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Proton-proton bremsstrahlung: What has been learned?

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Abstract

We summarize some of the information about the nucleon-nucleon force which has been obtained by comparing recent calculations of proton-proton bremsstrahlung with cross section and analyzing power data from the new TRIUMF bremsstrahlung experiment. Some comments are made as to how these results can be extended to neutron-proton bremsstrahlung.

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There has been a great deal of work on proton-proton bremsstrahlung, with the aim of learning about the off-shell aspects of the nucleon-nucleon force. In this report some of the theoretical approaches to this problem are summarized, a recent potential model calculation of the process is described,[1,2] and the results are compared with the data from a new TRIUMF experiment.[3-5] Some of the specific things which have been learned, or not learned, are then discussed. Finally a few remarks about the application of these calculations to neutron-proton bremsstrahlung are made.

There have been two major approaches to the bremsstrahlung problem, the soft photon approximation and non relativistic potential models. In the soft photon approximation[6] the bremsstrahlung amplitude is expanded in powers of the photon momentum k and gauge invariance is used to fix the coefficients of the first two terms in terms of information from the nonradiative process. Thus the amplitude is written as $M_{pp\gamma} = A/k + B + Ck^2$ with A and B fixed in terms of the elastic phases, i.e. in terms of on-shell information only. The cross section then goes as $d\sigma \approx A^2/k + 2AB + (B^2 + 2AC)k + ...$ with the A^2, AB, B^2 given by elastic information. In this approach the amplitude can be obtained in a relativistically and gauge invariant way, but since it does not contain any off-shell information, it gives information really only when it fails to fit the data. In fact one of the puzzles of the late 1970's was why this approach fit the then existing data as well as it did.[7,8]

The other major approach has been the non relativistic potential model. In this approach one assumes a non relativistic potential for the nucleon-nucleon interaction, assumes the two-nucleon electromagnetic current is known, and then solves the Schrodinger equation in coordinate space or the Lippmann-Schwinger equation in momentum space to get the radiative amplitude.

This potential model approach has been used by many authors over the years. We were motivated to look again at this approach by the puzzling agreement of the soft photon approximation with older data,[7,8] by the existence of modern potentials such as Bonn[9] and Paris[10] which had not been used in such a calculation, and by the fact that at the time a new experiment was planned at TRIUMF which would obtain an extensive set of analyzing power data, which had not been available before.

The details of our calculation are given in Ref. 1. We can summarize the main ingredients very briefly. The starting point is the two potential formalism in momentum space. The radiative T-matrix then gets contributions (the so called external radiation or single scattering diagrams) from situations when one of the four external legs radiates either before or after the nucleon-nucleon scattering. It is crucial to note that the nucleon-nucleon amplitudes are needed in these diagrams with one leg off shell and at two quite different energies. When the scattering precedes the radiation the scattering is at the beam energy. When it follows the radiation the scattering can effectively be at a very low energy since most of the energy has been carried off by the photon. Finally there are for p-p bremsstrahlung two additional diagrams (the double scattering or internal radiation diagrams) in which a strong p-p scattering both precedes and follows the radiation.

Such a calculation contains several general ingredients. Consider for example one of the diagrams where the strong scattering precedes the radiation. One then needs the half-off-shell nucleon-nucleon T-matrix with one leg off shell and evaluated at the initial beam energy. This T-matrix can be written as $t(E, q_{off}, q_{on}) = f(q_{off}, q_{on})t(E, q_{on}, q_{on})$ where q_{on}, q_{off} are the on- and off-shell center of mass momenta respectively, E is the energy, and where $f(q_{off}, q_{on})$ is the half-shell function, a real function calculable given a potential. One then includes a propagator, usually non relativistic, to get the nucleon to the electromagnetic interaction and an effective electromagnetic vertex obtained from a non relativistic reduction of the usual photon-nucleon coupling.

