use of Siegert's theorem¹ in reactions like $np \rightarrow d\gamma$. In this case current conservation is used to express the relatively complicated current density in terms of the charge density, which is presumably less sensitive to the details of the process. Soft photon theorems² are another example of the use of current conservation to obtain a simple result, in this case a result which expresses the amplitude for a radiative process in terms of that for the non radiative process through the first two orders in the photon momentum k . However, current conservation implies constraints among many different contributions, and a photon coupling to a particular diagram may often imply coupling to many other diagrams so as to enforce the conservation. Thus it is often hard to obtain a "simple" conserved current.

An essentially equivalent property of the electromagnetic interaction is that of "gauge invariance", really just another way of stating current conservation. The full theory must be gauge invariant and in practice this both requires the existence of more complicated contributions and enforces cancellations among the various contributions. For example consider bremsstrahlung in the scattering process,

depicted in Fig. 1, of a spinless particle of mass m on one of mass M . The amplitude corresponding to the first two diagrams,

$$M_1 + M_2 \sim g^2 e \left\{ - \frac{e \cdot p_1}{k \cdot p_1 (p_3 + p_4)^2 - M^2} + \frac{e \cdot p_3}{k \cdot p_3 (p_1 + p_2)^2 - M^2} \right\},$$

is not gauge invariant. We must add the contribution

$$M_3 = g^2 e \cdot (p_1 + p_2 + p_3 + p_4) \left\{ \frac{1}{(p_1 + p_2)^2 - M^2} + \frac{1}{(p_3 + p_4)^2 - M^2} \right\}$$

corresponding to radiation from the interior of the "strong" interaction in order to make the result gauge invariant. Observe that an ad hoc term $\tilde{M}_3$, of the form

$$\tilde{M}_3 = \frac{e \cdot X}{k \cdot X} \left\{ \frac{1}{(p_3 + p_4)^2 - M^2} - \frac{1}{(p_1 + p_2)^2 - M^2} \right\}$$

where X is any vector would also make $M_1 + M_2 + \tilde{M}_3$ gauge invariant. Such terms have often been added in calculations of radiative processes. They must be incorrect however (unless $X = p_1 + p_2 + p_3 + p_4$) since there are no possible diagrams, except for the external radiation diagrams Fig. 1a and 1b (which lead to $M_1 + M_2$) which can generate a $k \cdot X$ in the denominator of the amplitude.³ A similar example relevant to bremsstrahlung is given in Fig. 2 where one can show that to leading order in k the contribution from the double scattering term Fig. 2c is just that required to make the first two terms gauge invariant to that order in k .⁴

Fig. 1. Bremsstrahlung in a spinless scattering process.

Fig. 2. External radiation (a), (b) and double scattering (c) contributions to bremsstrahlung.

A very important but often ignored consequence of this cancellation enforced by gauge invariance is the fact that the relative magnitudes of the various diagrams are gauge dependent quantities. Thus to compare sizes of non gauge invariant subsets of diagrams, as has often been done for example in calculations purporting to show the importance of meson exchange corrections to radiative processes, is physically meaningless.

Thus to summarize, in this section we have considered some general properties of the electromagnetic interaction. It is "weak" and "known" and so should be a good probe of hadronic systems. It is however at the same time "complicated" and "constrained" by current conservation and gauge invariance and so provides a non-trivial and hence interesting window on these strongly interacting systems.

III. PROTON-PROTON BREMSSTRAHLUNG

To begin our consideration of specific radiative processes let us look first at proton-proton bremsstrahlung (PPV), one of the simplest of such processes, and one which we clearly must understand if we are to understand any coupling of the photon to a hadronic system. Bremsstrahlung has been advocated as one of the most straightforward ways to probe the off shell aspects of the nucleon-nucleon force. However for a variety of reasons, both theoretical and experimental, not much has been learned yet. A new PPV experiment⁵ is underway at TRIUMF however, which has brought about increased interest in the process and motivated some new theoretical calculations. This experiment will measure the cross section over a much wider kinematic region than ever before and also, for essentially the first time, the analyzing power using polarized protons. This should be very interesting as existing theories predict quite different results for this analyzing power.

