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HYPERONS IN NUCLEI

B. Povh

Max-Planck-Institut für Kernphysik, Heidelberg, Germany
CERN, Geneva, Switzerland

ABSTRACT

Experimental methods to study hypernuclear ground states and continuum states observed in the recoilless Λ production are reviewed. The two types of hypernuclear states give the most direct information on Λ -nucleus interaction. The Λ particle is a unique probe of the nucleus; it interacts strongly with the nucleus and is distinguishable from the nucleons. In light hypernuclei, gamma spectroscopy is a powerful tool to study the bound excited states.

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1. INTRODUCTION

In 1953, Danysz and Pniewski reported the first observation of the decay of a hypernucleus in nuclear emulsion. A high-energy particle interacted with a nucleus, thereby emitting fragments. One of the fragments, after the slowing-down process which took at least 10^{-12} sec, decayed at rest by emission of a charged pion and nucleons. It had been concluded that the fragment had a hyperon, most likely a Λ particle, bound to it. The Λ particle is the lightest strange baryon (hyperon) with a mass $M_{\Lambda} = 1115$ MeV; it is neutral and has spin $J^{\pi} = \frac{1}{2}^{+}$ and isospin $I = 0$. The strangeness of the Λ particle is $S = -1$. Because the strangeness is conserved in strong interaction and the Λ particle is the lightest hyperon, the latter is stable against strong decay also in nuclear matter. This is not the case for the heavier stable hyperons Σ , Ξ , and Ω , which in the presence of nuclear matter convert into Λ particles. Examples of some reactions for conversion of Σ , Ξ , and Ω in nuclear matter, all conserving strangeness, are

$$\Sigma + N \rightarrow \Lambda + N \quad (1)$$

and

$$\Xi + N \rightarrow 2\Lambda \quad (2)$$

and

$$\Omega + N \rightarrow \Xi + \Lambda \quad (3)$$

We shall therefore use the term "hypernuclei" when referring to systems with nucleons and Λ particles. In special cases, where one could expect to have heavier hyperons bound to the nucleus for long enough to enable the identification of such a system, we shall designate the latter as Σ or Ξ hypernuclei.

Hypernuclei are composed of three constituents, neutrons, protons, and Λ particles, and in this sense they represent the most general stable nuclear matter of presently known baryons. If more stable baryons with new quantum numbers conserved in strong interaction should be discovered, the foregoing statement will have to be revised. There are indications that an additional baryon family with a new quantum number, usually called "charm", may exist. If this is the case, not only hypernuclei, but also charm nuclei and their crossing charmed hypernuclei should be stable.

Hypernuclei decay via weak interaction with a lifetime of about 10^{-10} sec. This lifetime is long enough to allow the study of hypernuclear properties on bound and continuum states to quite the same extent as for short-lived β -unstable nuclei.

For almost 20 years experimental work on hypernuclei was nearly exclusively performed by means of emulsion technique and only in a few cases were bubble

chambers used (Pniewski 1972). The most efficient way to produce hypernuclei is to expose the target to either low-momentum or stopped negative kaons. In the reactions

$$K^- + N \rightarrow \Lambda + \pi$$

and

$$K^- + N \rightarrow \Sigma + \pi$$

(4)

which transfer the strangeness to a nucleon, only a small fraction (10^{-3} - 10^{-4}) of the K^- interaction with the nucleus leads to the formation of a hypernucleus. Nevertheless, the hypernucleus can be clearly identified through the characteristic decay fragmentation of its nucleus, with in some cases π emission. Our knowledge of the binding energies of the Λ particle in hypernuclear ground states is derived from the kinematical analysis of the decay products of hypernuclei and is summarized in Section 2.

In the late sixties, intensive K^- beams of sufficient intensity were constructed, whereby counter experiments on hypernuclei were made possible. Not only bound states, but also hypernuclear continuum states have become accessible to experiments.

For quite a long time hope has been entertained that the Λ particle could be used experimentally to investigate the nuclear structure. The nucleus is one of the best understood many-body systems of identical particles with strong interaction. A theoretical handling of such systems was successful, provided that one could find an equivalent system of independent particles with "weak" interaction. In such a model single-particle excitations and collective excitations reproduce well the behaviour of the system close to the Fermi surface. If the Λ particle can be implanted in the nucleus in such a way that it replaces the neutron, additional information can be expected from this experiment thanks to the fact that the Λ particle behaves like a "marked" neutron.

Of particular interest for this kind of question are the continuum states, whose configuration is closely related to that of the target nucleus. The unique possibility of producing selected configurations by means of "recoilless" Λ production is of great help in the investigation of these states. Experimental methods and results of measurements with recoilless Λ production will be described in Sections 3 and 4. In Section 5 we shall give a preliminary interpretation of the significant results relevant to the nuclear structure problems.

As far as light hypernuclei are concerned, the gamma spectroscopy has turned out to be quite a useful tool to investigate low-lying bound states. In particular, ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ are of great interest in hypernuclear physics. These two mirror hypernuclei play a role in hypernuclear physics comparable to that of the two-body system in nuclear physics.

2. HYPERNUCLEAR GROUND STATES

2.1 Binding energy of Λ hypernuclei

The Λ particles decay via weak interaction $\Lambda \rightarrow N + \pi$ and have a lifetime of 2.6×10^{-10} sec. The presence of nuclear matter renders an additional weak decay channel $\Lambda + N \rightarrow 2N$ possible with an energy release of about 180 MeV. This mode of decay prevails in hypernuclei. Experience shows that only decays with charged mesons, and all fragments producing visible tracks, come into question to measure hypernuclear binding energies. These conditions can be realized only in light hypernuclei; hence, the binding energies of hypernuclei with $A < 16$ could be determined by using this method.

In figure 1 (Powell et al 1959) a beautiful event of hypernuclear production and decay is shown: all sequences of the reaction can be individually identified in it. A K^- hits a ^{16}O nucleus, thereby transforming a neutron into Λ . A highly excited system disintegrates into $^7_\Lambda\text{Li}$, two alphas, and a proton. In the notation $^A_Z\Lambda$ for hypernuclei, Z gives the atomic species (the total nuclear charge Z) in the usual chemical notation and A is the total number of baryons. The subscript Λ indicates that the strangeness quantum number is $S = -1$. The decay $^7_\Lambda\text{Li}$ is easily recognizable and can be fully kinematically analysed by means of energy and momentum conservation. From known masses of particles M_i and their kinetic energy T_i , the mass of the hypernucleus

$$M_{\text{HY}} = \sum_i (M_i + T_i) \quad (5)$$

can be determined. In most cases, the hypernucleus decays from the ground state, because the electromagnetic transition is generally faster than the weak decay of the Λ particle.

The binding energy of Λ in the ground state is defined by

$$B_\Lambda(\text{g.s.}) = (M_{\text{core}} + M_\Lambda - M_{\text{HY}}) . \quad (6)$$

The mass M_{core} is merely the mass of the nucleus in the ground-state left over after removing the Λ particle. The known B_Λ collected by the European K^- Collaboration and by the Enrico Fermi Institute for Nuclear Studies are displayed in figure 2 and have been taken from Pniewski (1972).

It is very unlikely that the $B_\Lambda(\text{g.s.})$ of hypernuclei with $A > 16$ can be determined by the analysis of their decay, because one cannot identify the decay of a heavy hypernucleus uniquely. The lack of knowledge of the ground-state binding energy in heavy hypernuclei is very embarrassing. This energy is one of the most important pieces of information of the Λ -nucleus interaction, as well as the most natural reference according to which the energy of excited states

should be measured. In many heavy hypernuclei excited states have been observed, although their excitation with respect to the ground state can only be guessed.

The $B_{\Lambda}(\text{g.s.})$ in heavy hypernuclei can be calculated by assuming that the Λ particle feels a potential well of radius R approximately equal to that of the nuclear core and a depth V independent of the hypernuclear mass. In the ground-state, the Λ is always in the $1s$ state and therefore its binding energy increases with A . The kinetic energy E_{kin} of the $1s$ state for $A \gg 1$ and $R = 1.2A^{1/3}$ fm, using a square well potential, is approximately

$$E_{\text{kin}} = [V - B_{\Lambda}(\text{g.s.})] \frac{\pi^2 \hbar^2}{2MR^2} = 118A^{-2/3} \text{ MeV} . \quad (7)$$

In figure 3 (Bodmer 1973, Rote and Bodmer 1970) $B_{\Lambda}(\text{g.s.})$ are plotted in dependence on $A^{-2/3}$. We see that the expression (7) can be matched by the extrapolation from light nuclei and suggests a typical value of about 25 MeV for $B_{\Lambda}(\text{g.s.})$ in heavy hypernuclei and that the depth of the potential well is about 30 MeV.