Our calculations, while in the spirit of many previous calculations, included a number of new ingredients. First we used modern potentials, both Bonn[9] and Paris,[10] which had not been used before. We also tried an extended Reid soft core,[11] a quark based potential and several others. One pion exchange was included for those partial waves ($J \geq 6$) not obtained from the potential. Some Coulomb corrections were included. The so called relativistic spin corrections were included. These are relativistic corrections coming from the expansion of the electromagnetic vertex in powers of $1/m$. We included the original terms suggested by Liou and Sobel,[12] plus some higher order terms, plus the Krajcik-Foldy[13] corrections for coupling to loosely bound systems. Relativistic kinematics were used, as were proper relativistic transformations for the nucleon-nucleon amplitudes and for the various relative momenta. The calculation was forced to be gauge invariant to all orders in k. To order k^0 this procedure is essentially unique, being just the appropriate term (the leading piece of the double scattering term) which comes from the soft photon approximation. At higher orders an ad hoc term was added which makes the result gauge invariant, but not uniquely so. The calculation was done in the center of mass which, as is well known, suppresses the double scattering term, which has not yet been included in detail. Analyzing powers and cross sections were calculated, and it was checked in each case that the result has the proper soft photon limit. Of all of these corrections and refinements the relativistic spin corrections were the only ones which were very important. They could be 10-30% at the forward and backward photon angles, depending on the geometry.

We compared our results with the analyzing power and cross section data obtained in the new TRIUMF experiment.[3-5] In this experiment a polarized proton beam of 280 MeV was incident on a liquid hydrogen target and both final protons and the photon were detected, thus reducing unwanted background dramatically. The photons were detected in a series of 16 detectors, giving an almost complete distribution in θ_γ, the photon angle in the plane. The proton detectors were binned so that results are available for about 20 different proton angle pairs, again in the plane, ranging from $12^\circ - 12^\circ$ to $28^\circ - 28^\circ$ with both symmetric and asymmetric angle pairs in between. Thus this experiment covered a much wider range of kinematics and with much better statistics than any previous experiment in the medium energy range. The angle pairs were chosen so as to have some data at small proton angles, which corresponds to the kinematics farthest off shell, and some at large angles where one would expect the on-shell soft photon approximation to describe the data.

Fig. 1, taken from Ref. 3, shows a comparison of our calculations with the asymmetry data from this experiment. For the smallest angle pair $12.4^\circ - 14.0^\circ$, which involves the most off-shell kinematics, there is a clear indication that the soft photon approximation is not satisfactory. However both potential models describe the data well, as is also the case for the other angles. By the time one gets to the larger angles, say 27.8° – 22.0° or 27.8° – 28.0° there is essentially no difference between the soft photon and potential model calculations, and both fit most of the data.

Fig. 2, also taken from Ref. 3, shows such a comparison for some of the cross section data obtained. Here the distinction is somewhat less clear, though the soft photon approximation seems to be too low. At the larger, more on-shell, angles the calculations are all similar, but the data seems to have more scatter. The angle pair at 27.8° – 12.0° is probably the example with the worst qualitative agreement with the calculations. Note that all the data has been scaled by a factor of 0.67. This factor was never satisfactorily explained, though the presumption is that it is a systematic normalization uncertainty in the experiment. Possible refinements left out of the theory would be expected to produce much larger effects at the smaller, more off-shell, angles and to be negligible for large angle pairs where the soft photon approximation is adequate. This does not seem to be the case however. The required renormalization factor is roughly the same for all angle pairs.

From this comparison with the data one can conclude several things. First from the data for A_y for small angles there is clear evidence for non soft photon effects, presumedly related to off-shell effects. Secondly for most of the larger angles ($> 20°$) soft photon and potential model results are very similar. Thus to distinguish off-shell effects or to look for sensitivity to the various potentials one must look at relative small angles.[14] The Bonn[9] and Paris[10] potentials, both modern, theoretically based, potentials seem to fit the analyzing power data well and, modulo the renormalization factor, also most of the cross section data. Other potentials we have tried do not give much different results, so there seems not to be too much sensitivity to potentials which satisfy the requirements of a nucleon-nucleon potential (one pion tail, short range repulsion, intermediate range attraction, etc.).

