MAGNETIC ANALYSIS OF THE REACTIONS $pp \rightarrow np\Pi^+$ (I), $pp \rightarrow pp\Pi^0$ (II) AND $pp \rightarrow d\Pi^+$ (III) AT AN ENERGY OF 660 MEV

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(presented by M. G. Meshcheriakov)

The data on inelastic (p-p) collisions available now refer to the total cross-sections of π meson production[1, 2, 3], the energy distribution of mesons in reaction (I) [4, 5, 6] and the angular distribution of mesons in reaction (III)[7, 8, 9]. In order to obtain additional information on the nature of the process of π meson production in (p-p) collisions we undertook an experimental study of the energy spectra and angular distribution of the secondary protons emitted in reactions (I) and (II) at the energy of 660 Mev.

The problem of establishing the possibility of separating the deuterons formed in reaction (III) from the total flux of secondary particles in order to determine their degree of polarization was of interest by itself. Such an experiment, in conjunction with measurements of the total cross-section of the reaction (III) and its dependence on the energy, as well as the angular distribution of the π mesons and the asymmetry in the yield of the π mesons produced by protons having a given degree of polarization permits to carry out a complete phenomenological analysis of the reaction (III) including the determination of the relation between the intensities of the two possible transitions corresponding to the emission of mesons in the p-state: $^1S_0 - {}^3S_1$ and $^1D_2 - {}^3S_1$.

The experiments were performed by the Institute of Nuclear Problems of the USSR Academy of Sciences, on the six-metre synchrocyclotron. We used a proton beam with an intensity of 3×10^9 protons/cm^2 sec. ejected into the atmosphere by exciting radial oscillations in the region of the last orbits[10]. The energy of the protons determined from the angle of emission of the Čerenkov radiation, was equal to 660 ± 3 Mev. The half-width of the proton spectrum in the primary beam comprised $\pm$ 5 Mev. The high intensity of the beam made it possible to analyze the secondary products of the reactions (I)–(III) by means of a magnetic spectrometer with a resolving power of the order 3%.

Fig. 1 shows the diagram of the spectrometer and its position with respect to the primary beam and the concrete

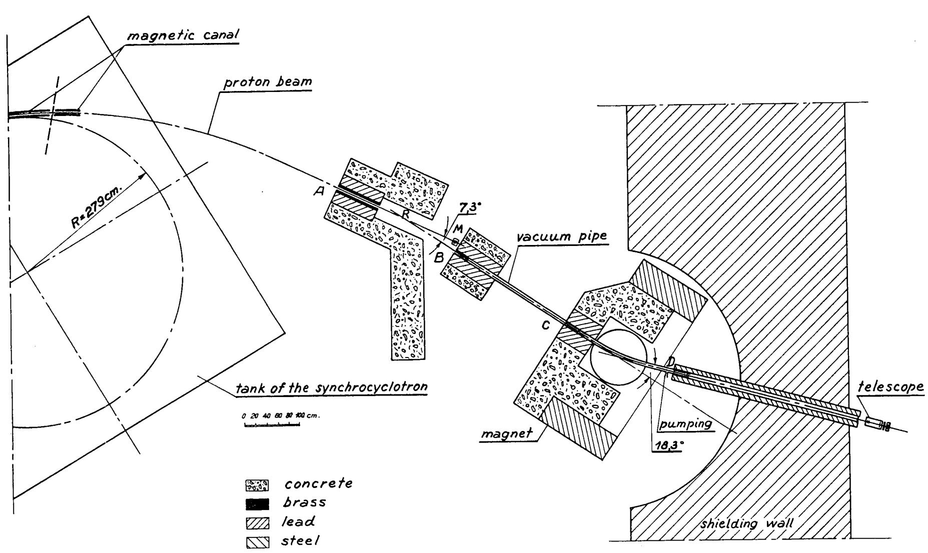

Fig. 1. Design of the spectrometer.

shielding in spectrum measurements at an angle of 7°. The main part of the spectrometer was a magnet with circular poles 100 cm. in diameter and 10 cm. air gap. The maximum obtainable field strength was 19,000 gauss.