These data will be constantly mentioned in the subsequent sections, and different models will be discussed on the basis of extrapolated $B_{\Lambda}(\text{g.s.})$. Even though the assumptions made in regard to the above calculation seem to be very general, we have to bear in mind that experiments may possibly give us surprises, and a good deal of our present conception will have to be altered.

From the ground-state spins (Dalitz 1964) of light hypernuclei, one also knows that the ΛN interaction in the singlet state is stronger than in the triplet one, contrary to the NN interaction.

These rather scarce data on hypernuclear ground states have been the main source of information as far as the ΛN interaction at low energies is concerned. The NN interaction has been extensively studied in scattering experiments with polarized particles. Qualitatively, the NN interaction can be understood and one can explain the low-energy behaviour in terms of one-meson exchange. The ΛN interaction should greatly differ, as the quantum numbers of Λ select different mesons to be exchanged in the interaction. An accurate notion of ΛN interaction would contribute to our knowledge of how the baryon-baryon interaction depends on the coupling of mesons to baryons. The analysis of the ΛN interaction from the $B_{\Lambda}(\text{g.s.})$ is rather tedious. One must find simultaneously the best elementary ΛN interaction and the best model to describe the hypernucleus. This analysis has been made by Dalitz and co-workers. In recent papers (Gal et al 1971, 1972, and Gal 1975), theoretical treatment of hypernuclei and deduced ΛN interaction is reviewed. In the last sections of the present article we shall discuss some aspects of the ΛN interaction, and especially its spin dependence and the charge-symmetry violation.

2.2 Lifetimes

The decay probability of the bound $\Lambda \rightarrow N + \pi$ rapidly decreases with the increasing binding energy of Λ in the nucleus. In the pionic decay of Λ only a 34 MeV energy is available, which is comparable to the binding energy of Λ in heavy hypernuclei. The phase space available for the pion emission decreases so fast that already hypernuclei with $Z \geq 2$ decay predominantly via the $\Lambda + N + 2N$ channel. The weak interaction being responsible for this decay, the rate mainly depends on the probability of finding Λ and N at relatively small distances. The short-range behaviour of the particles in the nucleus is not thoroughly understood. Nevertheless, the lifetimes of heavy hypernuclei should be A -independent, and they can be estimated (Dalitz 1964) to be of about 2×10^{-10} sec, i.e. the same as for free Λ particles.

At present, there is no suitable method to measure hypernuclear lifetimes, and only in few cases have they been experimentally determined (Fortney 1964, Murphy et al 1969), however with very low accuracy. But, in the near future, new possibilities can arise thanks to high-energy accelerators for heavy ions. Heavy ions traversing the target could transform nucleons into Λ . In this way we could obtain hypernuclei moving at relativistic velocities. By measuring the decay of relativistically moving hypernuclei along a macroscopic distance of a few centimetres, we can accurately determine their lifetime in the 10^{-10} sec region.

2.3 Σ , Ξ , Ω , and $\Lambda\Lambda$ hypernuclei

Σ particles are not stable in nuclear matter and react strongly via the



reaction, thereby conserving the strangeness. The Q value of this decay is 80 MeV. The question arises whether Σ hypernuclei live long enough to be likely to be experimentally observed. The first approach to find out the decay width of the Σ hypernucleus would be to compare nucleon states of comparable excitation. The only experimental evidence we have is collected from the systematic study of the $(p, 2p)$ reactions (Jacob and Maris 1973), where the excitation of 60 MeV in nuclei has been observed to have reasonable width. The chance of observing Σ hypernuclei is therefore not so bad if the Σ particles are at least as strongly bound to the nucleus as the Λ particles, which would correspond to an excitation of 60 MeV. However, the production of Σ in strongly bound states represents a more serious problem quite identical with that of producing ground states of Λ hypernuclei; we shall discuss it briefly when reviewing the strangeness exchange reactions.

The Ξ particles interact in nuclear matter via $\Xi + N \rightarrow 2\Lambda$ with a Q value of 30 MeV and the Ξ hypernuclei should live long enough to be observable. The low Q value for the decay into two Λ is responsible for a relatively large probability of forming a double hypernucleus as a decay product of the Ξ hypernucleus. So far, ${}_{\Lambda\Lambda}^6\text{He}$ (Prowse 1966) and ${}_{\Lambda\Lambda}^{10}\text{Be}$ (Danysz et al 1963) have been identified in emulsions through their decay.

The Ω^- particle interacts with nucleons via $\Omega^- + N \rightarrow \Lambda + \Xi$ with a Q value of 175 MeV. It seems rather unlikely that the width of the state at this high excitation can be narrow enough to be distinguishable from the background.

3. STRANGENESS EXCHANGE REACTIONS

For the determination of B_Λ in the ground states it is not of great importance to know how the hypernucleus has been formed. In high-energy interaction processes a Λ has been produced and it may get bound to the fragment of the nucleus. The hypernucleus has been identified through its decay; in favourable conditions, where all decay products could have been kinematically analysed, the energy of the ground state could have been determined. In counter experiments, however, the production of hypernuclei can more easily be investigated than their decay (Povh 1975). Therefore, it is of great importance to understand the reaction mechanism in which hypernuclei are produced. Of the many possible reactions in which a Λ can be produced only a few are of some interest, i.e. when the Λ particle gets small recoil momentum. The possibility of forming a hypernucleus is substantial only if the recoil momentum is comparable to the Fermi momentum of nucleons in the nucleus. Obviously, the hypernuclear spectroscopy is possible only if one can determine the energy and the momentum of the Λ recoil. Some examples of such reactions are as follows:

i) For the production of Λ hypernuclei:

$$K^- + {}^A_Z \rightarrow \pi^- + {}^A_\Lambda Z, \quad (8)$$

$$K^- + {}^A_Z \rightarrow \pi^0 + {}^A_\Lambda (Z-1). \quad (9)$$

ii) For the production of Σ hypernuclei:

$$K^- + {}^A_Z \rightarrow \pi^- + {}^A_{\Sigma^0} Z, \quad (10)$$

$$K^- + {}^A_Z \rightarrow \pi^0 + {}^A_{\Sigma^-} (Z-1), \quad (11)$$

$$K^- + {}^A_Z \rightarrow \pi^+ + {}^A_{\Sigma^-} (Z-2). \quad (12)$$

iii) And for the production of Ξ hypernuclei:

$$K^- + {}^A_Z \rightarrow K^0 + \Xi^-(Z-1) , \quad (13)$$

$$K^- + {}^A_Z \rightarrow K^+ + \Xi^0(Z-2) . \quad (14)$$

The advantage of the reactions quoted lies in their simplicity. The spectroscopy of the outgoing pion or kaon gives complete information on the hypernuclear system.

More complex, but still useful, are also:

$$K^- + {}^A_Z \rightarrow \pi^+ + \pi^- + \Lambda(Z-1) \quad (15)$$

and the associate production on nuclei:

$$p + {}^A_Z \rightarrow K^+ + p + \Lambda(Z-1) . \quad (16)$$

In the last two reactions, momenta of the two particles have to be measured in order to determine the energy of the hypernucleus.

3.1 Recoilless Λ production

The reaction (8) plays a central role (Podgoretski 1963, Feshbach and Kerman 1966) in hypernuclear physics. Let us first consider the reaction $K^- + n \rightarrow \pi^- + \Lambda$ on a free neutron. For pions emitted at 0° , the recoil momentum -- in this particular case a longitudinal momentum only -- of the Λ particle depends on the K^- momentum as shown in table 1. For K^- momenta between 300 and 1000 MeV/c the recoil of the Λ is less than 100 MeV/c under these special kinematical conditions (figure 4). The Fermi momentum of the nucleons in the nucleus is of the order of 250 MeV/c. When reporting on the kinematic conditions in which the Λ recoil is much smaller than the Fermi momentum -- which is the case for K^- momenta in the region of 300-1000 MeV/c -- we shall refer to "recoilless" production in order to emphasize that changing the neutron into Λ predominantly populated will be those states having a large overlap with the ground-state of the nucleus. For K^- momenta higher than 500 MeV/c and with small angles in relation to the K^- beam, the transverse recoil momentum of the Λ is

$$q_T \approx 2p \sin \frac{\alpha}{2} , \quad (17)$$

where α is the angle between π^- and K^- and $p \approx p_K \approx p_\pi$. In the forward direction the kinematics of the (K^-, π^-) reaction resembles strongly the kinematics of the elastic scattering. The analogy with the scattering of the strangeness exchange reaction for K^- momenta between 500 and 900 MeV/c is especially transparent if one considers that in the recoilless production a Λ particle replaces a neutron

in the nucleus, without otherwise changing its wave function. In the elastic scattering, the target remains in its ground state; in the Λ recoilless production, one populates the hypernuclear states with the same configuration as that of the target nucleus, but with the neutron replaced by the Λ . The possibility of comparing nuclear with hypernuclear states of identical configuration makes the Λ particle an interesting probe to investigate nuclear structure. The Λ particle is distinguishable from the nucleons and can therefore be used to "mark" neutrons in the nucleus. This particular aspect at present takes the limelight in hypernuclear research and constitutes the main topic of this article.