To better understand what has really been learned so far we can examine several questions. First, are off-shell effects important? Within the context of potential models one can make an on-shell approximation by putting the half shell function to one, i.e. $f(q_{off}, q_{on}) = 1$. This puts the T-matrices to on-shell values but preserves the different energies for the T-matrices of different diagrams. It is thus a different kind of on-shell approximation from the soft photon approximation. Fig. 3 shows the effect of this approximation which results in the upper curve for both analyzing power and cross section. Clearly such a modification is ruled out by the data. Thus we conclude that off-shell effects of some kind are absolutely necessary to explain the results.

Another question is to what ranges of off-shell momentum and what partial waves are these results sensitive. By examining the kinematics of the 280 MeV experiment more closely one can see that the usual on-sheil momentum ranges from 0 up to about 2 fm^{-1}, that the off-shell momentum can be as much as 2.5 fm^{-1} and that the difference ranges up to about 1.5 to 2 fm^{-1}. To see which partial waves are important one can drop partial waves one at a time. Such results are shown in Fig. 4. Clearly for the kinematics of the TRIUMF experiment it is the P waves that are most important. The S waves are essentially negligible except near the forward and backward directions for the cross section.

Thus to understand the sensitivity or lack of it to the various potentials we must compare the off-shell behavior of these potentials for mostly P waves and for off-shell momenta 1-2 fm^{-1} away from the on-shell value. Such comparison is made for a typical partial wave in Fig. 5 which shows the half shell function as a function of q_{off}. It is clear that among Bonn, Paris, and an extended Reid soft core potential there is little difference in these crucial off-shell parameters. Thus the lack of sensitivity to the potential for the kinematics of the experiment is perhaps understandable and a consequence of the fact that the potentials considered are very similar off shell, at least in the off-shell region probed by this experiment.

What about more exotic potentials? One such potential has been suggested by Kukulin[15] and collaborators. It has a deep central attraction, rather than repulsion, and leads to nodes in wave functions and forbidden states. Its off-shell behavior in the S state is in fact quite different from that of the Bonn and Paris potentials. However because of the lack of sensitivity of bremsstrahlung to the S states, differences produced by this potential are smaller than observable with the current experiment. However similar changes in the off-shell behavior of the P waves would produce rather larger effects as shown in Fig. 6 and could be ruled out by present data.

We can thus summarize what has been learned from proton-proton bremsstrahlung as follows. The new TRIUMF experiment[3-5] at 280 MeV has provided the first extensive set of analyzing power data and a comprehensive set of cross section data. A new calculation[1,2] using modern potentials and including a large number of corrections similarly has updated the theoretical situation. Comparison of the data with the calculations, particularly for the analyzing power, has provided clear evidence for non soft photon effects. The other obvious on-shell approximation, obtained by setting the half shell function to one also does not fit the small angle data. From this we conclude that off-shell effects of some kind are absolutely necessary. The fact that the theory using Bonn and Paris potentials fits the data over a wide range of angle pairs gives confidence in these potentials both on and off shell. These and other potentials are however very similar off shell in the partial waves (P waves primarily) and in the relevant range of off-shell momenta ($\leq 2\ \mathrm{fm}^{-1}$) which are appropriate and so at this time one cannot distinguish among the various reasonable potentials. However one can rule out drastic off-shell variations in P waves, of the type generated in S waves by "exotic" potentials such as that suggested by Kukulin.[15]

In view of the topic of this workshop it is appropriate to make a few remarks, perhaps better described as speculations by a non expert, on the applications of these ideas and results to neutron-proton bremsstrahlung.