There have been two major theoretical approaches to PPV which have been used in recent years. The first of these is the soft photon approximation^{6,7} (SPA) which is based on the low theorem.² The amplitude is expanded in powers of k , and gauge invariance used to fix the first two coefficients in terms of the on shell nucleon-nucleon amplitudes. The approach is simple, and easy to make gauge invariant and relativistic invariant. It however has no off shell content, so one hopes to find places where it fails. One of the puzzles seems to be that it actually works relatively well, even in kinematic situations where one would expect large off shell contributions.^{7,8}

The second major approach is a standard non-relativistic potential model approach, based on specific choices for the nucleon-nucleon potential. This approach contains off shell information, but is much harder to correct for gauge invariance or relativistic effects. Such calculations in existence at the time of the most recent medium energy experiment,⁸ one at 200 MeV at TRIUMF, did not fit the data as well as the purely on shell SPA.

Motivated by this discrepancy and by the possibility of additional data, particularly for the analyzing power, we have recently carried out a new potential model calculation.⁹ The calculation was designed to use one of the modern theoretically motivated potentials such as the Paris¹⁰ or Bonn¹¹ potential, which had not been done

before. It also includes a number of effects such as relativistic spin corrections, Coulomb effects, one pion exchange contribution for higher partial waves, relativistic kinematics, etc. which had not all been combined into one calculation before. The basic approach is to solve the Lippmann-Schwinger equation in momentum space for the half off shell nucleon-nucleon T matrix. This is combined with propagator and electromagnetic vertex functions to generate the amplitude. The important correction is the relativistic spin correction, which consists of terms of higher order in v/c at the electromagnetic vertex.

Some results of these calculations using the Paris potential and an extended version of the Reid soft core potential¹² are shown in Fig. 3 for comparison with the SPA. It is obvious that there are large differences between the on-shell SPA and the potential models, differences which should be measurable in both cross section and analyzing power. What is somewhat surprising however is the similarity of the results from the extended RSC and the Paris potentials. In collaboration with R. Machleidt we have also made calculations using the Bonn potential,¹³ with results which are again very similar to those of the others. In retrospect one can understand this in terms of the half off shell function for the various potentials. It turns out that it is essentially the same for all the potentials tried. Thus the similarity of the potential model results simply indicates that the potentials we have tried are very similar off shell as well as on shell.

Fig. 3. Cross section and analyzing power for ppγ at incident laboratory proton energy of 280 MeV, with final protons each at 10° from the incident beam, from Ref. 9.

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

section¹⁴ and thus increase the discrepancy between the potential results and either SPA or the existing data.

The experimental data for ppγ is rather sparse. The most recent experiment is a TRIUMF experiment at 200 MeV in equal angle geometry.⁸ Surprisingly, as can be seen from Fig. 4, it seems to agree better with the SPA than with the potential calculations, all of which are too high, even though calculations indicate that there should be sensitivity to off shell effects in this geometry. A new TRIUMF experiment at 280 MeV is now underway.⁵ With both cross section and analyzing power data over a wide kinematic range, it should be able to make a clean distinction between the potential model and SPA calculation.

Fig. 4. Comparison of the potential model calculations of Ref. 7 with ppγ data at 200 MeV (Ref. 8).

Given the rather puzzling apparent failure of standard potential models it would be very useful to have additional data at lower energies, say in the 100-200 MeV region where off shell effects are smaller but where some of the corrections to potential calculations are also less important. Such experiments are low rate coincidence experiments and hence almost have to be done at a high duty cycle machine such as IUCF or TRIUMF. Good definition of the target volume and low background are important also. Thus if the luminosity can be made high enough some of the thin target-clean beam aspects of the cooler might be useful.

IV. NEUTRON INITIATED PROCESSES

After ppγ the next most obvious reactions to consider are the closely related neutron processes, neutron-proton bremsstrahlung, $np \rightarrow np\gamma$, and neutron-proton radiative capture $np \rightarrow d\gamma$. These both would require monochromatic external neutron beams.

There have been few calculations¹⁵ and even fewer experiments¹⁶ on neutron-proton bremsstrahlung. It is of course very similar to ppγ. However there are some distinctive features. In particular the leading contribution to the nucleon-nucleon force now involves the exchange of a charged pion so that internal radiation diagrams such as

Fig. 5 will contribute to the bremsstrahlung. For ppy the simplest such diagrams would involve 2π exchange with an intermediate Δ^{++} rather than simple one pion exchange. Thus one would expect npy to be described less well than ppy by standard potential model theories and to be more sensitive to the non-trivial, and thus interesting, contributions of diagrams such as that of Fig. 5. Neutron experiments are more difficult than proton ones, but perhaps partially offsetting this is the fact that the npy cross section is larger, by as much as an order of magnitude in some kinematic situations, than that for ppy. This comes about because for npy the radiation is primarily electric dipole while for ppy the fact that the nucleons are identical suppresses the dipole radiation and makes the leading term electric quadrupole. Such npy experiments will obviously be very difficult, but if they could be done, particularly with polarized neutrons, they would be pioneering experiments and might give new insight into the nucleon-nucleon-photon interaction.