The states populated by recoilless Λ production are highly excited and are embedded in continuum. This is easy to understand qualitatively. By changing a neutron into a Λ a neutron hole is created. The Λ particle is produced in the state with the spin and orbit quantum numbers of the neutron. In general, this is not the 1s state corresponding to the hypernuclear ground state. The excitation energy of the states is therefore the sum of the neutron hole excitation and of the Λ particle excitation.

Indeed, one of the most important questions is whether the recoilless Λ production can be detected free from the background or not. The reaction (8) produces π^- with the highest momentum at 0° and is not contaminated by pions undergoing more than one interaction. If K^- or π^- are rescattered, they will reduce their momentum and scatter out at 0° direction. In the 0° direction will be rescattered those particles having already started with a non-zero angle and therefore with a lower momentum. Using these qualitative arguments we cannot say where the background starts, as this question can be settled only by experiment. Present experimental results indicate that at least the most energetic pions in an interval of 50 MeV/c come only from one-step reactions.

The cross-section for the recoilless Λ production can be rather accurately estimated from the known cross-section for the free neutron (Armenteros et al 1970), the latter being of the order of 2.3 mb/sr for 0° in the laboratory system.

To obtain the cross-section for the nuclei one has to take into account the absorption of K^- and π^- in the nucleus. As the total cross-sections for K^- and π^- at momenta above 500 MeV/c are of about 30 mb, the absorption is so strong that only a small portion of a thin nuclear surface contributes to the one-step strangeness exchange reaction at 0° . The effective neutron number is less than one and is almost independent of the nucleus.

Differential cross-section for pions from the recoilless Λ production should also have the same angular dependence as the elastic scattering and should fall off with the form factor of the nucleus.

"Inelastic processes" are those in which the strangeness exchange is followed by the jump of the Λ into a new orbit. The probability of changing orbit becomes appreciable when the recoil is of the order of the Fermi momentum, i.e. about 250 MeV/c. As for the momentum transfer of 250 MeV/c, it is very likely that the cross-sections for the "elastic" and the most prominent "inelastic" processes are about equal, but at least of an order of magnitude smaller than for the recoilless Λ production at 0° .

3.2 Associated production

The associated production (16) has also been considered for the investigation of hypernuclei. In this reaction, however, the momentum transfer to the Λ particle cannot be minimized further than to 600 MeV/c (figure 5), which is more than twice the Fermi momentum. There will be no strong selectivity in the production of hypernuclear states. This may turn out to be of some advantage if one looks at the general properties of hypernuclei, and especially at the bound and ground states. The cross-section for hypernuclear production in associate production is many orders of magnitude smaller than in the reaction (8). Nevertheless, the primary proton beams of accelerators are intense enough to compensate for the smallness of the cross-section. An experiment aiming to study hypernuclei by the reaction (16), via protons of 3 GeV, is in progress at Saclay. Both protons and K^+ are being detected by a spectrometer and their momentum is analysed with a resolution of a few hundred keV, this being sufficient to separate low-lying bound states in hypernuclei.

The reactions (8) and (16) are complementary. The associated production is not selective and should be suitable to observe general features of the hypernuclei, and particularly of ground and low excited states. The main advantage of the recoilless Λ production is its high selectivity to populate hypernuclear states with the same configurations as for the ground state of the target nucleus. For this reason, this state should be the simplest hypernuclear state to be dealt with theoretically.

At present, it is not very likely that any other reaction than (8) and (16) can be used in hypernuclear spectroscopy and therefore we shall not discuss them here.

3.3 Production of Σ and Ξ hypernuclei

The Σ and Ξ hypernuclei have not yet been observed experimentally but, as we have already pointed out, there is a good chance for their living long enough to be observed in spite of their strong decay. The production of Σ hypernuclei

seems straightforward, using reactions (10) and (12). The kinematics of these reactions is similar to that of reaction (8); this means that reactions (10) and (12) can be used for recoilless Σ production. But the states populated in recoilless Σ production have an excitation of 20-40 MeV in the Σ hypernucleus. Adding to this excitation $Q = 80$ MeV, for $\Sigma \rightarrow \Lambda$ decay in the nucleus, the Σ recoilless production leads to states which can decay releasing 100 MeV. The width of these states may already be too large to be seen. To observe the Σ hypernuclei it may be more advantageous to produce them in their ground state. As has already been shown (Faessler et al 1973), for Λ particles at a momentum transfer of 250 MeV/c the production of hypernuclear ground states is appreciable. This condition is easily fulfilled using stopped K^- or (K^-, π^-) reactions in flight, the reaction angle [equation (17)] being properly adjusted.

The Ξ hypernuclei may be more stable than the Σ hypernuclei ($\Xi + N \rightarrow 2\Lambda$, $Q = 30$ MeV), but are not easy to produce. The threshold of 1.1 GeV/c for reactions (13) and (14) is still acceptable for spectroscopy with reasonable resolution. But the cross-section, especially for reaction (14), is an order of magnitude smaller than for reactions (8) and (12). Even more critical is the large momentum transfer of at least 400 MeV/c on Ξ in reactions (13) and (14). The probability of forming the hypernucleus when the particle recoil is twice the Fermi momentum is drastically reduced.

4. SPECTROSCOPY WITH THE (K^-, π^-) REACTION

Experimental methods used in hypernuclear physics have been developed in the last few years in parallel with a similar development in intermediate energy physics. In both cases, experiments are being performed on high-energy accelerators with protons of rather large spread in momentum or, to much greater extent, with secondary beams of pions and kaons. To obtain a reasonable intensity, secondary beams should have large momentum bite and emittance.

A direct use of such beams in hypernuclear spectroscopy would give no answer to the relevant problems of hypernuclear physics. The energy resolution of the experiments should suffice to separate at least the most prominent excitations in the hypernucleus. As for the strangeness exchange reaction (8), where one does not expect many states to be populated, a resolution of about 1 MeV should be good enough, and magnetic spectrometers of rather modest resolution can be used for the momentum analysis of the beam and the reaction products.

A measurement of the momenta of K^- and π^- alone does not suffice to select the reaction events from the background (Bonazzola et al 1975). The most annoying background comes from the $K^- \rightarrow \pi^- + \pi^0$ decay. These pions overlap partially in

energy with those from the (K^- , π^-) reaction. To distinguish between the two possibilities, the kinematics of the (K^- , π^-) events has to be completely determined (Brückner et al 1975).

4.1 Low-momentum K^- beams

In the late sixties, the first low-momentum (< 1 GeV/c) K^- beams were constructed in such a way as to fulfil the minimum requirements for their use in counter experiments. At present, the best K^- beams operate at CERN using the 25 GeV Proton Synchrotron and at Brookhaven National Laboratory using the 30 GeV AGS proton accelerator (Palevsky 1973). The production of K^- by 25 GeV proton energy is about a factor of 100 smaller than the production of pions at small production angles, which is of interest because of the forward peaking of the particle production. The K/π ratio, however, drops fast with the growing distance from the production target for low-momentum beams. The lifetime 1.23×10^{-8} sec of the K^- is a factor of two shorter than the lifetime of the π^- . In addition, for momenta below 1 GeV/c, the velocities of pions and kaons of the same momentum differ enough to make an appreciable difference in the time dilatation for the two mesons. The beams have to be as short as possible and the pions have to be reduced in number by using particle separation.

Typical data of a K^- beam for 900 MeV/c in operation at CERN are given in table 2.

The typical size of the focus is ~ 2 cm², whereas the average emittance is 5 msr. The momentum spread $\Delta p/p = \pm 1.2\%$ carries an energy spread of 20 MeV for 900 MeV/c kaons. It is obvious that a momentum analysis of the beam is necessary if some reasonable resolution in the experiment is to be attained. Such an analysis is technically very simple if momenta of kaons are measured individually. Therefore the kaons have to be scanned at the entrance as well as at the exit of the spectrometer, most likely by some version of the multiwire proportional counters. For the present, beams of 10^4 K^- per sec and cm² are accompanied by 10^6 pions, which is just about the limit of the counting rates that the multiwire chamber would digest.