First it should be relatively easy to extend the potential model calculation described here to the n-p case for the external or single scattering terms. However for n-p bremsstrahlung that is not sufficient, as it is well known that exchange terms are essential. Even such terms, at least those involving only single scattering, could be incorporated probably without a lot of difficulty given an effective exchange potential since the electromagnetic potential used already has a few two body terms. Double scattering is more difficult however.

How important would off-shell effects be expected to be? A calculation by Nakayama,[16] based on a method originally used by Brown and Franklin,[17] claims that off-shell effects increase the one body contribution but reduce the exchange contribution for a net fairly small effect. However essentially all previous calculations have been for the cross section at relatively large angles which, based on our experience with the p-p case, would not be expected to show much off-shell sensitivity.[14] Clearly such calculations should be repeated for kinematics likely to be further off shell, e. g. for nucleon scattering angles in the 10° rather than 30° range.

What about S waves? Again Nakayama[16] finds that the $^1S_0$ is unimportant but the $^3S_1 -^3 D_1$ is significant. Thus n-p bremsstrahlung could perhaps rule out potentials such as that suggested by Kukulin.[15]

Finally from the point of view of a few body theorist, one of the most interesting questions addressed by a full understanding of neutron-proton bremsstrahlung is the question of how to get a fully conserved two nucleon current consistent with the strong interaction between the nucleons. While p-p bremsstrahlung touches on this question the n-p case is much richer because of the importance of exchange currents, and because of the relevance to other similar reactions such as $np \rightarrow d\gamma$ and deuteron electrodisintegration.

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Figure Captions

FIG. 1. Analyzing power results from the new TRIUMF experiment. The theoretical curves are calculated in soft photon approximation (lower solid line) and in potential models using the Paris potential (upper solid line) or the Bonn potential (dashed line).

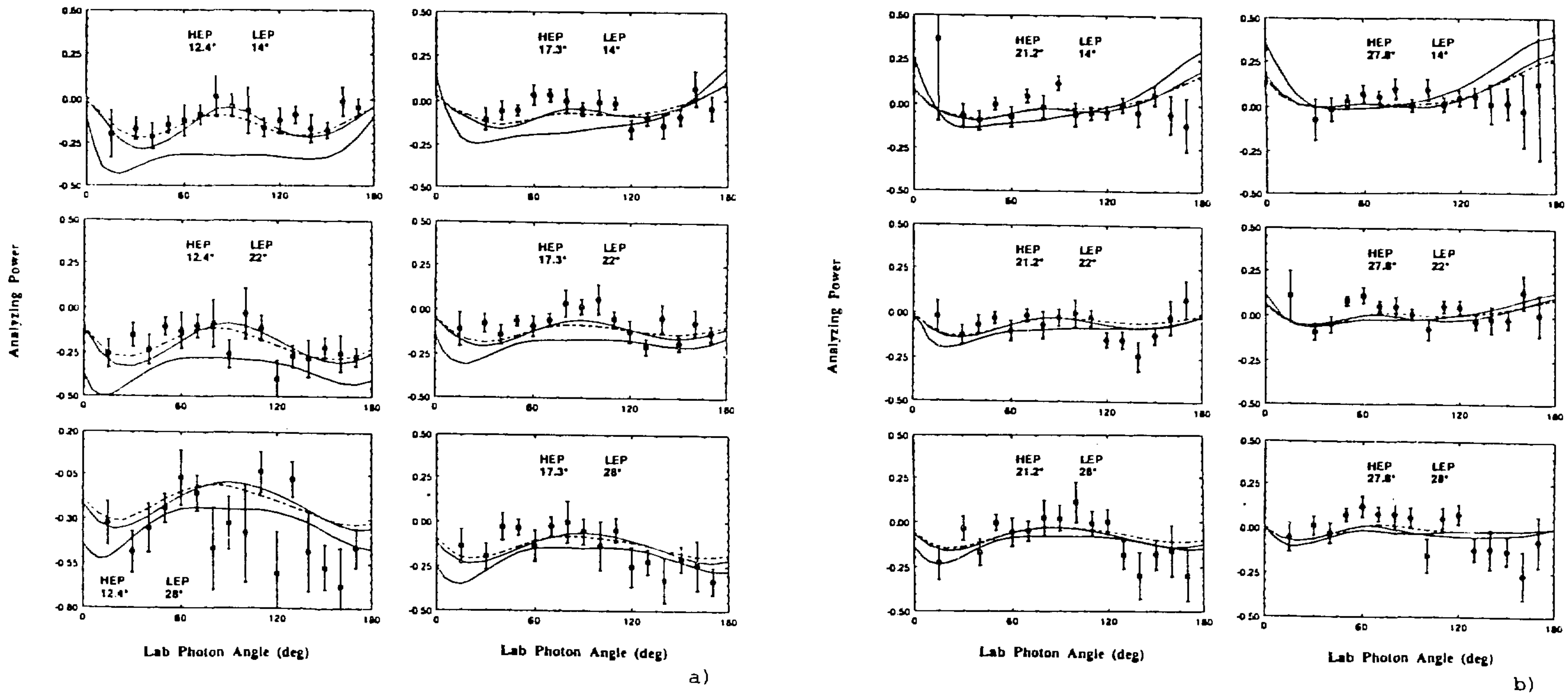
FIG. 2. Cross section results for some of the angle pairs of the new TRIUMF experiment. Theoretical curves are as in Fig. 1.