A target 1 cm. wide and 2.5 cm. high served as the first slit of the spectrometer. The secondary particles emitted from the target at an angle of 7° to the primary beam passed through collimators B and C with cross-sections 2×3 cm^2 and 3×3 cm^2, respectively, and through the analyzing field were sorted out by collimator D with a cross-section of 1×3 cm^2 and after passing through a channel in a 3.6 meter concrete wall entered the experimental laboratory, where they were registered. Collimators B and D were connected by a thin-walled brass vacuum tube bent along the trajectory of the particles in the magnetic field.

As a particle detector at the exit of the spectrometer we used a telescope of four scintillation counters connected in a triple and quadruple coincidence circuit. The efficiencies of detection did not vary with the energy of the particles. The threshold of registration was 1100×10^3 gauss-cm. The protons and deuterons, and in the lower part of the spectrum also the π mesons were identified by their momentum and range in the copper filter placed in front of the last counter which had a liquid scintillator 10 cm. in diameter. The crystal of the second counter with a cross-section of 2.5×2.5 cm^2 served as the exit slit of the spectrometer.

The relative spectrum of particle momenta was experimentally determined by varying the magnetic field. The hydrogen effect was found from the difference in the effects due to the polyethylene and the carbon targets, both of which had the same stopping power. The energy losses of the primary protons in the targets amounted to 1.1 Mev. The beam intensity was controlled throughout the experiment by means of an ionization chamber filled with helium under a pressure up to 0.5 kg/cm^2.

The momentum scale was calibrated with reference to the peak of elastic scattered protons. The results of the measurements were corrected for counting losses of the detection system, slowing down of the particles in the target and particle absorption in the target and the scintillators. The maximum total correction did not exceed 15%.

Fig. 2 shows the general view of the momentum spectrum of secondary protons and deuterons for equal intervals of $H\rho$ at an angle of 7°. The most intense peak in the spectrum corresponds to protons elastically scattered by protons at an angle of 17° in the centre of mass system (c.m.s.) The peak at $H\rho = 4520 \times 10^3$ gauss-cm and the peak at $H\rho = 2880 \times 10^3$ gauss-cm lying on the continuous spectrum of protons from reactions (I) and (II), correspond to deuterons from reaction (III). The first deuteron peak corresponds to an emission angle of 43°,

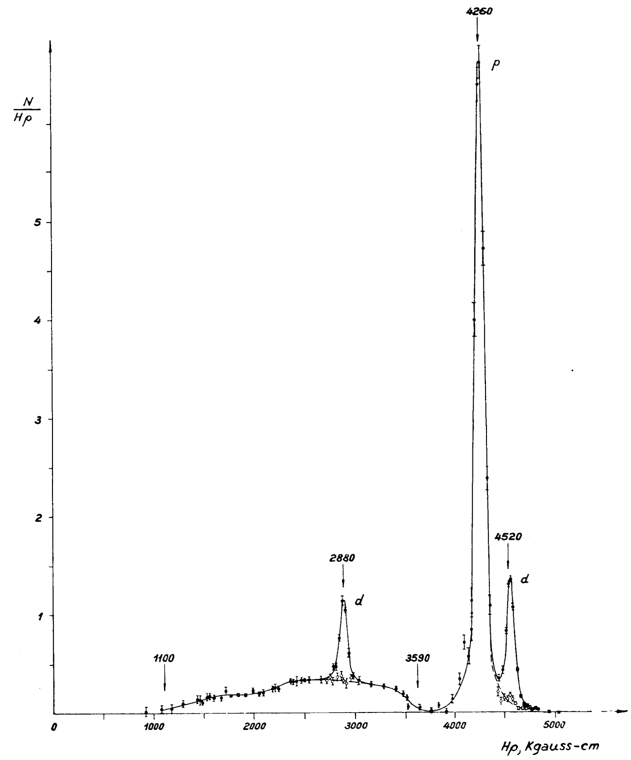

Fig. 2. Momentum distribution of protons and deuterons from p-p collisions at 7° in the laboratory system.

the second to 153.5° in the c.m.s. The position of the deuteron peaks relative to the peak of elastically scattered protons differs from the calculated value by not more than 1%, which indicates an insignificant distortion of the spectrum due to the non-linearity of the momentum scale.