It is obvious that any increase in the kaon intensity has to be accompanied by a corresponding improvement in the K^-/π^- ratio so as to keep the total flux below the 10^6 particles per sec and cm² limit, or, if this is not the case, one has to abandon the individual determination of the kaon momentum. This second possibility, however, requires that the optics of the beam has low aberration starting from the production target. We shall discuss it shortly later on, as it might be of some interest for future experiments.

4.2 Energy loss spectrometer

In the spectroscopy with particles below 1 GeV/c, it is of great importance to use a spectrometer with focusing properties. Multiple scattering in the multi-wire chambers, which is inversely proportional to the particle momentum, is the most serious limiting factor in the accuracy of the trajectory determination for particles below 1 GeV/c. The influence of the multiple scattering can be effectively reduced if position-sensitive counters are positioned only in the focal planes of the spectrometer, because in the lowest order the focusing properties of the spectrometer do not depend on the particle angle in the focal planes.

The kinematics of the (K^-, π^-) reaction in the region of the Λ recoilless production resembles elastic scattering. The K^- and π^- momenta differ by less than 10%. Under the existing conditions, an analysing system -- historically called energy loss spectrometer -- is preferentially used in experiments. In this type of spectrometer, one measures directly the difference between the momenta of the incoming and outgoing particles rather than their absolute values. A small difference between two large quantities would lead to a considerable error in the determination of the energy difference. The basic idea of the energy loss spectrometer, more properly momentum loss spectrometer, is demonstrated in figure 6, by means of optical symbols for focusing as well as for dispersive elements. In the magnetic analogy the prism is replaced by a magnet having a homogeneous magnetic field. In magnetic optics the focusing lens is realized by two or three singlet quadrupole lenses. From figure 6 it is easy to gather that the particles emerging from x_1 will be refocused in x_2 , independently of their momentum. The momentum bite accepted by the spectrometer is given by the dispersion and geometrical size of the spectrometer. To verify the above statement, one just has to follow the rays emitted by x_1 and x_2 for particles of the same momentum. They meet at the same x_0 in the intermediate focal plane of the spectrometer. If the target is placed in the focal plane, the above example corresponds to the elastic-scattering events. If the particles scatter inelastically on the same level, they all lose the same amount of energy ΔE , so that $E_2 = E_1 - \Delta E$. For $\Delta E \ll E$, it is evident that

$$\Delta E = \beta(\delta p_1 - \delta p_2) , \quad (18)$$

where $\beta = p/E$ and δp is the momentum deviation from the central momentum. It is easy to verify that all particles having lost the same energy will be refocused in the same x_2 as

$$x_1 - x_2 = D(\delta p_1 - \delta p_2) = D \Delta E / \beta , \quad (19)$$

where D is the dispersion of the two halves of the spectrometer.

These simple relations are no longer true for the reaction products. Because of the difference between the mass of the incoming and outgoing particles, the energy loss approximation is good only if the condition

$$\left(\beta_1 p_1 - \beta_2 p_2 \frac{D_1}{D_2} \right) \frac{\Delta p_1}{p_1} < \Gamma \quad (20)$$

is fulfilled within the accepted momentum bite $\Delta p/p$. Here Γ is the energy resolution aimed at in the experiment and D_1 and D_2 are the dispersions of the first and second half of the spectrometer, respectively. For the (K^-, π^-) reaction at K^- momentum of 900 MeV/c this condition is well fulfilled. For a typical momentum bite $\Delta p/p = \pm 1\%$ and for a symmetrical spectrometer, $\Gamma < 100$ keV.

This particular property of the (K^-, π^-) kinematics has not yet been experimentally exploited, as it is very easy to determine the coordinates in focal planes using multiwire proportional counters and applying numerically the correction in the resolution. It may, however, turn out to be of great importance for future experiments if beams of much higher intensities than the present ones become available and if it is not possible to measure the position of the beam particles by counters.

4.3 Experiments with K^- in flight

The CERN spectrometer used in a strangeness exchange reaction on nuclei is shown in figure 7 (Brückner et al 1975, 1976). It has only been used to measure the (K^-, π^-) reaction at 0° . More general experiments aiming also at the investigation of angular dependence of this reaction are currently in progress at Brookhaven National Laboratory (Palevsky et al 1974) and at CERN (Bertini et al 1976). This spectrometer has been built by means of standard beam transport elements and allows the energy loss to be determined to better than 1 MeV. This accuracy cannot be obtained by focusing the spectrometer itself, the latter being corrected to first order only, but it can be achieved by applying the necessary higher order corrections during the evaluation. For this purpose, not only the space coordinate in all focal planes, but also the corresponding angles in the first and last planes have been measured using twenty planes of multiwire proportional drift chambers. These chambers allow the particle coordinate to be determined to an accuracy of 0.4 mm FWHM.

The (K^-, π^-) reaction has been identified by measuring the time of flight between the entrance and the exit of the spectrometer with two plastic scintillators. The time of flight is 68 nsec for K^- and 60 nsec for π^- . Therefore 64 nsec is expected to be the time of flight for the (K^-, π^-) reaction.

In order to suppress the background coming from the $K^- \rightarrow \pi^- + \pi^0$ decay -- which is kinematically very close to the reaction events -- two additional conditions for selecting the proper events were indispensable: i) the particle

trajectories calculated from the coordinates on both ends of the spectrometer have to meet within a few millimetres inside the target; ii) a liquid hydrogen Čerenkov counter was placed behind the target, thereby discriminating between K^- and π^- . In this way, K^- decaying into 2π after passing the target have been vetoed out. The spectra measured so far are illustrated in figure 8. The scale is given in the binding energy of the particle in the hypernucleus. The zero of the scale indicates the threshold of the Λ and the nucleus core in the ground state. The use of this scale in the present stage of development is reasonable, because it merely depends on the known masses of the particles involved in the reaction. Different representations of the data, particularly in terms of excitation energies, are likely to be convenient for the interpretation of the results. Nevertheless, we do not use them here, as the ground states of the hypernuclei investigated are not known experimentally.

4.4 Experiments with stopped K^-

At first sight, experiments with stopped K^- seem to be of great usefulness. Technically they are much simpler, as they do not need any spectrometer for K^- if one makes sure that K^- have really been stopped prior to the reaction.

The momentum transfer of 250 MeV/c (table 1) is still small enough to ensure that only states closely related to the target nucleus configuration be populated. The only difference with the experiment in flight is that $\Delta\ell = 0$ and $\Delta\ell = 1$ transitions are of comparable strength. The states reached in the stopped K^- experiments are still strongly selected. A neutron changing into Λ either stays in the same orbit or changes orbit for $\Delta\ell = 1$ without changing the nuclear part of the wave function.

There are essentially experimental reasons that render measurements with stopped K^- less suitable for spectroscopy than experiments in flight.

The set-up for an experiment with stopped K^- performed by a CERN-Heidelberg-Warsaw Collaboration (Faessler et al 1973) is displayed in figure 9. The momentum of π^- emitted at $90^\circ \pm 30^\circ$ with respect to the incoming beam is determined by a magnetic spectrometer. The resolution of the spectrometer is about 5 MeV. The multiple scattering of pions in the chambers does not allow an accurate determination of the trajectories, which would lead to a better energy resolution. An additional restriction on the resolution is the straggling of pions in the target; the latter must be sufficiently thick to guarantee a reasonable yield.

The spectrum of π^- measured with 8×10^8 K^- stopped in a carbon target is shown in figure 10. At 273 ± 1 MeV/c and 261 ± 1 MeV/c two peaks with production rates of $(2 \pm 1) \times 10^{-4}$ and $(3 \pm 1) \times 10^{-4}$ per stopped K^- have been observed.

From the masses of ^{12}C , ^{11}C and Λ , one knows that a pion momentum of 261 MeV/c corresponds to the Λ binding energy $B_\Lambda = 0$. In a remarkable experiment (Jurić et al 1972) with nuclear emulsions this state has also been observed and turned out to have a width of less than 1 MeV. The observation of such a narrow state in continuum considerably stimulated the research of hypernuclear states in continuum. The peak at 273 MeV/c corresponds to a binding energy $B_\Lambda = 11 \pm 1$ MeV in $^{12}_\Lambda\text{C}$ and belongs to the hypernuclear ground-state configuration. The ground-state of the mirror hypernucleus $^{12}_\Lambda\text{B}$ is known to be $B_\Lambda(\text{g.s.}) = 11.37 \pm 0.06$ MeV.