FIG. 3. An on-shell approximation (dot dashed line) obtained by putting $f(q_{off}, q_{on}) = 1$. The other curves correspond to soft photon approximation (short dashed line) and potential model calculations with Bonn (solid line), Paris (dashed line) or extended Reid (dotted line) potentials.

FIG. 4. The curves labelled S, P, and D show the effects of dropping the corresponding partial waves in the nucleon-nucleon interaction. The solid curve is the full Bonn potential calculation.

FIG. 5. Some examples of the half shell function as a function of q_{off} for several potentials as in Fig. 3. The dot dashed curves are from a simple one pion exchange model.

FIG. 6. Effects of changing the off-shell behavior of the P waves by amounts comparable to the S wave changes induced by the Kukulin potential[15] (dashed curves). The dotted curves correspond to using the Kukulin potential for the S waves and the solid curve is the standard Paris result.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HEP 17.3° LEP 14°
HEP 12.4° LEP 22°
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HEP 21.2° LEP 14°
HEP 27.8° LEP 14°
HEP 21.2° LEP 22°
HEP 27.8° LEP 22°
HEP 21.2° LEP 28°
HEP 27.8° LEP 28°
Analyzing Power
Lab Photon Angle (deg)
a)
b)

Fig. 1

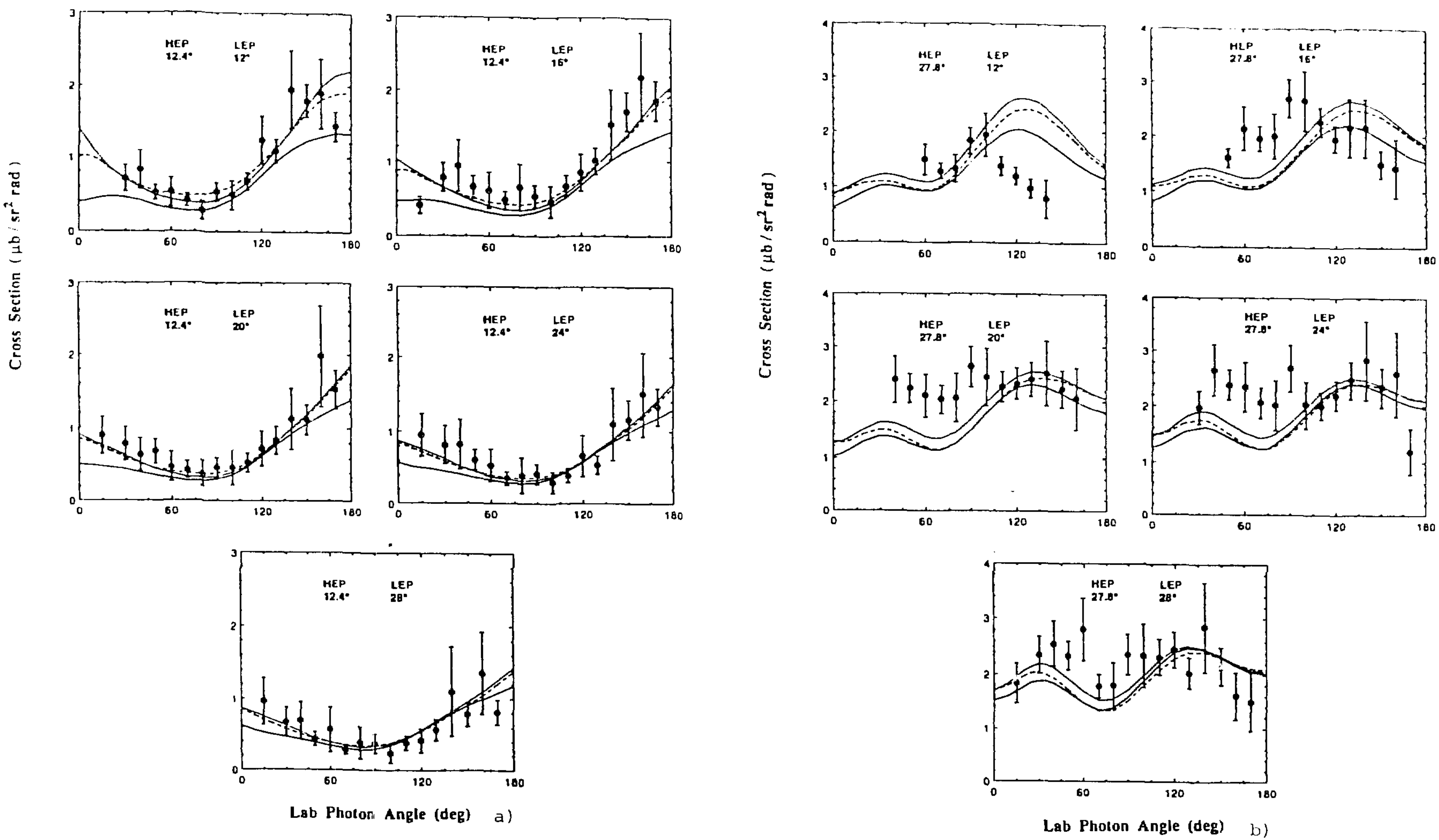
Cross Section (μb / sr² rad)
HEP 12.4° LEP 12°
HEP 12.4° LEP 16°
HEP 12.4° LEP 20°
HEP 12.4° LEP 24°
HEP 12.4° LEP 28°
Lab Photon Angle (deg)
a)
HEP 27.8° LEP 12°
HLP 27.8° LEP 16°
HEP 27.8° LEP 20°
HEP 27.8° LEP 24°
HEP 27.8° LEP 28°
Lab Photon Angle (deg)
b)