A reaction very closely related to npy is the radiative capture reaction $np + d\gamma$, which would also require an external neutron beam. Unlike either of the bremsstrahlung processes, here there are many experiments, lots of data, and a multitude of theoretical calculations. Unfortunately there are sizeable disagreements among data sets, among different theoretical calculations, and between data and theory, so our understanding of this process is surprisingly shaky. An extensive review of both theory and experiment can be found in the proceedings of a recent workshop held at TRIUMF,¹⁷ so the comments here will be brief.

Clearly $np + d\gamma$ is one of the most fundamental of the two nucleon radiative interactions. Since it is also a two body interaction it is much easier to handle than ppy or npy and as a result there has been much more work on it, both theoretically and experimentally, than on the bremsstrahlung processes. It is an interesting reaction because it provides a testing ground for many of our ideas of how to write down the two nucleon electromagnetic current and to incorporate the various corrections due to meson exchanges and to isobars. One of the first triumphs in this regard was the work of Risaka and Brown¹⁸ who showed that meson exchange corrections (MEC), specifically the diagram of Fig. 5 and the pair term of Fig. 6, together with some isobar contributions, were sufficient to explain a long standing discrepancy in the threshold cross section. Later calculations have shown the importance under various circumstances of other meson exchange corrections, of the D state in the deuteron, of off shell aspects of

Fig. 5. A term in the neutron-proton electromagnetic current contributing to $np + npy$ or $np + d\gamma$

Fig. 6. Pair current contribution to $np + d\gamma$.

the nucleon-nucleon interaction, of the $\Delta(1236)$ and more recently of relativistic corrections. Not all of these effects are independent, which has been a source of some confusion. For example, as emphasized by Arenhövel,¹⁹ most MEC can be included via gauge invariance using the Siegert theorem, with the result that the residual "MEC" are small. Alternatively all MEC can be calculated explicitly, as for example in Ref. 20 in which case the "MEC" are large. In either case however, it is clear that $np + d\gamma$ depends on a number of important and interesting effects.

Perhaps because of this multitude of effects, the theoretical situation is rather confused and there are several different approaches which give only qualitatively similar results. The original calculation by Partovi²¹ takes the matrix element of a simple one body electromagnetic current between two nucleon wave functions, and includes other corrections via the Siegert theorem. More recent calculations by Hwang, Londergan, and Walker,²² Rustgi²³ et al., and Friar et al.²⁴ extend and improve this basic result in a variety of ways. Greben and Woloshyn²⁵ looked specifically at off shell effects. Laget²⁰ adopts a completely different approach, based on a sum of an extensive set of diagrams which include a variety of MEC, effects of the Δ , etc. Siegert's theorem is not used, but instead the set of diagrams is made gauge invariant. This approach avoids a partial wave expansion, and so may be more practical at higher energies. Leidemann and Arenhövel²⁶ use a coupled channel formalism including nucleon-nucleon and nucleon-delta channels analogous approaches which have been used for $pp + nd$. While the results of the various authors are all qualitatively the same they differ in detail and none provide a real quantitative fit to the data. Clearly a lot of theoretical work is still necessary.

Until very recently the data situation has been equally confused. There are many experiments both as $np + d\gamma$ and $nd + \gamma$ and the results have not agreed well. For example one of the more modern and comprehensive experiments, that of the Lund group,²⁷ is as much as 40% higher than most other results in the photon energy region 100 to 200 MeV. There has been some improvement in the last year or so however. A new experiment²⁸ at IUOF at $T_n=185$ MeV seems to agree with an equivalent energy experiment²⁹ at $E_\gamma=100$ MeV from Frascati and a new experiment³⁰ at SIN, although averaging over a large energy bin, seems to be consistent with both. All of these are below the Lund data at this energy. At somewhat higher energies experiments from Bonn³¹ and Tokyo³² seem to agree reasonably well. If we are to make progress in understanding this reaction, highest priority should be given to obtaining a consistent and believable set of cross section data over the medium energy range.