Let us consider the experimental problems inherent in this measurement. The $K^- + A \rightarrow \pi^- + \Lambda + (A-1)$ is the strangeness exchange reaction with the highest Q value. Therefore, one would expect to have no background for momenta above 261 MeV/c which correspond to $B_\Lambda > 0$. In general, there are two reasons for which the background in this region is comparable to the yield of hypernuclear states. K^- entering the target have an energy of 40 MeV and 30% of them decay before they completely stop. With angles up to 120° the decay in flight generates pions with momenta above 261 MeV/c. In the experiment described, six scintillator counters, each of 1 cm thickness, were used as targets. By recording the energy loss of the K^- in each target slice, it was possible to discriminate between the interaction with K at rest and those decaying in flight. Measurements with other targets have been attempted, but without any success, owing to the background caused by the decay in flight.

The second source of background results from the decay $\Sigma^- \rightarrow \pi^- + n$. The Σ^- are produced by absorption of K^- in the nucleus. The Σ^- recoil can be very large, in particular if produced in two nucleon reactions $K^- + pn \rightarrow \Sigma^- + p$ (Pietrzyk 1976), so that the pion coming from its decay may have momenta much higher than 260 MeV/c.

One could think of improved experiments with stopped K^- . The most noteworthy one would be the measurement with a large solid-angle spectrometer at 180° with respect to the K^- beam. In this case all difficulties coming from the K^- decay in flight would be avoided.

The background conditioned by the Σ^- decay remains. It should be tested experimentally whether hypernuclear states will equally show up against this background in heavy nuclei. This risk is largely responsible for the existing reluctance to plan experiments with stopped K^- .

5. CONTINUUM STATES

As has already been pointed out, the recoilless Λ production on nuclei leads to continuum states in the hypernuclei. The excitation of these states is the sum of the Λ excitation and the energy of the neutron hole left over by changing the

neutron into Λ . Possible properties of these states were first discussed long before experimental techniques to investigate these states were developed (Lipkin 1965, Feshbach and Kerman 1965). It had been suggested that the $n \rightarrow \Lambda$ transformation may take the same energy independently of the particular shell the neutron occupies in the nucleus. The strangeness exchange reaction in the Λ recoilless production would then lead to a single state, i.e. to the strangeness analogue state. In this approximation, the strangeness exchange reaction would be as collective as the elastic scattering we already considered as being analogue to the strangeness exchange reactions. More recently, some arguments have been advanced to show that the strangeness exchange reaction would rather lead to well-separated particle-hole states in the hypernuclei (Hüfner et al 1974, Auerbach and Gal 1974). Different energies are needed to transform the neutron into Λ in different shells. The source of this difference is twofold. The spacing of the Λ shells corresponds to that of a single particle moving in the potential of the nucleus; the spacing between the neutron shells results from complicated Hartree-Fock mutual interaction, and is in general different from the Λ spacing. In addition, the two potentials for Λ 's and neutrons have different depths conditioned by different two-body interactions of NN and NA (figure 11).

Both pictures correspond to the well-known extreme types of nuclear excitations, of the collective and the single-particle type. The strangeness analogue state uses the collective description of the state, whereas the single particle-hole excitation -- hereinafter called strangeness exchange resonance -- starts with the single-particle picture. In general, one expects an intermediate situation with at least partial mixing of single-particle states. It is advantageous to use both pictures for the description of the state, as in this way different insights into the problem come to light. This situation is very familiar in nuclear physics. For example, our present understanding of the electric dipole giant resonance could not be as profound if both collective and single-particle descriptions had not been used. Before we start with their interpretation, the possible sources of background, as well as the absorption in the (K^-, π^-) reaction, should be mentioned.

5.1 Distortion in the (K^-, π^-) reactions

An interpretation of the (K^-, π^-) experiments makes sense only if we are sure that the reaction took place on a single nucleon without any additional interaction of either incoming K^- or outgoing π^- . The kinematical conditions used in the recoilless Λ production are such that they warrant clean spectra at the highest π^- momentum observed. Any additional interaction would degrade the energy of pions and scatter them out at 0° direction. The question is, however, how large the momentum bite is when only the contribution of a single interaction of the

strangeness exchange reaction is expected. This question can be answered by experiment only. In default of experimental evidence, we shall give some arguments supporting the assumption that the observed spectra at 0° in figure 8 represent only single-interaction processes.

Let us first consider the cross-sections of the reactions. In table 3 the cross-sections are given separately for narrow peaks and broad bumps. In addition, the integrated cross-section is also shown. This cross-section should be compared to the elementary cross-section for the (K^-, π^-) reaction on a neutron, which is 2.3 mb/sr at 900 MeV/c for 0° . One sees that only a fraction of this cross-section is observed if measured on nuclei. The effective neutron number for recoilless Λ production in nuclei is about 0.5 (table 3). This low number is by no means surprising (Deloff 1973, Hüfner et al 1974). The mean free path of the K^- and π^- in the nucleus is about 1 fm. Only the very narrow ring of the nuclear surface (see figure 12) contributes to the 0° single-step reaction. Very simple geometrical considerations show that the volume of the ring is independent of the radius of the sphere, if one keeps constant the mean free path of the particles. Therefore, all the cross-sections for one-step reactions on nuclei should be identical. Within experimental errors, the cross-sections for narrow peaks as well as broad bumps are target-independent and consistent with the assumption of the single-step process. As the momentum bite in which the hypernuclear excitations are observed is rather large, one should try to understand why the (K^-, π^-) reaction is so clean, at least when measured in the forward direction. The most dangerous contamination is expected to come from events where K^- and π^- scatter in the nucleus losing a few MeV of energy. The inelastic scattering means that the nucleus gets excited. In this process, the quantum numbers of the nuclear state change and for 0° inelastic scattering is therefore strictly forbidden. Therefore, the background can arise only from multiscattering events degrading the energy in each scattering and is also energetically separated from the "elastic" events. The one-step process in the (K^-, π^-) reaction is selected by the requirement that K^- and π^- be collinear. Collinearity selects a very small part of phase space in which the one-step reaction dominates.

The measurement of even larger momentum bites in the (K^-, π^-) reaction, as well as the angular dependence of the cross-section, can eventually give an answer as to how clean the (K^-, π^-) reaction at 0° is. We have to keep in mind that the interpretation of the spectra strongly depends on the assumption that we deal with a single-step reaction only.

5.2 The (p, 2p) reaction

The (p, 2p) reaction is in many ways interesting in comparison with the strangeness exchange reactions. When a neutron has been changed into a Λ particle, without altering its wave function, the state originally occupied by the neutron is vacant and a neutron hole appears. It is important to understand the hole state, as it is the essential component of the particle-hole state produced in the recoilless Λ production. We shall consider proton holes and assume that the overall behaviour of the neutron and proton holes is identical, except for the shell effects in individual elements. Equivalent information on the hole states can be obtained by the (e, e'p) and pick-up reactions on nuclei. But the (p, 2p) reaction is very illustrative as compared with the strangeness exchange reactions, because of their similar time scale and distortion problems. We shall discuss only this particular source of information about the hole states.

Deep-lying hole excitations in nuclei can be observed in the (p, 2p) reactions only if initial and final states are kinematically very carefully chosen to correspond to the quasi-elastic scattering of protons and nucleons. These kinematical conditions deviate only slightly from the scattering of protons on free protons if one just takes into account that the protons in the nucleus are bound and that energy has to be given into the hole excitation. As to the rest nucleus, no momentum is transferred in the process and its recoil momentum corresponds to the Fermi momentum of the nucleon before the quasi-elastic process takes place. The states obtained correspond to the removal of a single particle from the nucleus, but all other particles stay in their original states. In the shell-model picture the hole states are the eigenstates of the Hamiltonian and do not decay. But they are embedded in continuum states, and residual interaction mixes these states with the hole states. The strength of the residual interaction determines width and lifetime of the hole states. A surprising feature in nuclear physics is that these deep-lying states live long enough to be seen experimentally at an excitation as high as 60 MeV. Bombarding nuclei by high-energy protons (in some experiments the kinetic energy of protons was 600 MeV), the probability of producing a single-nucleon hole state is negligible if compared with the total cross-section. But in the very limited portion of the phase space selected by the quasi-elastic scattering, the hole states show up from the background. The background can result from the rescattering of incoming and outgoing particles and its origin is similar to that of the background expected in the (K^-, π^-) reaction. The fact that single-hole states seem to be observable up to 60 MeV excitation in the (p, 2p) reaction gives some additional support to the assumption that the excitation in hypernuclei, being even about 20 MeV lower in energy, may also be free of background. The binding energy of protons in nuclei depending on the atomic number A is shown in figure 13 (Jacob and Maris 1973).