Fig. 2

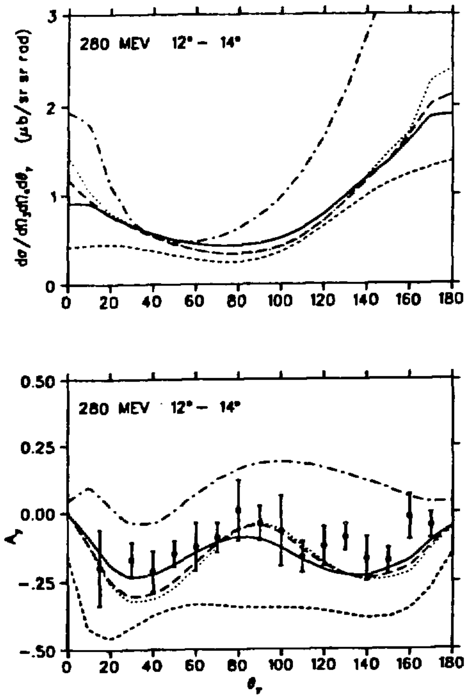

Fig. 3

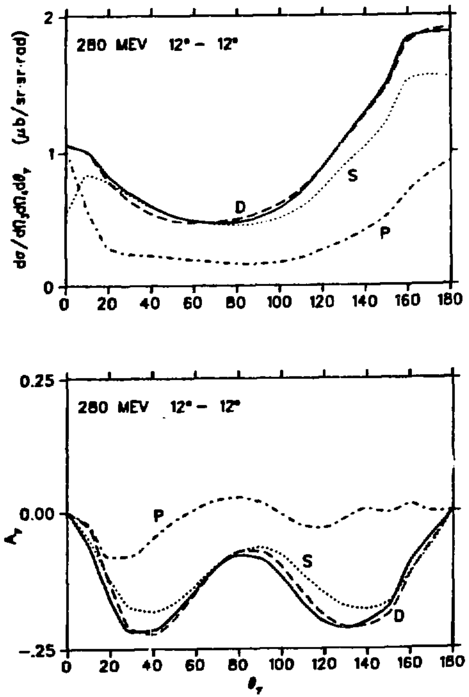

Fig. 4

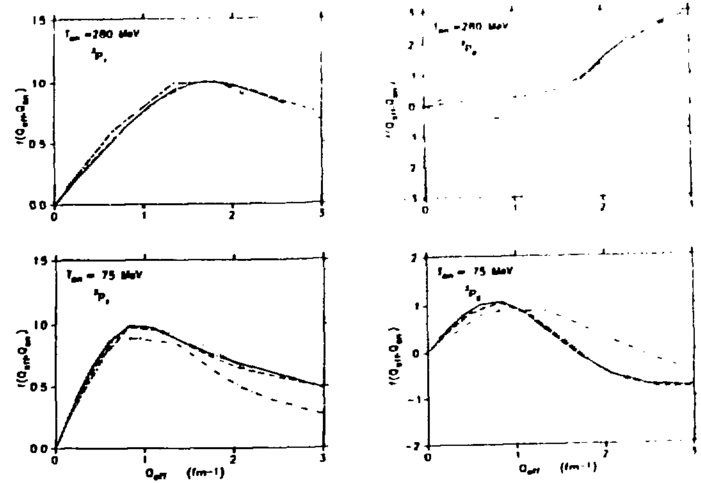

Fig. 5

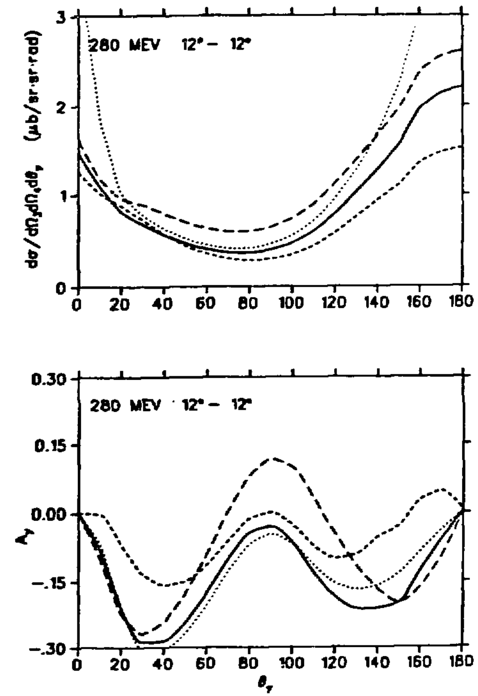

Fig. 6