Also in the last year we have seen the first measurements of the analyzing power in the medium energy region.³³ There have been a few calculations of this analyzing power and at the moment there seems to be a clear discrepancy with available calculations at 270 MeV, (as can be seen from Fig. 7), although results at 180 MeV seem okay.

The other persistent discrepancy in $np + d\gamma$ has been the 0° cross section as a function of energy. The original data of Hughes³⁴ has now been reasonably well confirmed by new data from Louvain³⁵ and IUOF.²⁸ A variety of MEC, deuteron D state effects, relativistic

Fig. 7. Comparison, taken from Ref. 33, of the measured analyzing power in $np + \gamma$ with theoretical calculations of Partovi²¹ (solid line) and of Leidemann and Arenhövel²⁶ (dashed line).

Fig. 8. 0° cross section for $np + \gamma$ as calculated in the full soft photon approximation of Ref. 37 (solid line) or an approximation to it of Ref. 36 (dashed line). Data is from Refs. 34, 35, 28.

effects, etc. have been incorporated in various calculations, and usually do produce some improvement over Partovi's original work. One of the better fits to the Hughes data however, as shown in Fig. 8, comes from a simple soft photon approach, which uses gauge invariance to relate the cross section to the amplitude for the non radiative process, just as is done for $pp\gamma$.^{36,37} In this case, this simply requires the low energy properties of the $np + d$ vertex function. This approach does not fit the angular distributions very well. Its relative success at 0° (and 180°) may simply indicate that it is more important to get relativistic and gauge terms, and hence the leading

MEC, correct to leading orders in k — which is done in the soft photon approach — than to have a good calculation of the various effects to all orders. As regards relativistic effects this is consistent with the results of Ref. 38, 24 who find that the inclusion of relativistic effects is an important improvement at 0° .

What needs to be done next? Clearly good, consistent data is important and one should look carefully to see if the possibility of a high quality tagged neutron beam would make some of these experiments cleaner and easier. It is obviously of interest to continue the measurements of analyzing powers. It is also feasible now to consider double spin experiments, i.e. polarized neutrons on polarized protons or a polarized neutron experiment with measurement of outgoing deuteron polarization. Such experiments should be sensitive to subtle interferences of the various amplitudes. There seem to be no calculations; thus theorists should be encouraged to explore such double spin configurations.

V. FEW BODY REACTIONS

We turn now to the next most complicated system, that involving three nucleons, and consider the reaction $pd + {}^3\text{He} \gamma$. This will serve as a prototype (and best known example) of a class of few body radiative processes including for example such reactions as $nd + \gamma$, $pt + {}^4\text{He} \gamma$, $n{}^3\text{He} + {}^4\text{He} \gamma$, $dd + {}^4\text{He} \gamma$, etc. Some of the general comments will apply also to these other reactions.

Why are such processes interesting? In the first place they offer some of the simplest examples of embedding a two nucleon process in a more than two nucleon system, so one might learn something about the techniques required for such embedding which could be useful in looking at similar processes in more complicated nuclear systems. At the same time they are simple enough that there is some hope of obtaining a microscopic understanding of the reaction. Furthermore much is known about the wave functions of such simple systems, particularly for the three nucleon system where there have been extensive Faddeev calculations.

For the specific process $pd + {}^3\text{He} \gamma$, low energy calculations suggest that certain spin correlations may give specific information about small components of the ${}^3\text{He}$ wave function.³⁹ This reaction is also one of the simplest which allows direct comparison with the analogous (p, π) reaction, in this case $pd + \pi$, which has been well studied experimentally. One might hope to learn something extra about both processes by making the comparison. Since many of the ingredients, such as wave functions, proton distortion, and kinematics are essentially the same one might for example, with a full understanding of $pd + {}^3\text{He} \gamma$, be able to isolate important features of the pion production mechanism or of pion distortion in $pd + \pi$.

Our theoretical understanding of $pd + {}^3\text{He} \gamma$ is not particularly good as yet. At low energies there have been detailed and fairly sophisticated calculations, eg. Ref. 40. Both of cross section and of analyzing powers. There is some indication that some spin correlations, particularly the analyzing power measured with tensor polarized deuterons, are very sensitive to D state components in the three body

wave function.³⁹ It would be very interesting to extend such considerations to higher energies.