5.3 Strangeness exchange resonance

In ${}^{12}_{\Lambda}\text{C}$ not only the strangeness exchange resonances, but also the hypernuclear ground states have been experimentally determined. In figure 14 (Brückner et al 1975) the known states and their tentative configuration are shown. It is very easy to guess the excitation of the particle-hole state in the 1s shell. It is directly deducible from the experimentally known neutron binding energies. The energy of this excitation merely corresponds to the difference between the neutron binding energies in the 1s and 1p shells in ${}^{12}\text{C}$. From figure 13 one can deduce that the excitation of the strangeness exchange resonance with the Λ particle and the neutron hole in the 1s state is about 20 MeV. How can we guess the excitation of the $(1p, 1p^{-1})_{\Lambda n}$ strangeness exchange resonance? It is nothing but the energy difference between the 1s and 1p shells for the Λ particle. But these energies are not experimentally known. The state at 11 MeV excitation in ${}^{12}\text{C}$ was tentatively ascribed to this configuration. The reason is simple: the binding energies of the Λ particle in the ground states suggest a potential well of about 30 MeV depth. In this potential well, the calculated excitation energy of the 1p state is 11 MeV in the case of ${}^{12}\text{C}$. From this fact, it has been deduced that the two configuration assignments were consistent and that they did explain most of the experimental facts. Because of the large spacing between the two strangeness exchange resonances, the mixing of the states can only be weak (Hüfner et al 1974).

In a similar way, one can qualitatively understand also the rest of the spectra. The narrow peak or peaks stem from the configuration of the last neutron shells, whereas the broad bump stems from the contribution of the stronger bound nucleons.

In ${}^{16}_{\Lambda}\text{O}$ (figure 8) the two narrow peaks at $B_{\Lambda} = 3$ and 8 MeV should correspond to the $1p_{1/2}$ and $p_{3/2}$ particle-hole configuration. In ${}^{32}_{\Lambda}\text{S}$ the state at $B_{\Lambda} = 6$ MeV should agree with the strangeness exchange resonance having a $d_{5/2}$ particle-hole configuration. The state with a $2s_{1/2}$ configuration is too weak to be seen well in spectra with poor statistics.

The ${}^{40}_{\Lambda}\text{Ca}$ spectrum is quite a surprise. The narrow peak is missing. With some imagination, however, one can interpret the sharp rise of the low momentum part of the broad peak as resulting from the narrow peak embedded in the broad one. The narrow peak should also come from the $d_{5/2}$ configuration, which should be most pronounced in the case of ${}^{40}\text{Ca}$.

The ${}^9_{\Lambda}\text{Be}$ is more complex and we shall not discuss it here, as it has already been extensively treated by Brückner et al (1975).

If one tries to explain the excitation energies and relative intensities of different strangeness exchange resonances one blunders into many unsolved problems. A simple calculation for Λ excitation in a Saxon-Wood potential, reproducing the hypernuclear ground states correctly, yields, for the energies of the energetically lowest strangeness exchange reactions in ^{16}O , ^{32}S and ^{40}Ca , $E_{\text{exc}} = 11, 19$ and 19 MeV, respectively. However, the narrow peaks are observed at 19, 28, and 33 MeV of excitation. The relative intensities are also hardly proportional to the neutron number of the particular shell. The contribution of the strongly bound neutrons is much too high, especially if one considers that the strongly bound neutrons should be less represented than the loosely bound ones in the nuclear surface where the reaction takes place. The results of the (K^-, π^-) reaction on nuclei are not yet quantitatively understood. The Λ particle is certainly the cleanest case of a single particle moving in the potential of the nucleons. The disagreement between the experiment and simple potential well solutions shows that important many-body effects are essential in the Λ -nucleus interaction.

The calculation could easily be corrected by assuming an effective mass of Λ particles which would reproduce the few observed spectra. An effective mass of 0.8 of Λ particle mass would bring the measured and observed energies into agreement. But the range of cases measured is too small to enable one to check whether such a parameter is physically significant or not.

There are other possibilities to fit the data, for example through energy dependence of the potential depth seen by Λ particles. The reasons for the corrections mentioned above are manifold. In the first case, polarization of nuclear matter in the presence of Λ particles determines its effective mass; in the second case, strong energy dependence of the Λ -N interaction cannot be incorporated into the average energy-independent potential. Understanding of the excitation energy, width, and intensity of the narrow peaks, which probably belong predominantly to particle-hole excitation in the outer shell, will give us a rather realistic view of the "single particle" properties of lambdas in nuclear matter.

An important piece of information gathered from the recoilless Λ production is that the energy spacing between the Λ particle shells and neutron shells is remarkably similar. One cannot neglect the mixing between the strangeness exchange resonances if one aims at understanding the intensity distribution of the (K^-, π^-) reaction to hypernuclear states. Because of the appreciable mixing of the strangeness exchange resonances the alternative description starting with the collective state -- strangeness analogue state -- becomes very attractive.

5.4 Strangeness analogue resonance

Strangeness exchange reaction can happen to any neutron in the nucleus, thereby producing strangeness exchange resonances. If the resonances are energetically close together, they will mix. There is the possibility of coherent excitation of a particular linear combination of the strangeness exchange resonances, each of which has a different neutron in the nucleus converted into a Λ particle. One such linear combination has been called strangeness analogue state or resonance by analogy with the isobaric analogue states in nuclei:

$$\left| \text{SAR}, A_Z \right\rangle = \frac{1}{\sqrt{N}} \left| \sum_n c_\alpha^+ b_\alpha \text{ ground state } A_Z \right\rangle, \quad (21)$$

where c^+ creates a Λ in the state α , b destroys a neutron in the same state, and N is the number of neutrons in the target.

The analogue state is characterized by its permutation symmetry. According to the Pauli principle, the wave function for the target nucleus has to be antisymmetric with respect to all the neutrons and protons in the nucleus. No such symmetry principle exists between the hyperon and nucleon, and all possible permutation states are allowed. In the strangeness analogue state attained in the $K^- + n \rightarrow \Lambda + \pi^-$ reaction a neutron in the target is changed into Λ and the exact wave function remains unchanged, and so does the permutation symmetry. The hypernuclear wave function is also antisymmetric with respect to the interchange of any neutron and Λ particle.

If the strangeness analogue states are well realized in the hypernuclei, there is a very elegant way to describe these states using the properties of the $SU(3)$ symmetry.

In nuclear physics, the isospin has been powerfully used in the classification of the states. Neglecting Coulomb interaction, the proton and the neutron have the same interaction and the nuclear states are eigenstates of $SU(2)$ in a very good approximation. To keep the track of protons and neutrons in the nucleus the two particles have different z components in the isospin space. The Coulomb interaction does not conserve the isospin and the $SU(2)$ symmetry is broken. But it is very convenient to look at the states as being eigenstates of a Hamiltonian, with a high symmetry in order to classify the states according to their dominant features. In the second step, the wave function is corrected by including the symmetry-breaking effects. In the same spirit, one should try to describe the strangeness analogue resonance in the three component systems, proton, neutron, and Λ particle, neglecting the differences in their mutual interaction. Isospin and strangeness quantum numbers take care of particle identity. To describe a three-component system it is useful to consider the unitary symmetry $SU(3)$.

In elementary particle physics, the octet model of the SU(3) symmetry has been very successful in describing low-energy excitations of the hadrons. In addition to proton, neutron and Λ , Σ and Ξ equally belong to the components of the octet model. In hypernuclear physics, the octet model cannot be of great importance. The mass splitting of 80 MeV between Λ and Σ is too large on the energy scale of the hypernuclear excitations. The octet model would classify the hypernuclear states in a linear combination of Λ 's and Σ 's if we limit ourselves to $S = -1$ states. But hypernuclei contain only Λ , as Σ decay into Λ in nuclear matter. Therefore, an SU(3) model with triplet basis $np\Lambda$ is of relevance for hypernuclei.

Prior to the success of the octet model in hadron physics, Sakata (1956) already tried to create the hadron states using the triplet basis of $np\Lambda$. This model is no longer interesting for hadron physics, but can be directly applied in hypernuclear physics. The operator $U^- = \sum_{\alpha} c_{\alpha}^+ b_{\alpha}$, which appears in equation (21), is nothing but the lowering U-spin operator of Sakata's SU(3) model.