The relative half-width of the peak of elastically scattered protons $\Delta H\rho/H\rho$ comprised 3%. The sufficient resolution of the deuteron and proton peaks in the upper part of the spectrum and the considerable intensity of the deuteron beam obtained ($\sim 10^3$ deuterons/minute) made it possible to carry out an experimental study of the polarization of the deuterons generated in reaction (III).

In considering the continuous spectrum of protons from reactions (I) and (II) it should be kept in mind that the form of the spectrum may be distorted due to scattering and slowing down of the primary protons in collimators.† On the assumption that the level of the background throughout the entire region of the continuous spectrum remains the same as at its upper limit, we estimated the contribution to the continuous spectrum due to blurring of the peak of elastic scattered protons as a result of slowing down in the collimators to be about 3%. The fact that the observed upper limit of the continuous spectrum coincides so well with the computed maximum value of

† In the immediate vicinity of the synchrocyclotron the background due to spurious radiations was exceedingly high, and this excluded the possibility of separating the beam of secondary particles at the spectrometer entrance by means of a combination of scintillation counters.

the proton momentum (3560 × 10^3 and 3590 × 10^3 gauss-cm. for reactions (I) and (II), respectively) also supports our conclusion that the scattering of secondary particles in the collimators has a small effect on the shape of the spectrum. The fact that the spectrum does not reveal to any noticeable degree the two regions corresponding, approximately, to half-values of the momenta of the two groups of deuterons may be interpreted as an indication of the small probability that the proton and the neutron in reaction (I) and the two protons in reaction (II) will be emitted in approximately the same direction with approximately the same velocities.

A spectrum of secondary particles originating from (p-p) collisions analogous to the one described above has been observed also at an angle of 12.2° to the direction of the primary beam. In this case the deuteron peaks were observed at $H\rho = 3220 \times 10^3$ and $H\rho = 10^3$ gauss-cm to the left of those corresponding to the elastic scattering of protons.

The spectrum of secondary particles originating from (p-p) collisions measured at an angle of 18° where no deuterons from the reaction (III) are observed, is plotted in fig. 3. The spectra measured at the angles of 24° and 30° have the same form as that at 18°.

Normalization of the spectra in absolute units was made by two following methods :

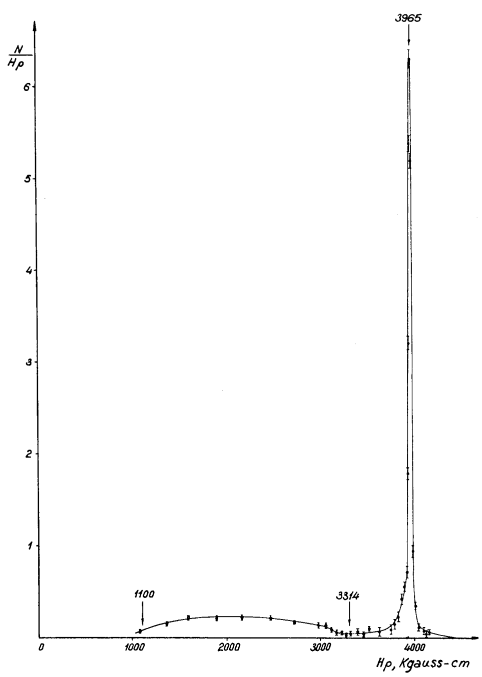

Fig. 3. Momentum distributions of protons from p-p collisions at 18° in the laboratory system.

† All quantities referring to the c.m.s. are marked by asterisks.