At medium energies the theoretical situation is much worse. Older calculations of Craver et al.⁴¹ and of Finjord⁴² are relatively unsuccessful. A new calculation by Laget,⁴³ based on a series of diagrams does better, and does seem to give qualitative agreement with analyzing power data.

Another approach,⁴⁴ which has been relatively successful for the cross section over a range of energies is based on a distorted wave impulse approximation and is motivated by the idea that one should be able to compare $pd + 3He\gamma$ and $pd + \pi\gamma$. The model is based on Fig. 9a and is essentially the same as that used earlier for $pd + \pi\gamma$.⁴⁵ The cross section is then given by the $np + d\gamma$ cross section times a kinematic factor times a form factor derived from wave function overlaps. One of the biggest uncertainties is the $np + d\gamma$ cross section. Some results are shown in Fig. 10 for the Lund²⁷ $np + d\gamma$ data which is higher than most and for the average of a set of data which may be low. Results for other energies can be found in Ref. 44.

A very similar calculation, though differing in technical details, has been made by Prats⁴⁶ who includes diagrams b and c of Fig. 9 as well as a. His results, which are shown also in Fig. 10, are similar except for the dip in the forward direction which is in

Fig. 9. a) Distorted wave impulse approximation model for $pd + 3He\gamma$ used in Ref. 44. b), c) Additional diagrams included also in Ref. 46.

Fig. 10. Results for $pd + 3He\gamma$: Solid curves - DWIA calculation of Ref. 44 using Lund²⁷ data for $np + d\gamma$ (upper curve) or all other data (lower curve). Dotted curve - calculation of Ref. 46. Data is from Refs. 49, 50.

fact marginally suggested by the data. In Prats' calculation the dip originates in the interference of diagrams 9a and 9b. However some portion of the proton radiating diagram 9b appears also in a representation of the process $np + d\gamma$ and hence taking the $np + d\gamma$ cross section from experiment in Fig. 9a and at the same time including Fig. 9b must involve double counting to some extent. It would be very interesting to have sufficient additional data to see if the dip is really there.

The experimental situation is still not very good, though like for $np + d\gamma$, there has been a marked improvement as a result of several recent experiments. There are a number of older measurements⁴⁷ in both the γ - $3He$ and the pd directions which differ among themselves by factors of two or three, and at least one newer experiment⁴⁸ designed to resolve the problem, which is also in disagreement with the others. However the three most recent experiments - radiative capture experiments at TRIUMF⁴⁹ and IUCF⁵⁰ and a photodisintegration experiment at Bates⁵¹ - are in reasonable agreement with each other. Some of this data is shown in Fig. 10 along with the theoretical results.

An exciting recent development is new data on analyzing power. There are data from IUCF⁵⁰ at 100, 150, 200 MeV and from TRIUMF⁴⁹ at several energies in the range 200-500 MeV and the two agree in the region of overlap. There has also been one as yet unpublished measurement of the tensor analyzing power for this reaction.⁵² It would be very interesting to further pursue some of these spin correlation measurements.

To summarize then, it has just been very recently that experiments are beginning to converge on a consistent result and just recently that data on analyzing powers is becoming available. The theorists are behind. There are tantalizing indications from low energy calculations of sensitivities to things like small components of the $3He$ wave function, but few calculations at medium energies. Additional experiments, particularly of various spin correlations, would undoubtedly stimulate further theoretical work.

Finally we mention very briefly another reaction, $dd + 4He\gamma$, which has been of interest at IUCF where efforts are being made to measure cross section and tensor analyzing powers.^{52,53} This reaction has some interesting features: the particles all have isospin zero, so it is hard to find a simple mechanism which involves the delta. The initial state has two identical particles and all particles are bosons, so the spin aspects of the process should be simpler than some to describe. However it is not just a single particle capture, so the electromagnetic current operation may be somewhat complicated and may provide a stringent test of our ability to handle an electromagnetic interaction in a few body system. There however seem to be no published calculations of this process in the medium energy region.

VI. (p, γ) REACTIONS ON "REAL" NUCLEI

So far we have considered only few body radiative reactions which, although complicated, are simple enough so that there may be some hope of understanding the full reaction microscopically. Next we

turn to the reaction $p + A \rightarrow \gamma + (A+1)$ where A is a "real" nucleus with $A > 4$. In this case a full understanding of the complete many body process at the microscopic level is probably impossible. Thus the reasons for studying such processes will be somewhat different than for few body processes. On the one hand, we now have the possibility of using the process as a probe of nuclear structure. On the other, we may learn interesting things about how to embed a few nucleon process in a many body system.

