Vol. B2 (1971) ACTA PHYSICA POLONICA Fasc. 1

SCATTERING OF HIGH ENERGY PROTONS FROM NUCLEI

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(Presented at the X^{th} Cracow School of Theoretical Physics, Zakopane, June 12–26, 1970)

This afternoon I wouid like to tell you about some physics that was started at Brookhaven several years ago. The work was an experimental study of the interaction of 1 GeV protons with nuclei.

1. Introduction

As an introduction to the subject I will try to present in very simple terms my initial reasons for being attracted to this line of research, and I must ask all the experts who have expressed these same arguments themselves or who have heard me talk this subject before to please bear with me for a while.

What does one hope to learn from the studies of the nucleus with high energy protons. In the broadest sense we are trying to understand whether the nucleons, neutrons and protons inside the nucleus are the same entities as free nucleons. This is certainly a problem central to the understanding of the physics of the nucleus. In this regard I remember some remerks made by Professor Weisskopf some twenty years ago. He pointed out that even if we were to understand the free nucleon-nucleon force it might be impossible to derive the properties of the nucleus from this force. I interpreted these words to mean that because of the nature of the strong interaction nucleons inside the nucleus might disassociate and we would have to understand the nature of the mesonic nuclear currents in order to understand the properties of the nucleus. Fortunately the situation does not seem to be that complex. The success of the Brueckner theory is an indication that nuclear matter is not so dense. The recent Hartree-Fock calculations also seem to indicate that nucleons inside the nucleus do appear to possess properties similar to the free nucleon properties. Well if nucleons retain their identity inside the nuleus in principle one should try to measure the nucleon pair density distribution inside the nucleus and obtaining this kind of information was the broad goal of our program.

Now one needs high momentum incident particles in order to probe the small internuclear spacings. Consider the nucleus as an ensemble of individual nucleons separated by

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some average distance d. Then a necessary condition to be able to sample a separation d is that the momentum transfer

$$\hbar|\boldsymbol{k}_f-\boldsymbol{k}_i| \geqslant \frac{\hbar}{d}$$

for incident protons of $T = 1$ GeV, $p = 1.7$ GeV/c and $k_i = 8.5$ fm^{-1}. To sample distances of 0.5 fm; $k\theta \sim 2$ fm^{-1} or $\theta \sim 1/4$ R or 15° in the lab which is a very reasonable angle to measure.

The momentum transfer condition is not a sufficient condition to probe the inner structure of an ensemble of scatterers. The other conditions depend on the nature of the fundamental interaction, that is between the incident particle and the scattering center and may also depend on the type of measurement one is attempting.

To make the point a little clearer let us refer to some experiments we believe we understand, the elastic scattering of high energy electrons from nuclei. The momentum transfer criterion is easily met here but we know that if one measures the elastic scattering one obtains information about the density distribution for single particles (protons) of the system. The physical reasons for this is that the electromagnetic interaction which is the means by which the electrons are coupled to the protons is weak and an electron traversing the nucleus has a small probability of interacting. In this case the Born Approximation is a good one and the observed differential cross section in Born App. is given by

$$\sigma(\theta) \sim \frac{1}{\sin^4(\theta|2)}\left|\int e^{i\boldsymbol{k}\boldsymbol{r}}\varrho(\boldsymbol{r})d\boldsymbol{r}\right|^2$$

where $\hbar^2k^2 = 2p^2(1-\cos^2\theta)$ and ϱ $(\boldsymbol{r})$ is the single particle charge density distribution. So as we all know the high energy electron scattering gives information about the shape of the nucleus; that is the average overall single particle configurations but tells nothing about the distribution of one particle with respect to another.

Now where and how in physics do we measure the position of one scattering center relative to another. In general these are diffraction experiments and the diffraction of X-rays from a liquid is an appropriate one to discuss.

Originally Zernike and Prins derived a relation between the observed intensity of X-ray scattered from a liquid and the correlation of atoms or molecules in the liquid. On the basis of an elastic scattering model the relation is

$$I \sim \left[1+\int 4\pi r^2 g(r)\,\frac{\sin kr}{kr}\,dr\right] Nf^2$$

where the 1 comes from the self-correlation and $g(r)$ is the pair correlation which describes the average density distribution as seen from a particle in the system. Today we know that in fact the observed X-rays in these liquid measurements are not elastic, but reflect the whole spectrum of inelastic states of the liquid itself. The same formula is obtained by applying closure in Born Approximation Scattering. The point here is that for weakly interacting probes one has to measure properties of the inelastic states to study correlations. This same idea has in fact been discussed by a number of people with regard to high energy electron scattering experiments. The idea is to sum over all the inelastic state in e-Nucleus scattering measurements and thereby obtain information on nucleon correlations in the nucleus. As far as I know such measurements have not produced very much meaningful results to date. The principal difficulty with interpreting the inelastic electron scattering experiments is that in addition to the nuclear inelasticity there are radiation effects (bremsstrahlung) which produces a large background in the energy region of the desired nuclear effect. It turns out that it is very difficult to make a good quantitive correction for these radiation effects.

Well this is the sort of information I had stored in my memory when our group was working at the Cosmotron on *n-p* charge exchange experiments. I slowly began te realize that it might be possible to perform GeV proton scattering experiments on the nucleus with sufficient energy resolution to separate the elastic from the inelastic scattering and I became rather exited about the possibility of trying to measure nucleon correlation by summing over the inelastic state because the bremsstrahlung effects would be negligible for protons. Two factors made the program at the Cosmotron feasible.