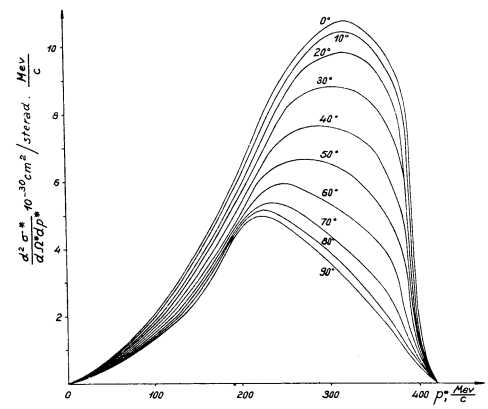

Fig. 4. Momentum distributions of protons in the c.m. system.

1. The integral yield of secondary protons from the reactions (I) and (II) was measured by means of excluding elastically scattered protons and π mesons from the total flux of secondary particles measured at corresponding angles in a special experiment, the same telescope as at the exit of the spectrometer being used. The differential cross-sections of proton emission of a given momentum from reaction (I) and (II) were normalized to the integral yield thus obtained.

2. The second method of determining the differential cross-section of emission of secondary protons in (p-p) collisions consisted in comparison of the areas under the peak corresponding to elastically scattered protons and under the continuous spectrum of protons.

Within the limits of experimental errors both methods have led to the same results. It should be noted that the differential cross-sections of the reaction (III) for the deuteron emission angles of 43° and 153.5° which have been found by comparing the areas under the deuteron peak and the peak corresponding to elastically scattered protons have turned out to be $(0.33 \pm 0.10) \times 10^{-27}$ and $(0.36 \pm 0.10) \times 10^{-27}$ cm^2/sterad, which is consistent within experimental errors with the known angular distribution of π mesons in the reaction (III)[9].

Spectra observed in the laboratory system were used in plotting the momentum spectra of secondary protons from reaction (I) and (II) at various angles in the c.m.s. The results are shown in fig. 4; the ordinate axis is divided in absolute values of $d^2\sigma^*/d\omega^*dp^*$ and the abscissa in proton momentum.†

From this figure it is seen that the form of the momentum spectrum of secondary protons changes significantly with the emission angle. The protons with momenta greater than 250 Mev/c turned out to be emitted mostly forward and backward, while those of smaller momenta have a distribution which is near to the isotropic one.

From comparison of areas under the curves in fig. 4 it was found that the dependence of $d\sigma^*/d\omega^*$ on the proton emission angle θ^* is expressed by

$$d\sigma^*/d\omega^* \approx 1.3\ (0.8 + \cos^2\theta^*)\ 10^{-27}\ \text{cm}^2/\text{sterad}.$$

It is essential to note that at large angles the curves of the momentum spectra show a clear maximum near the energy of 220 Mev/c. This peculiarity of the spectra can be explained qualitatively in terms of the assumption that the given energy pion production in p-p collisions passes through an excited intermediate state of the nucleon, the life-time of which is of the same order of magnitude as that of nucleon collision. In the conditions of the present experiments, the available energy of 305 Mev should be spent nearly completely for the formation of the excited state of the nucleon having excitation energy of about 300 Mev. As a result of such an interaction the excited nucleon and the other nucleon participating in the collision must have small velocities in the c.m.s. being thus in an S-state with respect to each other. This circumstance favours the observation at large angles of the protons originating from the free decay of an excited nucleon. Consequently, if spectra at large angles are regarded as spectra of recoil protons emitted in the decay of an excited nucleon after separation of the colliding particles, it turns out that the maximum of the proton momentum spectrum near 200 Mev/c (or a kinetic energy of recoil protons of 25 Mev) corresponds to the maximum of the energy spectrum of π mesons close to 125 Mev. If this proton recoil energy and the rest mass of the π meson are taken into consideration we obtain a value of about 290 Mev for nucleon excitation energy equal to the energy at which the resonance in pion-nucleon scattering is observed. Such a coincidence leads us to believe that there must be some correspondence between the processes of pion-nucleon scattering and production of mesons in the reactions (I) and (II).

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