Recall that the (p,γ) process, just like (p,π) or (p,d) involves a very high momentum transfer to the nucleus. Figure 11 shows a typical range of momentum and energy transfer accessible at medium energy machines. Thus for example at 200 MeV incident energy, center of mass three-momentum transfers in the 400-700 MeV/c range are accessible. In the simple picture where a single nucleon radiates, the amplitude is proportional to the Fourier transform of the single particle wave function. This idea was used with marginal success to analyze early (γ,p) data to try to extract the high momentum behavior of the wave function.⁵⁴ Such a picture is now known to be far too simple, but the very fact of such massive momentum transfers suggests that the reaction will probe regions not easily accessible in other ways.

The reaction may also be very interesting for the possible new insight it may give regarding the (p,π) reaction. The two processes are very similar, with (p,γ) presumably being simpler since no pion distortion is involved. The suggestion is that the two processes should be compared was made long ago⁵⁵ and such comparisons have been made for very light nuclei.⁴⁴ Now that there is a wealth of (p,π) data on a variety of nuclei, similar data for (p,γ) would allow a systematic comparison to be made.

Finally the process may lead to interesting new discoveries in the nuclear structure realm. One of the very exciting results coming from IUCF in recent years was the observation of strong excitation of relatively high lying stretched

Fig. 11. Energy and momentum transfer range accessible for $\theta_{\gamma}=0^{\circ}, 180^{\circ}$ as a function of the incident lab proton energy. Shown are the four momentum transfer $\sqrt{t}=|(p-k)|^{2/2}$, the center of mass three momentum transfer $|q|=|p-k|$ and the kinetic energy transfer in the center of mass, $k - T_p$.

configuration states using the (p,γ) reaction at 40-80 MeV proton energy.⁵⁶ It would be interesting to see if similar such phenomena exist also at higher energies.

On the theoretical side not much has been done in the medium energy region although there have been a number of calculations at very low energies. The situation is reminiscent of the state of affairs for (p,π) just a few years ago. The several calculations which do exist all give some aspects of the qualitative behavior correctly, but are not quantitatively very good and are at the same time sensitive to the various input ingredients.

Just like for (p,π) there are two major approaches to (p,γ) . The direct mechanism is essentially the analog of the single nucleon model (SNM) of (p,π) and the various isobar calculations parallel the two nucleon mechanism (TNM) calculations for (p,π) .

In the direct or SNM the photon is radiated from the incoming photon via a single particle charge plus magnetic static coupling. Usually proton distortion is put in as well. Typical calculations of this type are Refs. 57, 58. In the absence of distortion this model gives an amplitude directly proportional to the Fourier transform of the single particle wave function and thus is very sensitive — too sensitive — to high momentum components of the wave functions. For the (γ,p) reaction in the energy region $E_{\gamma} < 100$ MeV this approach, with distortion, does give qualitative agreement with the available data at a fixed energy.⁵⁷ It does not reproduce the energy dependence very well however and there is sensitivity at the level of factors of two or three to the potential chosen for the proton distortion, and probably to other ingredients as well. This SNM also fails to predict the (γ,n) cross section, which experimentally is of the same order as the (γ,p) , but which in this model is much smaller than (γ,p) because it can go via magnetic coupling only. There are some indications however that including charge exchange in the distortion might improve the situation.⁵⁹

There have been several different two nucleon models all based on the idea that at medium energies the two nucleon interaction currents, particularly those involving the $\Delta(1236)$, must be important. Garl et al. 60 were one of the first groups to perform such calculations. They found that various non-resonant exchange currents were important, more so than the isobar contributions. Londergan et al. 61 calculate both the SNM and some specific isobar contributions (Fig. 12). They find that the isobar contributions dominate for $E_{\gamma} > 100$ MeV and give qualitative agreement with the data. More recently Cheung and Keister 62 have performed a similar TNM calculation. Their results, which include the Δ but not all of the one body contributions, reproduce the shape of the cross section, but are much lower in magnitude than the data. They find that the Δ contributions are important, but not as large as found by Londergan, et al. 61. The differences in these three calculations indicate some of the uncertainty which exists in such calculations. Obviously there is a need for more theoretical work.