1) The inherent energy spread of the Cosmotron beam when properly adjusted turn out to be ~ 1 MeV at 1 GeV.

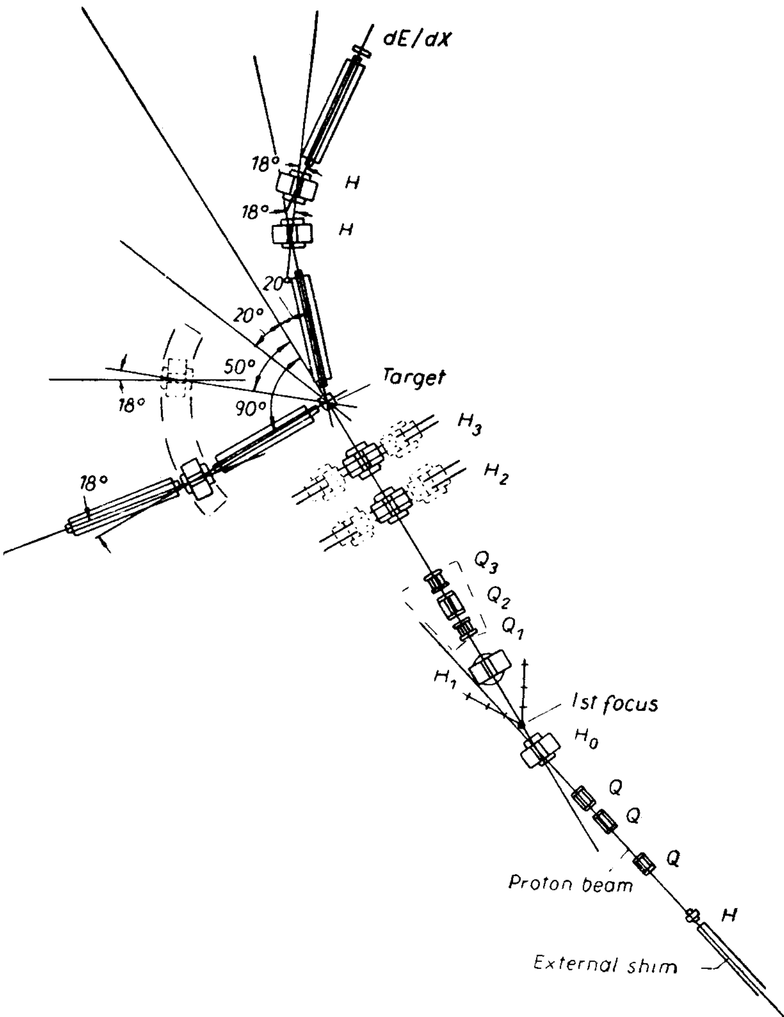
2) The development of wire spark chambers for high energy experiments provided a dectector with the necessary resolution together with enough solid angle to give us reasonable counting rates.

Even through I became enthusiastic I should point out that in discussions with my theoretical friends they were skeptical as is in their nature. They were mainly concerned about the interpretation of the results if we ever get them because all my intuitive arguments were based on Born Approximation and they were concerned about the validity of such interpretations for a strongly interacting probe. I could not be too concerned because I figured if we could be ingenious enough to carry out the experiment the theoreticians would probably match our ingenuity. What I didn't know was that in fact the theoretical groundwork for analysing our results had already been set down several years before by Professor Glauber at Harvard.

2. *Experiments*

What I should like to do now is briefly describe the method of measurements at the Cosmotron and give some of the results pertinent to the study of correlations.

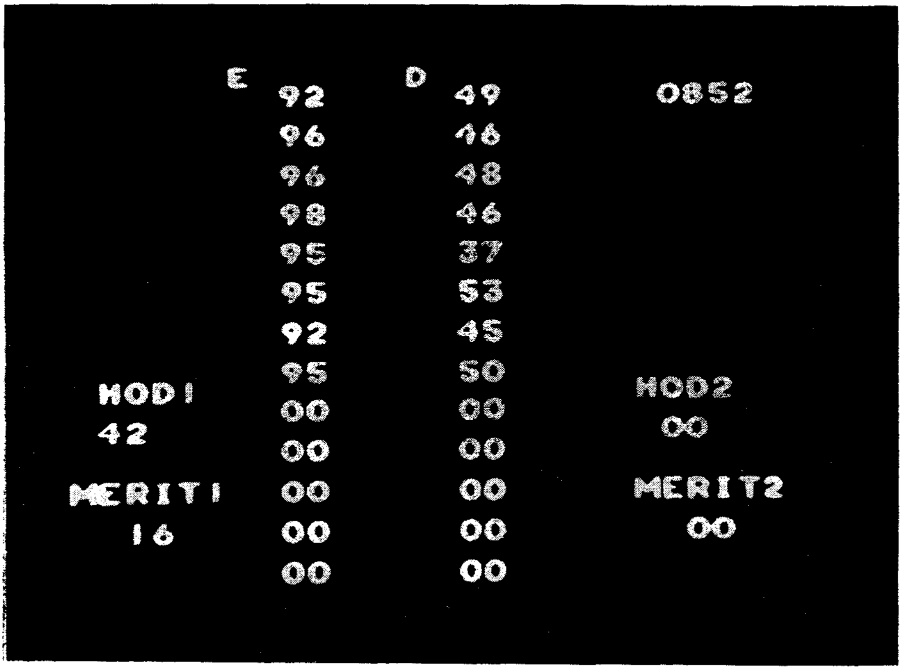
Slide 1. Shows the experimental layout of the experiment on the Cosmotron floor. Sample at target position. The scattered protons are measured by a wire spark chamber magnetic spectrometer, about 50 ft. in length as the proton flies. The protons first pass trough a scintillation counter S1–4 spark planes and then are bent through 36° by two $18'' \times \times 26''$ magnets and thereby dispersed in momentum. The trajectories after the magnets are determined by 4 more spark chambers and then the protons pass through a scintillation counter S2 and finally a dE/dx counter which allows a separation of d from α particles. The spark chambers sit in a quiescent state until a proton of broadly the correct momentum provides the proper S1–S2 coincidence. High voltage is then applied to the planes and sparks are produced at wires where the protons have passed. The spark sets magnetic cores which are then read out into the computer and the computer calculates the straight line trajectories



