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SEPARATION OF HIGH-ENERGY PARTICLES BY MEANS
OF STRONG INTERACTION PROCESSES

by

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G. Goldhaber^{*}, S. Goldhaber^{**}

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During the last few years, knowledge of strong interaction processes has increased to the point, where it appears possible to use them for physically separating different particles. This becomes important in an energy region where mass separation by electromagnetic methods is no longer possible or becomes cumbersome and expensive. Apart from being useful for separating high-energy charged particles, separation by strong interactions possesses the advantage of being applicable to neutral particles as well.

Nuclear properties have been applied before to effect physical separation of particles; one often makes use of the difference in the total absorption cross-sections of two types of particles by using absorbers in which the more strongly interacting component is absorbed preferentially. In this manner one obtains for instance pure μ -meson beams of arbitrary high energy by filtering out π -mesons, K-mesons and nucleons. It appears possible, however, to apply nuclear forces also to the physical separation of high-energy π -mesons, K-mesons, baryons and antibaryons from each other, by making use of more subtle differences in the behaviour of the various types of particles: kinematics, partial cross-sections, angular distributions, etc.

The study of strongly interacting particles in the GeV region has produced some experimental results of a general nature which seem fairly well established, and can be extrapolated to 10 GeV and probably even to much higher energies. These results are:

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- 1) In high-energy nuclear reactions of π -mesons, K-mesons, baryons and antibaryons the cross-sections for charge exchange with small transfer of momentum remains an appreciable fraction of the total cross-section; therefore, there are many interactions in which a particle, belonging to the same isotopic multiplet and carrying the same baryon number as the incident particle, emerges within a narrow cone around the forward direction and with a large share of the available energy¹⁻⁴).
- 2) In collisions between high-energy π -mesons (presumably also K-mesons) with nucleons, a baryon is emitted in the backward hemisphere in the centre-of-mass system. This has been shown to be the case in π -p collisions from 7 to 8 GeV, where the baryon may be emitted as nucleon, hyperon or as cascade particle^{5,6}), and for protons from π -N collisions in the same energy interval⁷). It has also been shown⁸) that it holds for Λ and Σ production in π -p collisions at 16 GeV.

Examples for the application of these two experimental results to obtain enriched antineutron, antiproton and positive K-meson beams will be discussed in the following three sections. In the last section we discuss the extension of these principles to the energy region of 100 GeV and above, and indicate the feasibility of particle separation at future ultra high-energy accelerators.

* * *

A Separator for High-Energy Neutral Particles

The two experimentally established properties of high-energy collisions can be used to eliminate, for instance, most of the neutrons in a neutral beam and make it possible to obtain a fairly well focused high-energy beam of antineutrons and K_2^0 -mesons. The intensity of such a beam should be more than adequate for bubble chamber work.

Fig. 1 illustrates a possible arrangement. The momentum analysed beam of negative particles is focused by the quadrupole magnets, Q, onto the bubble chamber, B.Ch. An absorber, A, converts some of the negative particles into other charged and neutral particles. Neutral particles produced at very small angles in A will thus still be effectively focused at the bubble chamber. The charged component is removed from the beam by the sweeping magnet, H_1 , while the neutral particles proceed. These neutral particles consist of:

a) Antineutrons which are produced mainly in charge exchange reactions and therefore are strongly collimated in the forward direction.

b) Neutral K-mesons which are produced partly by K^- -mesons in quasi-elastic charge exchange reactions, partly in collisions of π^- -mesons with protons. The former will presumably be strongly collimated in the laboratory system, the latter, however, only slightly, since the angular distribution of K^0 -mesons in the centre-of-mass system of π -N collisions is known to be nearly isotropic^{5,8}).

c) Neutrons which are produced primarily in π -N interactions; they move backward in the centre-of-mass system⁵⁻⁸) of the collision and therefore have a wide angular distribution and comparatively low energy in the laboratory system.

These neutral particles as well as the γ -rays from decay processes fall onto the lead sheet Pb which absorbs most of the γ -rays or degenerates them into low-energy quanta emerging with large angles. All other neutral particles including the K_1^0 -component of the neutral

K-meson decay within or shortly behind the converter A.

The lead sheet Pb is followed by a second magnet H_2 , which removes electron pairs as well as other charged particles emerging from the lead. Thus the particles proceeding towards the detector consist of high-energy antineutrons and K_2^0 -mesons in a well-collimated beam, and some K_2^0 -mesons in a wider cone and probably of lower energy. This beam is contaminated by some neutrons and γ -rays of comparatively low energy and with a large angular spread.