One of the very interesting discoveries of the past few years has been the importance of relativistic effects in medium energy reactions. A number of groups have shown that particularly spin correlations in p -nucleus reactions are well described in a Dirac formalism. In such an approach the amplitudes are calculated as matrix elements

Fig. 12. Some isobar contributions to the (p,γ) and (γ,p) reactions.

of 4×4 Dirac operators taken between 4-component states which are obtained by solving the Dirac equation in the presence of strong scalar and vector potentials. This approach has had a great deal of success for elastic and inelastic proton-nucleus scattering. At least three such calculations of (p,γ) are now underway.⁶³ Such calculations are particularly aimed at spin variables and so it will be interesting to see what new predictions emerge for the various spin correlations.

On the experimental side, in the medium energy region, the (p,γ) reaction is almost totally unexplored. There is data from both (γ,p) and (p,γ) at lower energies, but the only medium energy data seems to be the IUCF (p,γ) data⁵⁶ mentioned above, at the very low energy end of what might be considered "medium energy", and some isolated (γ,p) data at higher energies⁵⁴ although there are unpublished experiments from Bates.⁶⁴ In the (p,γ) direction one can use polarized protons and measure analyzing powers. This has been done for (p,π) with very interesting, though puzzling results. There seems to be essentially no such data for (p,γ) , except on the very light nuclei. The situation is similar to that for (p,π) of 5-10 years ago. Since then we have seen the very nice systematics which have come from the (p,π) program at IUCF, TRIUMF and elsewhere. One could probably anticipate similarly interesting results from a systematic (p,γ) program.

There are two possibilities for new types of experiments which may be feasible as a result of some of the unique features of the machine being planned here. The very good energy resolution, coupled with the possibility of using very thin targets might make it feasible to detect the recoil nucleus directly. Figure 13 shows the maximum and minimum recoil energy obtained in the reaction $^{12}\text{C}(p,\gamma)^{13}\text{N}$ as a function of the incident proton energy. In the medium energy range for at least at some angles it should be possible to detect such

Fig. 13. Maximum and minimum laboratory kinetic energy of the recoil nucleus in $^{12}\text{C}(p,\gamma)^{13}\text{N}$.

recoils though to separate out some of the low lying excitations would require very good resolution. If the γ were measured in coincidence, one might be able to significantly clean up the experiment.

A second feature, more speculative but very exciting, is the possibility of using polarized atomic beam targets. Such targets would allow polarized proton on polarized target experiments on a variety of targets not now available in a polarized state and without the extraneous material and extra background normally associated with a polarized target. There is no data and no theory for such doubly polarized (p,γ) processes. However, normally the more complicated a spin correlation becomes the more sensitive it is to various interfering amplitudes and so one might expect with such data to provide very sensitive confrontations with the theory.

In summary then, of this section on (p,γ) in real nuclei, it appears that detailed calculations are difficult, probably almost as difficult as have been the very similar calculations for (p,π) , even though one does not have the added uncertainty of pion distortion. At present few such calculations have been carried out and those that have give only a very qualitative representation of the data. However there is as yet little data, essentially nothing involving spin correlations, to stimulate such calculations. A systematic study of (p,γ) which would allow detailed comparison with the (p,π) results would undoubtedly stimulate theoretical activity.

VII. SUMMARY AND OUTLOOK

We have surveyed a number of radiative reactions initiated by nucleons. All of these reactions tell us very interesting things about the way a photon couples to a several nucleon system and thus probe aspects of the primary strong interaction. On the theoretical

side the common features seem to be that calculations are complex, so that different authors do not always agree. There are still puzzles in fitting existing data, and in many cases the calculations simply have not been done. Obviously then, there is much interesting theoretical work left to be done. On the experimental side, in the medium energy region, when data exists there often have been disagreements among various experiments, and thus there is a need for more, careful work to resolve these disagreements. In many cases there is simply no data. Thus experiments on np γ , on analyzing powers for many of the reactions, and particularly on more complicated or double spin correlations would be essentially exploring new territory. It appears that some of the novel features of a cooled proton beam machine could be useful — the high resolution, clean beam, thin targets which would allow recoil measurements, tagged neutron beam and particularly the possibility of a wide range of polarized targets obtained using atomic beams. We look forward to the results of some of these explorations.

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