Slide 1

before and after the magnets, from these, calculates the angle of bending, and from the current calibration of the magnet determines the momentum of the proton passing trough the system. Because the line up of the wire spark planes was most critical ~ ±0.010″ we decided to leave the planes fixed in position and change the scattering angle by swinging the direction of the incident beam by means of the beam transport magnets. The scattering angle could be changed from —4 to 44° lab allowing us to put the direct beam (greatly attenuated) straight down the spectrometer and thereby directly measure the overall instrument resolution. We left room on the floor to construct another arm to do p-$2p$ measurements if the beam characteristics proved suitable, and we actually did carry out two such measurements which are reported in the literature and I shall not discuss here. The incident proton beam was monitored by two scintillation counter hodoscopes, counting mesons produced in a thin grass foil in the beam at the first focus. Cross section was measured relative to ^{12}C $(p, pn)C$ activity in polyethylene foils irradiated at first and second foci. This cross section is known to $\pm 5\%$.

Slide 2. Is one of the displays that was available for us to monitor the operation of the equipment. Column marked E gives efficiency of each plane, column marked D gives the % of adjacent double wire sparks. From tests in the laboratory we knew that the best spacial efficiency was obtained with about 50% double firings and we could adjust the various supplies in the trailer and watch the display until we reached the desired operating characteristic. When this photograph was taken only the HRS was in operation so readings are shown for only the first eight planes. HOD1 gives the overall efficiency of the HRS spectrometer.

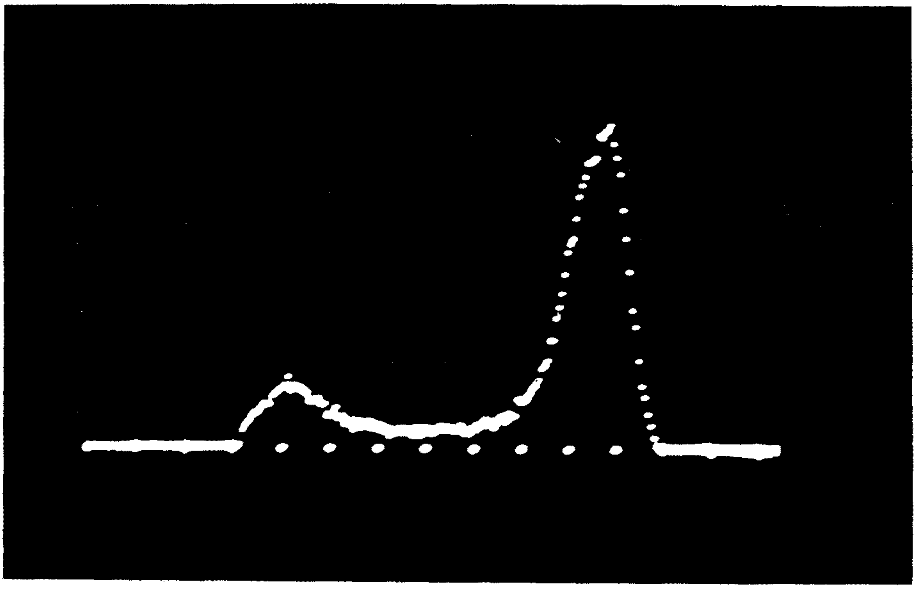


Slide 2

MERIT 1 gives the figure of merit for the particular one is counting, in this case, deuterons in a sea of protons.

Slide 3. In addition to the computer generated displays we had a separate time of flight display. On the next slide is shown the time spectrum of all particles observed coming from carbon at 7.5° scattering angle in the lab. The large peak to the right is the shortest time of flight and represents scattered protons. The flat portion represents accidental coincidences and the small peaks to the left are deuterons coming from the carbon. From this display we could set switches to tell the computer which time group was protons, which accidental coincidences and which deuterons.