Apart from this unwanted background due to neutrons and γ -rays, all interactions occurring in the bubble chamber represent either the transformation or the annihilation of an antibaryon, or else the production of at least one strange particle. The relative frequency of such events per picture will therefore be considerably higher than can be obtained in an unseparated high-energy secondary beam.

A rough estimate of the expected intensities in a particular momentum interval can be made as follows: at the CERN Proton Synchrotron, for instance, a pulse of 2×10^{11} protons (of which about half interact in the target) with an energy of 25 GeV gives rise to a negative secondary beam which at a momentum of 8 GeV/c has an intensity of $\sim 2 \times 10^{10}$ particles (steradian) $^{-1}$ (GeV/c) $^{-1}$ in the forward direction. In addition to negative pions such a beam contains about 4% K^- -mesons and 0.8% antiprotons⁹).

One may select a fairly wide momentum band of 8 ± 0.2 GeV/c and then focus the beam on a bubble chamber. With an aperture of $\sim 10^{-4}$ steradians for the focusing magnet, the beam will then contain about 6400 antiprotons per pulse. If one now inserts a low Z converter, for instance, lithium hydride, paraffin or liquid hydrogen into the beam, some antiprotons will annihilate or be removed from the beam by inelastic collisions; others will suffer a charge exchange reaction and proceed as antineutrons with little loss in energy and with only a small change in direction of motion. Since diffraction scattered particles in our geometry will remain part of the beam, the optimum production

of antineutrons occurs for a thickness of converter A equal to one absorption mean free path for antinucleons; the fraction of antiprotons suffering charge exchange will then be :

$$\frac{\sigma_{\text{charge exchange}}}{\sigma_{\text{absorption}}} e^{-1} .$$

In the momentum range from 0.5 to 3 GeV/c the charge exchange cross-section for antinucleons remains reasonably constant and approaches about 10% of the total cross-section at 3 GeV/c¹⁰). In the following estimates we have assumed that the charge exchange cross-section remains 10% of the total cross-section up to momenta of 8 - 10 GeV/c provided elastic as well as quasi-elastic charge exchange processes are included. In that case ~ 3% of the antiprotons incident on the converter A undergo charge exchange. In this process the antinucleons suffer a deflection whose angle is of the order of magnitude $\mu_{\pi}/P_{\bar{p}}$.

If one interprets this characteristic angle as representing the half angle of the cone which contains 50% of the antineutrons, one finds that 8 antineutrons per pulse will traverse a bubble chamber which subtends a solid angle of 10^{-4} steradians at the converter A.

If, on the other hand, one bases one's estimate on the available experimental data¹⁾ at the comparatively low momentum of 1.65 GeV/c one obtains a half angle of $2.6 \mu_{\pi}/P_{\bar{p}}$. This leads to 1 antineutron per pulse, an estimate which is perhaps somewhat too conservative.

The K_2^0 -mesons traversing the bubble chamber consist of two groups. Those produced in charge exchange reactions by the K^- -component; of these there will be 4 per pulse or 0.5 per pulse depending on which of the two methods is used for estimating the angular distribution characteristic of the charge exchange reaction. The second component consists of K_2^0 -mesons which arise from neutral K-mesons produced in π, N collisions. Their distribution in the centre-of-mass system is

nearly isotropic at high energies^{5,8)} and contributes about 1 or 2 K_2^0 -mesons per pulse¹¹⁾. On the average their energy will be much lower than that of the charge exchange K-mesons. (The K-flux has been calculated on the assumption that the distance from machine target to converter is 80 metres and from the converter to the bubble chamber, 15 metres.)

Finally one can estimate the intensity of the background neutrons. Practically all of them must be due to the interaction of π^- -mesons with the nuclei of the converter. The reaction $\pi^- + N \rightarrow p + \pi^-$ at 7-8 GeV/c, leads to protons^{5,7)} which in the centre-of-mass system are emitted into the backward hemisphere with an average momentum of 0.9 GeV/c and an average transverse momentum of 0.38 GeV/c. Thus the characteristic solid angle in the laboratory system is of the order of 0.7 steradians. Assuming a similar distribution for neutrons produced in π^-N collisions, the fraction falling into solid angle interval of 10^{-4} steradians is $\sim 0.35 \times 10^{-4}$. On the basis of these estimates, the expected beam will contain 1-2 neutrons. These estimates together with the expected number of interactions^{*)} in an 80 cm bubble chamber are summarized in Table I.