The unitary symmetry assumes that the Λ -nucleon interaction coincides with the nucleon-nucleon one. Although this symmetry is a very poor approximation to the two-body system, contrary to the charge independence in the proton-neutron case which is violated only by small electromagnetic contributions, in the nucleus the Sakata symmetry may still be very useful. As for hypernuclei, it has been pointed out by Lipkin (1973) that the difference between the Λ -nucleus and nucleon-nucleus interaction is important. This difference, at least as far as the Sakata model is concerned, may be small enough to justify a description of this model.

The validity of the shell-model description of complex nuclei allows us to replace the major portion of the sum over a two-body interaction by an average field in which the single nucleon or hyperon moves. The radius of the baryon-nucleus interaction potential is determined by the size of the nucleus and is independent of whether the baryon concerned is a nucleon or a Λ particle. The main difference is expected to be in the depth of the potential well seen by nucleons and Λ particles. This difference is also the major cause for the breaking of the Sakata symmetry in hypernuclear states. The dominant effect of different potential depths will be the energy displacement in nuclei and hypernuclei, but a smaller effect is expected on the wave function which may well be approximated by the Sakata model.

In this simple model the strangeness analogue state is obtained from the nuclear ground-state by applying the U^- operator of the Sakata model, which in turn transforms the neutrons of the nucleus into Λ particles. This operation is symbolically shown in figure 15. Within this model there is only one parameter

$\Delta V_{n\Lambda}$ likely to determine the energy position of the strangeness analogue state measuring the difference between the depth of the nucleon-nucleus and the Λ -nucleus potential well. This difference should be about 20 MeV. At least for heavy nuclei, where the shape of the potential well remains unchanged, $\Delta V_{n\Lambda}$ should be independent of the target nucleus.

The symmetry-breaking effects will mix in other SU(3) representations, thus destroying the purity of the Sakata state. If they are small, the splitting of the Sakata state may be understood by the symmetry-breaking interaction in the Λ -nucleus system. This interaction is the result of averaging over the two-body interaction in the nuclear system. This is the same averaging responsible for the surprisingly successful description of the nuclei by the independent particle model. If we are well informed about the symmetry-breaking effects of the strangeness analogue states, we can learn a lot about the underlying physics connecting the "physical" nucleus with the shell model.

If one interprets the observed spectra in figure 8 by a strangeness analogue resonance, it follows that this resonance is split into two or more components. In this case one should rather use the parameter $\Delta V_{n\Lambda}$ for the average over-all states forming the strangeness analogue resonance. These average values $\langle \Delta V_{n\Lambda} \rangle$ are given in table 3. It has been observed that this parameter is the same for all targets with the exception of ${}^9_{\Lambda}\text{Be}$. But the shape of the potential well of ${}^9_{\Lambda}\text{Be}$ is certainly so very different from others that one cannot expect the same $\langle \Delta V_{n\Lambda} \rangle$. On the other hand, all other nuclear targets have very much the same properties, isospin $I = 0$ and large neutron-binding energy strongly influencing the position of the strangeness analogue state. It would, therefore, be much too early to give a critical judgement on how well the description of hypernuclear states via the Sakata model works.

The present experimental information is too trifling to continue this discussion without running into the danger of pure speculation. The aim of the last two sections was to show that hypernuclear states seen in recoilless Λ production furnish interesting information about the nucleus. We may eventually learn what interaction a particle feels in the nucleus without first averaging the interaction over all the identical particles of the system. In this respect, the strangeness exchange resonances correspond to the states with "marked" neutrons. Further, through understanding of the symmetry-breaking interaction in the picture of the strangeness analogue state, more insight into the averaging mechanism of the two-body force in the nucleus (eventually leading to the effective interaction of the shell model) can be obtained.

6. GAMMA SPECTROSCOPY

The first counter experiments in hypernuclear physics were in fact performed to look for gamma transitions in light hypernuclei (Bamberger et al 1971, 1973). It is obvious that the gamma spectroscopy offers the simplest way to achieve a good resolution in hypernuclear spectroscopy without using large magnetic spectrometers for the charged particles involved in the production of hypernuclei. Hypernuclei produced in the K^- interaction with a nucleus may be produced in excited states; observing the gamma transitions between the bound states one can reconstruct the level scheme of the hypernuclei, provided that one finds a way to identifying the hypernucleus to which the gamma belongs. So far no such ambitious program has been planned. The first experiments were simply based on the fact that K^- interacting in ${}^6\text{Li}$ and ${}^7\text{Li}$ cannot produce bound excited states of nuclei whose gamma decay would be unknown.

The K^- interaction on the nucleus leads to excitation in continuum followed by emission of particles. The hypernuclei produced will probably have at least one or two masses less than the target nucleus. Therefore, K^- stopped in ${}^6\text{Li}$ and ${}^7\text{Li}$ targets are unlikely to give heavier hypernuclei than ${}^5_{\Lambda}\text{He}$; the latter does not have any bound excited state. In fact, the only gamma-rays one would expect could come from ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$. In the first experiment of the CERN-Heidelberg-Warsaw group (Bamberger et al 1971, 1973) two gamma transitions, 1.09 MeV and 1.42 MeV, were observed and were assigned to the transitions between the first excited state and the ground state in ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$. Recently, in a more refined experiment of the Lyon-Warsaw group (Bedjidian et al 1976), it was possible to prove that the assignment was actually correct.

6.1 Experimental method

The experimental set-up is shown in figure 16. The K^- were identified with a set of counters and made to stop in the target. The gamma-rays were detected by a NaI counter of 10×7.5 cm size. The time of flight from target to counter had to correspond to the speed of light. The K^- interacting in the target produces one to two neutrons per interaction. These neutrons, on the other hand, eventually give gammas either in the shielding or in the counter itself. The time of flight selection was sufficient to select only the gammas from the target. Gamma spectra with the correct timing are displayed in figure 17 and show the 1.09 MeV and 1.42 MeV lines.

The ${}^4_{\Lambda}\text{H}$ decays predominantly into ${}^4_{\Lambda}\text{He} + \pi^-$ with monoenergetic pions of 40 MeV. The Lyon-Warsaw group showed that the 1.09 MeV gamma transition is in fact in coincidence with the 40 MeV π^- and belongs to the ${}^4_{\Lambda}\text{H}$. It still has to be shown that the 1.42 MeV line does coincide with π^0 coming from ${}^4_{\Lambda}\text{He} \rightarrow {}^4\text{He} + \pi^0$.

One such experiment is currently in progress. Even if there is no unambiguously proven assignment for the 1.42 MeV line to ${}^4_{\Lambda}\text{He}$, we shall nevertheless refer to it in the context.

6.2 The hypernuclear mass 4 system

The hypernuclei ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ are mirror hypernuclei. The combined information for emulsion and gamma work is shown in figure 18. One should observe that the scale of both hypernuclei is given in terms of the binding energy of Λ in ${}^3\text{H}$ and ${}^3\text{He}$, respectively. The two neutrons in ${}^3\text{H}$ are coupled to spin 0, so that the splitting in ${}^4_{\Lambda}\text{H}$ comes predominantly from spin-spin interaction between proton and Λ . Similar arguments can be used to show that in ${}^4_{\Lambda}\text{He}$ the neutron- Λ interaction determines the splitting of the states. The two paired nucleons act just as spectators. It is obvious that the mirror hypernuclei should behave in the same way, except for the difference in the Coulomb energy. The splitting of the singlet and triplet states does not depend on the Coulomb force. Therefore, the difference in the excitation of ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ gives direct information on the isospin violation in the ΛN interaction. This is upheld by the observation of the binding energies of the ground state which are contrary to expectations (figure 18). Adding a Λ into ${}^3\text{H}$ having a single charge $Z = 1$ does not change the Coulomb energy. Adding a Λ into ${}^3\text{He}$ contracts the nucleus, thus increasing the Coulomb energy. Therefore, we would expect to find $B_{\Lambda}(\text{g.s.})$ in ${}^4_{\Lambda}\text{He}$ to be smaller than in ${}^4_{\Lambda}\text{H}$. All this indicates that the ΛN force violates the isospin.

The ΛN force behaves quite differently from the NN force, especially in the long-range part, which is most important in the low-energy interaction. The main features of the NN force are qualitatively understood. It is experimentally known that the spin-spin and tensor forces have the largest range and stem from one-pion exchange. The spin-orbit interaction has a shorter range ~ 0.7 fm, the ρ exchange being mainly responsible for it. In the ΛN interaction, single π or ρ exchange is isospin-forbidden, because Λ has isospin $I = 0$. In the lowest order the ΛN interaction comes from two- π and K exchange with a range corresponding to K exchange (figure 19a).