Slide 4. Shows another display available from the on line computer. It is actually the display of the characteristics of the direct beam being deflected straight down the spectrometer. The abscissa as shown is divided into 100 bins programmed in this case to be 1/2 MeV/c



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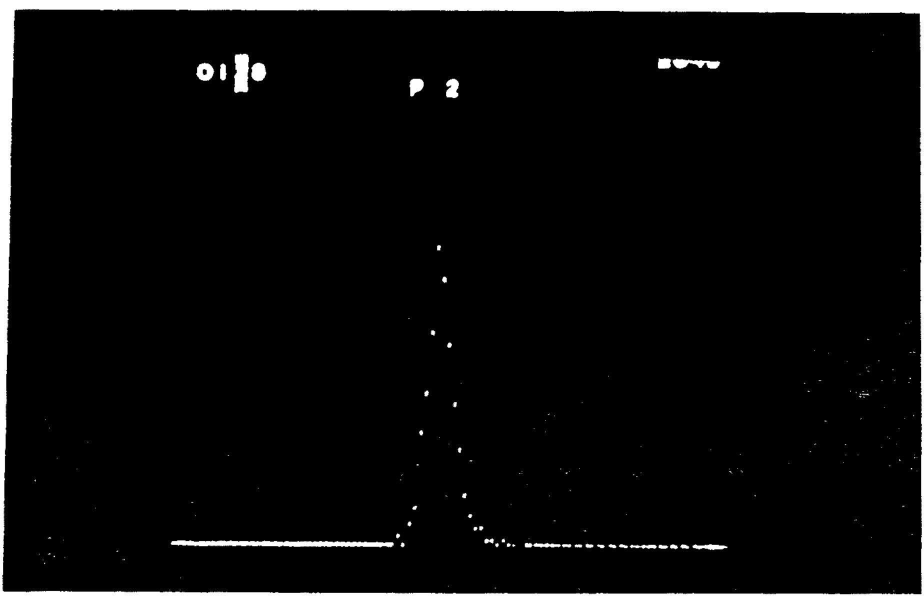
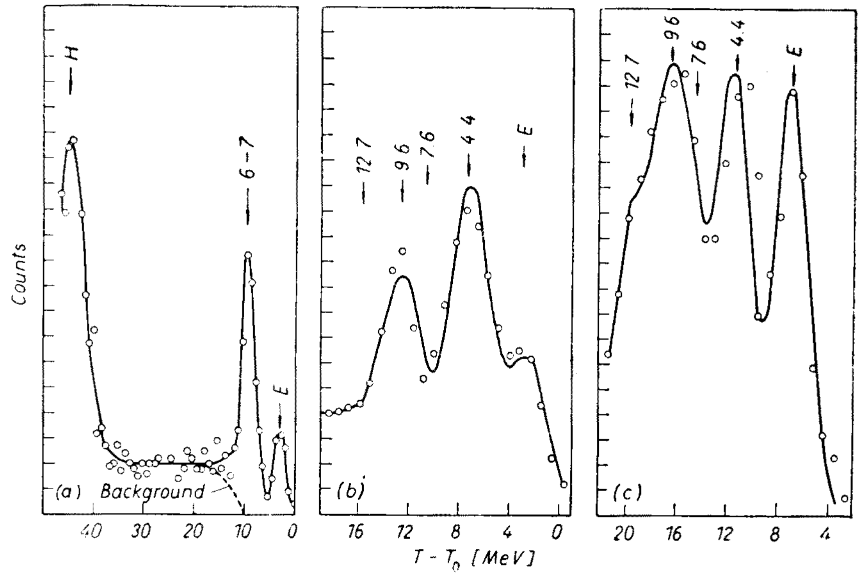


Slide 4

wide. The ordinate scale (128 full scale) is shown in upper left hand corner and this can be expanded or contracted by means of a light pipe which we place on the appropriate dot of the oscilloscope face. P2 means protons and 2 as the center bin of the 3 adjacent computer bins covering a total of 1° in angle. Number in upper right hand corner identifies the particular run. Full width at 1/2 maximum ~ 2 MeV/c out of 1.7 GeV/c or 1 part in 1000. This measured resolution, of course, implies that all elements of our accelerator spectrometer system were remaining constant to within this uncertainty. In fact, the computer was used to automatically sample various measurement elements to assure the required consistency. If some element drifted, a bell rang and a combination of lights identified the guilty element. The computer also automatically rejects that datum. The on line computer has certainly brought about a new era in experimental physics.



Slide 5

Slide 5. The next slide shows some early spectra taken with about 3 MeV resolution from H_2O and C samples.

a) H_2O at 10° scattering angle,

b) C at 10° scattering angle,

c) C at 7.5° scattering angle.

Slide 6. Shows the measured Hydrogen cross section at our incident momentum. This was an important measurement for two reasons.

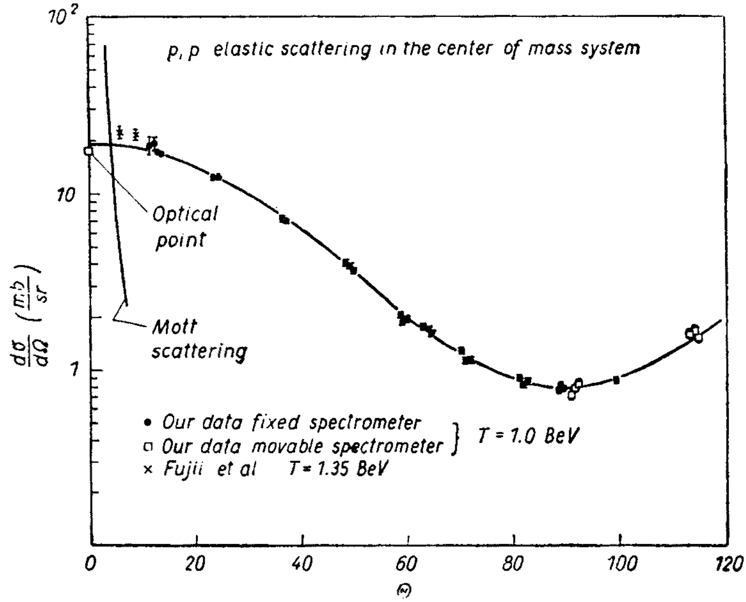
1) allowed us to check that we correctly understood the geometry of our system by comparing our cross section to other measurements in this energy region.