TABLE I

Yield Estimates

(For an 8 GeV/c negative beam of 8×10^5 particles incident on the converter)

Particle	Particle Yield per pulse	Mean free path ^(a) in liquid hydrogen (metres)	Number of interactions per 100 pictures in an 80 cm bubble chamber
$\bar{n}$	1 - 8	5.0	15 - 120
K_2^0	2 - 5	12.0	12 - 30
n	1 - 2	6.5	12 - 25

(a) From cross-section measurements quoted in references 9 and 12.

*) It is important to note that by using neutral instead of charged particles for studying the behaviour of fast antinucleons and of strange particles, the bubble chamber can handle a large number of traversing neutral particles per picture. Certain types of data can therefore be accumulated much faster than it could be done if the incident particles were electrically charged.

The neutral beam which one obtains by charge exchange from a momentum analysed and focused negative beam is still a mixture of three types of particles, so that the interpretation of nuclear reactions observable in the chamber will sometimes be ambiguous.

There are, however, certain reactions in the class of associated production of hyperon-antihyperon pairs which can be attributed uniquely to antineutrons.

Such reactions are:

The reactions

can be identified uniquely in a heavy liquid bubble chamber and also in a hydrogen chamber, provided the antibaryon decays via the charged mode. Other combinations involving Σ^0 , and baryon-antibaryon pairs of unequal mass, i.e. $(\bar{\Lambda}\Sigma)$ or $(\Lambda\bar{\Sigma})$ will also occur. All these processes lead to baryon pairs^{*)} whose mean-life is short enough so that a considerable fraction will decay in the chamber.

There are also a number of reactions involving K-mesons and hyperons which in favourable cases can be attributed unambiguously to the K^0 -component of the beam. An example is the reaction:

*) It should be noted that these processes have a comparatively low threshold and some may compete favourably with associated production of $\bar{Y}K + (N)$ and $YK + (\bar{N})$ by antineutrons.

Finally it should be noted that the ratio of antiprotons to K^- -mesons in the negative beam can be varied somewhat before conversion by changing the distance between the machine target and the converter A in Fig. 1; this will produce a corresponding change in the ratio of antineutrons to K^0 -mesons in the converted beam.

* * *

A Separator for High-Energy Negative Particles

The method discussed above is also applicable for obtaining a beam enriched in antiprotons and negative K-mesons. The arrangement could be that shown in Fig. 2. Here an unanalysed but collimated beam of neutral particles (from which γ -rays have already been removed) is permitted to fall on a converter A. The emerging charged particles are focused by quadrupole magnets Q on the bubble chamber, B.Ch. One selects again only particles within a narrow cone of order 1° in the forward direction and then makes a charge and momentum analysis in the field H. The negative beam is directed towards the bubble chamber. Since antiprotons and negative K-mesons produced in charge exchange reactions are strongly collimated in the forward direction, the beam contained in this narrow cone will be enriched in these two components. The contamination consists of π^- -mesons, mostly produced in n-n' and n-p collisions at angles distributed over a wide cone in the laboratory system. It is difficult, however, to calculate the composition of such a beam since this involves detailed knowledge of the composition and energy spectrum of the neutral beam before conversion.

The enrichment may well be lower than in the first case which we discussed. Furthermore, the incident flux is limited here not by the output of the machine but by the permissible number of incoming tracks in each bubble chamber picture.

* * *

A Two-Stage Separator for High-Energy Charged Particles

Given a negative secondary beam which after rough momentum analysis and focusing contains 10^7 particles or more, it is possible to operate the two separators (Figs. 1 and 2) in series; one then obtains comparatively weak but pure and still useful separated beams^{*)}. The output of the second stage in a momentum interval close to the incident momentum consists now of a positive beam of K^+ -mesons and a negative beam containing a mixture of antiprotons and K^- -mesons. These are the only energetic particles which can be produced in charge exchange reactions by antineutrons and K_2^0 -mesons present in the intermediate neutral beam. None of the other particles of the intermediate beam possess sufficient energy to produce charged particles in the same momentum range. A very large part of the proton and π^+ background in the separated beams can therefore be eliminated by the second momentum analysis.