2) provided the needed parameters for the parametrization of the p-p amplitude.

$$f(\theta) = \frac{\sigma_T k}{4\pi}(1+i\varrho)\, e^{\frac{bt}{2}}, \quad -t \leqslant 0.4 \left(\frac{\text{GeV}}{\text{c}}\right)^2$$

$$\varrho_p \sim -0.05$$

$$\varrho_n \sim -0.6$$



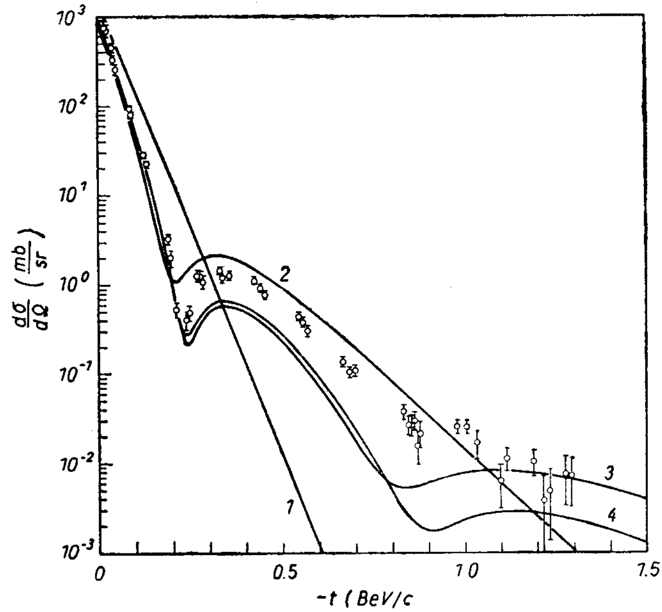
Slide 6

$$\sigma_T = 47.5 \text{ mb}$$

$$b = 5.14 \pm 0.2 \left(\frac{\text{GeV}}{\text{c}}\right)^{-2}$$

We then scattered p from d, He, C and O and I would like to discuss the He elastic scattering data which are shown on the next slide.

Slide 7. You see a very clearly defined first minimum and not so well defined second minimum. These minima were at first very puzzling because the charge factor for He as measured by electrons was known to be Gaussian and had shown no structure in the region of momentum transfer measured. Making the reasonable assumption that isospin is conserved in light nuclei then leads one to believe the matter distribution would also be Gaussian and therefore produce a Gaussian potential. The scattering from a Gaussian shaped potential is known not to produce any diffraction minima. It was for these reasons that the sharp minimum observed in the p-He data was a surprise to me. Well the origin of these minima as we know today is an entirely different phenomenon than the diffraction minima produced when a weakly interacting particle is elastically scattered from the boundary of a nucleus. Because the proton is strongly interacting it has a good chance of colliding with more than one nucleon before escaping the field of the nucleus and the minima we observed are the result of interference between single and double scattering and then between double and triple scattering and so on. Czyż and Leśniak in Cracow and Bassel and Wilkin at Brookhaven were the first to recegnize the origin of the He minima and they used the Glauber theory for calculating the results shown as solid lines on this slide. The calculations exhibit the two minima at the correct momentum transfer. The magnitude of the calculated cross



Slide 7

section is correct up to first minimum then a factor of two too small. Now the acceptance of this explanation means that the Born Approximation which is just single scattering is not sufficient to account for the p-He results. One must take into account the multiple scattering effects inside the nucleus and it is this very fact that gives us a new way of probing correlations inside the nucleus, a method involving elastic scattering measurements rather than inelastic. Perhaps I can reiterate what I have just said better by means of the next slide.

Slide 8. In principle this formulation shows that if one had good e and p data on the same nucleus one could use the electron data to fix the single scattering terms and from the proton data derive the pair correlation. In practice calculations are not done in this way but the Glauber formalism is used (which I cannot discuss here in any detail, but can relate its main points). The Glauber theory is used. The Glauber theory is an eikonal theory which sums the phase shifts of the incident proton wave as it passes through the nucleus encountering nucleons at various impact parameters. The phase shift for the elementary interaction is obtained from the Fourier transform of the measured nucleon nucleon scattering amplitude, and the distribution of particles inside the nucleus given by whatever wave function is used. Then for a particular nucleon wave function one calculates the expected differential scattering cross section and compares with the data. Such an approach was used by Bassel and Wilkin to try and fit both the p-He and e-He data and their best fit is shown on the next slide.

Slide 9. Note that the region after the first minimum is now in good agreement with the data. The filling in of this region comes from a repulsive correlation term in the wave function they used. The correlation having a range of $\sim$ 0.4 fm. The electron data shown is not the measurement cross section but the charge form factor obtained by dividing the

$$\frac{d\sigma}{d\Omega}(\theta) = |F(\theta)|^2$$

Single Scattering

$$F(\theta) = f_c(\theta) f_1(\theta)$$

$$f_1(\theta) \sim \int \rho(r) e^{i\vec{k}\cdot\vec{r}} d\vec{r}$$

Multiple Scattering

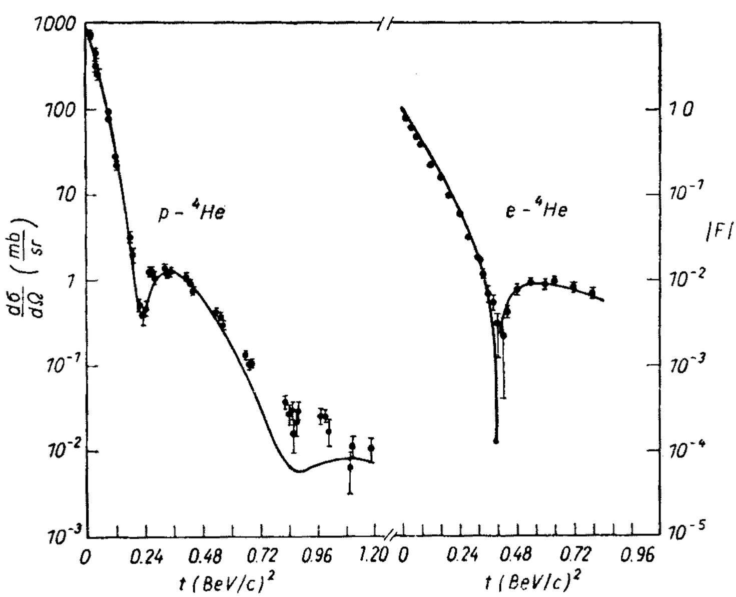
$$F(\theta) = f_c(\theta) f_1(\theta) + f_c(\theta_1) f_c(\theta_2) f_2(\theta) + \ldots$$

$$\theta_1 + \theta_2 = \theta$$

$$f_2(\theta) \sim \int G(\vec{r}_1, \vec{r}_2) e^{i\vec{k}\cdot(\vec{r}_2 - \vec{r}_1)} d(\vec{r}_2 - \vec{r}_1)$$

$G(\vec{r}_1, \vec{r}_2)$ = nucleon pair correlation function

Slide 8



Slide 9

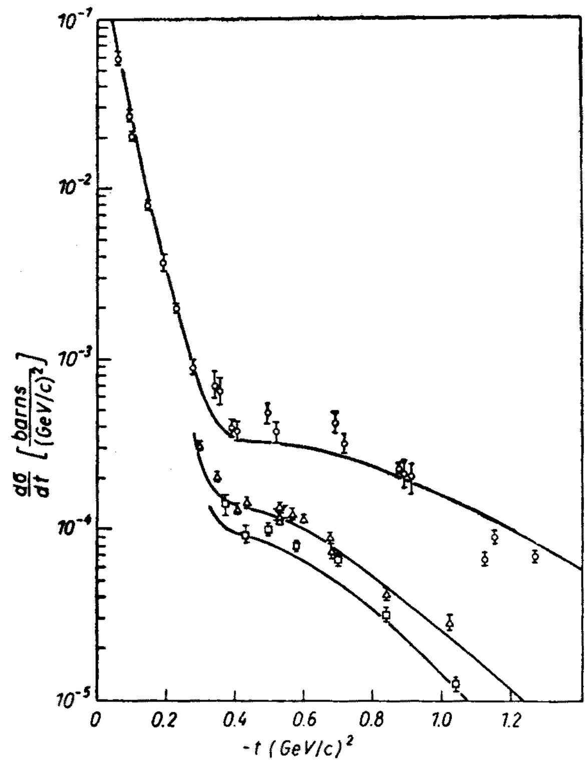
measurement cross section by the Mott term. The actual measured minimum is not so pronounced. However, it is important to note that this minima which related to the fact that the charge distribution departs slighly from Gaussian occurs at $-t$ of ~ 0.40 (GeV/c)^2 whereas our p-He first minimum occurs at 0.24 (GeV/c)^2.

Since these results were obtained two-three years ago, there has been a great deal of discussion among the theoreticians concerning whether in fact our data prove the existence of correlations inside the nucleus. One of the arguments goes as follows. The theory is a high energy or more precisely small angle theory since it is assumed that the phase shifts simply add. The question then is not contained within the present framework of the Glauber theory. In the problem of high energy scattering from a potential as worked out many years ago by Schiff the domain of validity of the small angle approximation in fact defines the problem and it turns out the $\theta_c < \left(\frac{1}{kR}\right)^{1/2}$ where k is the incident wave number and k the range of the potential. For He, using R of 1.60 fm $\theta_c \leqslant 15°$ and since the region we are supposedly seeing correlation effects $\theta > 16°$ the interpretation is suspect. However, Czyż maintains that in the context of the Glauber theory R refers to the nucleon radius in the elementary collision and in this case $\theta_c \sim 22°$ and maybe the theory is allright. Ross, a student of Schiff's has used an extension od Schiff's original work to large angles and claims that he can fit our He data with a simple product Gaussian wave function with no need for a correlation term. The only trouble is that in order to fit our data he must involve a value for ϱ the ratio of real to imaginary part of nucleon wave scattering amplitude of 0.83, whereas the directly measured value is $0.3 \geqslant 0.05$. Everyone who has made Glauber theory calculations knows that the most sensitive parameter in the theory is ϱ and $\varrho = 0.83$ is completely unrealistic. Recently Kujawski, a graduate student of Professor Kerman of MIT has tried to fit our data in the framework of the Watson multiple scattering theory. Starting from a potential derived from the single particle charge density obtained from elastic electron scattering he finds that he cannot fit our e and p data. He then adds a non local second order potential characterized by a correlation length λ. He find a best fit to our data with $\lambda^2 = 0.3$ fm^2, consistent with the earlier Glauber analysis of Bassel and Wilkin.