In estimating the flux obtainable in the two-stage charge exchange separator, one should take into account that it is possible to transport the K-mesons over appreciable distances in the long-lived K_2^0 -state.

* * *

Separation of Particles at Very High Energies

The method of particle separation described here makes use of two asymmetries in the family of elementary particles:

- a) the absence of negative nucleons in ordinary terrestrial matter;
- b) the absence of neutral pions with a lifetime comparable to that of the charged pion component.

These asymmetries make it possible to eliminate strongly forward collimated nucleons in a beam by passing through a negative beam stage and

*) At the completion of this paper an internal report by F.J.M. Farley (CERN 1958 unpublished) was pointed out to us in which he suggests a method of double-charge exchange to obtain enriched antiproton beams in the 0.5-2 GeV region.

to eliminate strongly forward collimated pions by passing through a neutral beam stage.

We have given numerical estimates for the particular case of particles of momentum in the range of 8 GeV/c where relevant experimental data on pion-nucleon and proton-nucleon collisions exist. One can show, however, that the method remains applicable and that the obtainable separation factor actually increases as one goes to still higher energy. In order to make this plausible it is necessary to establish the following points:

- 1) the cross-section for charge exchange collisions of nucleons and therefore of antinucleons in which the incident baryon loses a comparatively small fraction of its energy remains an appreciable part of the geometric cross-section;
- 2) the laboratory angle characteristic of such charge exchange interactions decreases at least as fast or faster with increasing energy as does the angle characteristic of the production of nucleons in pion-nucleon collisions and of pions in nucleon-nucleon collisions.

Evidence for point (1) can be found in the studies of nuclear interactions at cosmic-ray energies¹⁵⁾. It has been established that nucleons in the energy range of 10^{11} - 10^{14} electron volts lose on the average less than 25% of their energy in pion producing collisions in air. The average energy loss per collision in hydrogen is certainly smaller and lies perhaps within 15-20%. Since these collisions are accompanied by the production of several charged particles, the emerging nucleon, which in half the cases carries more than 80% of the available energy, has a nearly equal chance of being charged or neutral. The cross-section for such "quasi-elastic charge exchange" processes in which no more than ~ 20% of the incident energy is lost in particle production represents therefore about 25% of the geometric cross-section. One could interpret these collisions being associated with impact

parameters greater than some value b_0 . The probability of such quasi-elastic charge exchange processes does therefore not decrease and may possibly increase somewhat as one approaches ultra-relativistic energies. We expect a similar behaviour to hold for antinucleon-nucleon collisions. At these energies the annihilation process will probably be confined to small impact parameters corresponding to antinucleon-nucleon core collisions and would therefore not compete significantly with the quasi-elastic charge exchange process.

Regarding point (2), the particle emerging close to the forward direction in the centre-of-mass system retains a large fraction of its original momentum. Therefore the characteristic angle in the laboratory system for quasi-elastic charge exchange processes decreases as $1/P$ where P is the momentum in the laboratory system. In pion-nucleon collisions on the other hand, the nucleon is emitted backward in the centre-of-mass system and the characteristic angle varies at most as the velocity of the centre-of-mass system, i.e. as $1/\sqrt{P}$, while for quasi-elastic collisions the characteristic angle tends to a large constant value. The angle varies thus less rapidly than the angle associated with the charge exchange process.

The angle characteristic of the production of pions in nucleon-nucleon collisions has been studied actively over a very wide range of energies during the last few years. All investigators agree that it has a value of $\alpha \mu_\pi / P_\pi$ where α lies between 2 and 3. Since the pion multiplicity increases somewhat, if only slowly, with the primary energy the momentum of the meson P_π increases less rapidly than the primary momentum P .

From these considerations it follows that the fraction of background nucleons and pions which fall into the solid angle characteristic of quasi-elastic charge exchange reactions tends to decrease with energy. The method for separating particles by strong interactions which we have discussed here is therefore not limited to the energies available in the laboratory at present. Particle separation at future accelerators in the 100 GeV range should thus be feasible.

* * *

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* * *

FIGURE CAPTIONS

Fig. 1 : Schematic diagram showing a possible experimental arrangement for obtaining an enriched anti-neutron - K_2^0 beam.

Fig. 2 : Schematic diagram showing a possible experimental arrangement for obtaining an enriched antiproton- K^- beam.

* * *

FIG. 1