Last year we had the opportunity to carry out some measurements at the Bevatron in Berkeley and we decided to do an experimental study on the break down of the Glauber theory. The idea of the experiment was simple. We measured the elastic p-d differential scattering cross section in the forward direction as a function of the incident proton momentum for a series of momenta ranging from 1.7 to 6.5 GeV/c. Since the Glauber theory is a small angle theory, for a given momentum transfer one expects to see systematic deviations from the theoretical predictions as one lowers the incident momentum.

Slide 10. Shows our Bevatron results. The upper curve represents the 1.7 GeV/c data, the middle 4.5 GeV/c and the lower 6.45 GeV/c. Note the measurements go out to a momentum transfer of $\sim$ 1 (GeV/c)^2 which at the lowest momentum corresponds to a laboratory scattering angle of $\sim 20°$. We observe no systematic deviations within our experimental error of about 5%.

As I stated in the introduction, the effects of nucleon cerrelations inside the nucleus can be studied in a number of ways. The most direct data relating to n-p correlations has come from the observation of the scattering of incident protons by quasi-free *n-p* pairs on the nuclear surface. We first observed this effect in the time of flight spectrum I showed earlier (Slide 3). This spectrum was seen in all the data we took during elastic scattering measurements. Before these eleastic measurements were completed we instructed the computer to display the momentum spectra of those events passing through our spectrometer which

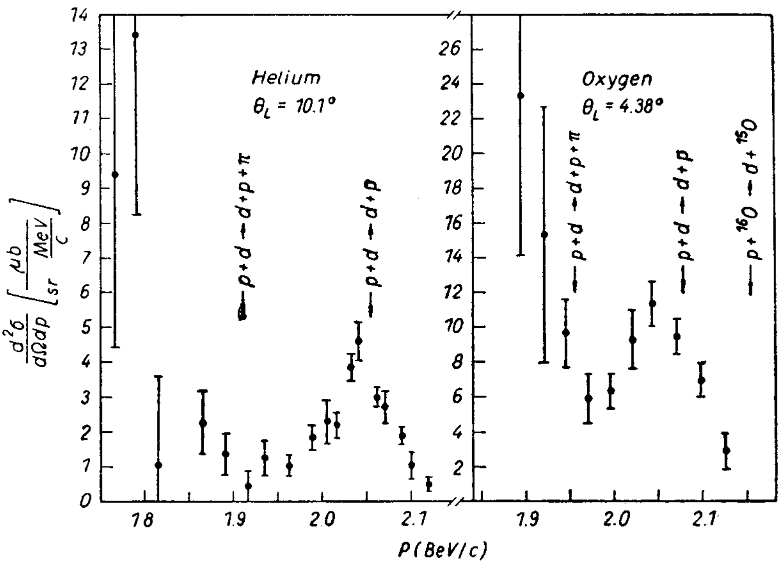


Slide 10

corresponded in time of flight to deuterons. The spectrum from the computer showed only a small fraction of the deuterons observed in the time of flight data. We were confused but went ahead and completed our elastic measurements.

We then realized that the low counting rate together with the high resolution of the magnetic spectrometer (1 part in 10^3) probably meant that the magnetic spectrometer was for the wrong momentum when viewing deuterons. So we varied the magnetic field of our bending magnets and traced out the spectrum of deuterons and the results for helium and oxygen are shown on the next slide.

Slide 11. You will note that a peak in the deuteron intensity is observed at $\sim$ 2.05 BeV/c a much greater momentum than is possible for any incident proton scattered in the forward direction to attain. The peaks both in helium and oxygen are much broader than our resolution and the width is a measure of the momentum distribution of these correlated n-p pairs inside the nucleus. The arrow marked $p+d \to p+d$ is the expected position of the free two body peak from p-d scattering. I believe it was Radvanyi of Orsay whe first called my attention to similar results of Ashgirey *et al.* obtained at the Dubna synchro cyclotron ten years earlier. This group did not separate the protons and deuterons by time of flight but clearly observed the deuterons as shoulder on the high energy tail of the elastically scattered protons and interpreted the results exactly as we did. I must say that this interpretation of scattering from correlated or clustered n-p pairs was met with some

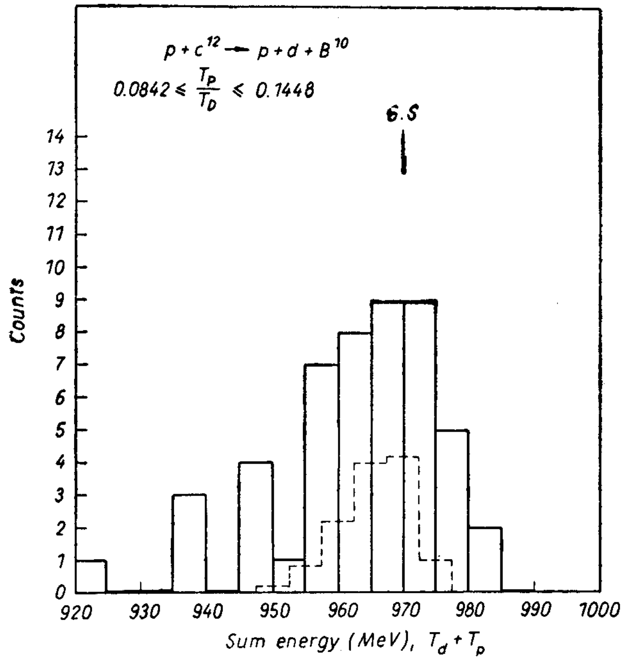


Slide 11

skepticism by theoreticians in the United States. They kept insisting that the observed forward scattered deuterons might result from multiple collisions with uncorrelated protons and neutrons which then in a final state interaction would produce a deuteron. In order to shed more light on the process we arranged the apparatus so that we could look at the energy spectrum of the protons in coincidence with the forward deuterons. The proton pulse heights were observed in a large NaI crystal. A scatter plot of the proton energy versus deuteron energy exhibits a clear diagonal band of events. A summed energy spectrum for cell events for which the ratio of proton-to-deuteron energy was between 0.084 and 0.145 is shown in the next slide.

Slide 12. This range of proton-to-deuteron energy ratio corresponds to dinucleon energies inside the nucleus of 0–3 MeV, much less than the average of 14 MeV deduced from the width of the deuteron peak itself. These results demonstrate that most of the events leave the B^{10} nucleus at or near the ground state, a result I find difficult to explain on the basis of multiple scatterings from single nuclei.

I believe that these results very clearly show that the incoming protons is interacting with a n-p pair simultaneusly. Whether the neutron and proton are close together because



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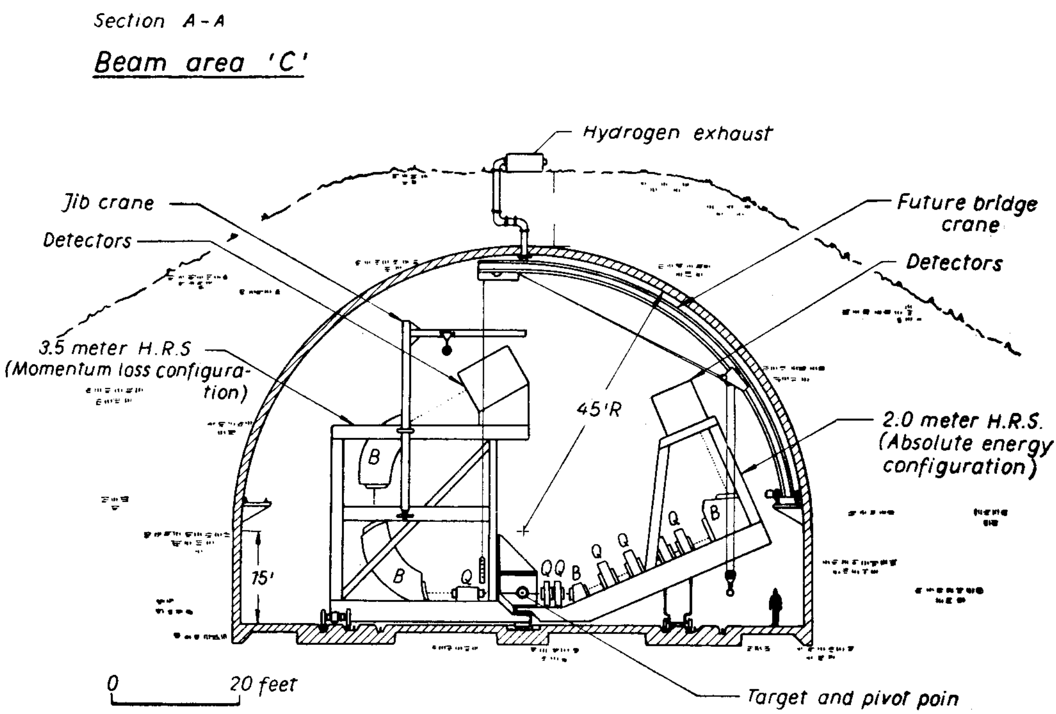

Slide 13

of a density fluctuation (chance correlation) as proposed by Blokhintsev or because of some true correlation is a question which needs further investigation. We attempted a measurement which could throw some light on this matter. We looked for correlated p-p events coming from the sample. The experiment was not clean but the result indicated that the cross-section for p-p correlated events was at least one order of magnitude below the n-p cross-section. If true this would seem to throw some doubt in the Blokhintsev explanation.

I will close by saying that we have made a crude attempt to analyze the quasi-free scattering of protons from the nuclei in carbon, by summing over the inelastic states. The results again show a repulsion of nucleons when they approach a separation of 0.5 fm.

We expect that systematic study of correlations of nucleons inside the nucleus will be one of the first programs of research to be carried out at the Los Alamos Meson Factory.

Slide 13. Shows a diagram of the spectrometer we are building at Los Alamos for p-nucleus studies. It is expected to have a resolution of 50 keV at 800 MeV. It is an energy loss spectrometer consisting of a quadrupole followed by two dipoles. The focal plane detectors will be Charpak wire spark chamber with a spatial resolution of $\sim 0.015'' = \sim 0.4$ mm.