It has been suggested by Dalitz and von Hippel (1964) that the ΛN interaction should have quite an appreciable isospin-violating part. The Λ particle does not have a pure $I = 0$ isospin. This is the consequence of the isospin mixing of baryons and mesons within their $\text{SU}(3)$ multiplets. Both Λ and Σ^0 differ in their quantum numbers only by their isospin 0 and 1, respectively. Actually they are not pure eigenstates of isospin, but have small isospin impurity resulting from mutual mixing. In this case, the one- π^0 exchange is allowed and contributes to

the long-range spin-spin interaction (figure 19b). It is straightforward, but beyond the scope of this article, to show that the amplitude for the π^0 exchange has different sign in the Λ -neutron and Λ -proton cases, the consequence of which is that this contribution is isospin-violating.

Determination of the splitting of 0^+ and 1^+ states in ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ replaces the measurements of Λ -neutron and Λ -proton scattering with polarized Λ 's. The analysis of the splitting in terms of elementary interaction is, however, less reliable than in the scattering experiments, because of many-body contributions which are not easy to estimate. But scattering experiments will hardly ever be made with polarized Λ of low energy. So far, only low-momentum Λp scattering in a bubble chamber has been measured, but the accuracy was too low even to separate the triplet and singlet scattering (Alexander et al 1968).

A detailed analysis of the isospin-violating effects in the mass 4 system has not been made yet, but the observed effects are consistent with an admixture of 2% of Σ^0 amplitude in the Λ particle.

7. CONCLUDING REMARKS

Hypernuclear spectroscopy was at first performed by means of a nuclear emulsion technique, which is generally applied to particle physics if experimental conditions are too hard to allow for detection of particles by counters. The systematic knowledge of the light hypernuclear ground states stems from these experiments. The limitations inherent in the emulsion technique do not allow its application to further investigation of relevant problems in hypernuclear physics. The development of strong K^- beams and new experimental methods permit counter experiments and allow the study of hypernuclear excited states, in particular of those in the continuum. Both the ground and the continuum states obtained in the recoilless Λ production are of central interest in hypernuclear physics as they supply direct information about the Λ -nucleus interaction. The present results in light hypernuclei demonstrate that the Λ particle is an excellent probe of "strong" properties of nuclear matter. The next generation of experiments aiming at statistics of an order of magnitude higher than the present ones is scheduled to study the ground states and the continuum states with recoilless Λ production in medium and heavy nuclei. The first successful experiments with pion-gamma coincidences hold out well-founded hopes that excited bound states of light hypernuclei can be investigated systematically.

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Table 1

The recoil Λ momentum in the $K^- + n \rightarrow \pi^- + \Lambda$ reaction
if pions are detected at 0°

K^- momentum (MeV/c)	0	100	300	500	700	900
Λ momentum (MeV/c)	250	190	70	0	40	80

Table 2

The typical values of the present K^- beam
in operation at CERN

$\Delta p/p = \pm 1.2\%$	$K^-/\pi^- = 1\%$	$K^-/\text{burst} = 10^4/\text{burst}$
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Table 3

The main parameters of observed resonances in the (K^-, π^-) reaction on different nuclei. B_A is the only directly measured quantity. $B_A = 0$ corresponds to zero relative energy between the A particle and the core nucleus ground state. The ground-state energies with an asterisk are theoretical estimations. V_{nA} is the difference in binding energy between the last neutron in the target nucleus and B_A : $V_{nA} = B_n - B_A$. The error in the relative yields amounts to about 30%. The numbers in parentheses represent a tentative description of the low-energy shoulder as weak narrow peaks. The decomposition is not significant statistically.

Target nucleus	Ground state	Narrow peak					Broad bump					Whole spectrum		
		B_A (MeV)	Γ_{exp} (MeV)	V_{nA} (MeV)	$\sigma(0^\circ)$ (mb/sr)	B_A (MeV)	Γ_{exp} (MeV)	V_{nA} (MeV)	$\sigma(0^\circ)$ (mb/sr)	$\langle B_A \rangle$ (MeV)	$\langle V_{nA} \rangle$ (MeV)	$\sigma(0^\circ)$ (mb/sr)		
${}^9\text{Be}_A$	7		5	11	0.3	-21	11	23	0.8	-16	18	1.1		
${}^{12}\text{C}_A$	10		4	19	0.4	-12	13	31	0.8	-8	27	1.2		
${}^{16}\text{O}_A$	14*		$\begin{smallmatrix} 7 \\ 4 \end{smallmatrix}$	$\begin{smallmatrix} 17 \\ 23 \end{smallmatrix}$	$\begin{smallmatrix} 0.2 \\ 0.4 \end{smallmatrix}$	-17	14	33	0.7	-11	27	1.3		
${}^{32}\text{S}_A$	20*		5	21	0.4	$\begin{smallmatrix} -16 \\ -27 \end{smallmatrix}$	$\begin{smallmatrix} 10 \\ 12 \end{smallmatrix}$	$\begin{smallmatrix} 31 \\ 42 \end{smallmatrix}$	$\begin{smallmatrix} 0.5 \\ 0.3 \end{smallmatrix}$	-15	30	1.2		
${}^{40}\text{Ca}_A$	21*		$\begin{smallmatrix} 5+5 \\ 5 \end{smallmatrix}$	$\begin{smallmatrix} 15 \\ 25 \end{smallmatrix}$	$\begin{smallmatrix} 0.2 \\ 0.2 \end{smallmatrix}$	(-22	17	38	0.7)	-14	30	1.1		

Figure captions

- Fig. 1 : Production of the ${}^7_{\Lambda}\text{Li}$ hypernucleus in the (K^-, π^-) reaction on ${}^{16}\text{O}$ and its decay (Powell et al 1959).
- Fig. 2 : Measured binding energies in light hypernuclei (Pniewski 1972).
- Fig. 3 : The binding energies B_{Λ} versus $A^{-2/3}$. The two curves are fitted to the values of B_{Λ} for the indicated values of r_0 , in order to correspond to a Λ kinetic energy given by an infinitely deep square well of radius $R = r_0 A^{1/3}$ for large A (Rote and Bodmer 1970, Bodmer 1973).
- Fig. 4 : In collinear events in the (K^-, π^-) reaction, the Λ recoil is $p_{\Lambda} < 100 \text{ MeV/c}$ providing that the K^- momentum is in the interval between 300 MeV/c and 1000 MeV/c.
- Fig. 5 : In the associate production the momenta of the proton and K^+ have to be measured in order to determine the Λ recoil. The recoil momentum p_{Λ} cannot be reduced further than to 600 MeV/c.
- Fig. 6 : Optical analogy of the energy loss spectrometer: the white light originating at x_1 will be dispersed in the first prism and focused in x_0 . If a condenser lens is put at x_0 all light will be accepted by the second part of the system and refocused in x_2 independently of the wavelength. If a milky glass is put at x_0 , the light will scatter isotopically in the glass. But the correlation between the colour and x_0 remains unchanged. Therefore the light accepted by the second part will be refocused at x_2 equally independently of the wavelength.
- Fig. 7 : Magnetic double spectrometer: BM - bending magnets, Q - quadrupoles, P - plastic scintillators, W - multiwire drift chambers, T - target, Č - liquid-hydrogen Čerenkov counter (Brückner et al 1975, 1976).
- Fig. 8 : Spectra obtained in recoilless Λ production on ${}^9\text{Be}$, ${}^{12}\text{C}$, ${}^{16}\text{O}$, ${}^{32}\text{S}$, and ${}^{40}\text{Ca}$, as a function of the Λ binding energy B_{Λ} . $B_{\Lambda} = 0$ corresponds to a zero relative energy between the Λ particle and the core nucleus ground state (Brückner et al 1976).
- Fig. 9 : Magnetic spectrometer: multiwire proportional chambers P_1 , P_2 , P_3 and hodoscope E define the K^- coordinates necessary to calculate the energy loss of pions for the thick target. Multiwire proportional chamber P_4 and multiwire drift chambers D1, D2, D3 determine the pion trajectory in the magnet and thus its momentum (Faessler et al 1973).

- Fig. 10 : Spectrum of π^- measured with 8×10^8 K^- stopped in ^{12}C . The insert shows the spectrum above 250 MeV/c after subtraction of the smooth background. The dashed curves are calculated contributions to the background normalized to the experimental data (Faessler et al 1976).
- Fig. 11 : Single-particle energies of neutrons in a potential well of 50 MeV depth and Λ particles in a potential well of 30 MeV depth. The states have different spacings. If the single particle energies reproduce the Λ -excitation correctly, the difference between the Λ and neutron binding energies give the transformation energy $n \rightarrow \Lambda$ for each shell.
- Fig. 12 : K^- and π^- are strongly absorbed in the nucleus. The mean free path is about 1 fm. Only a thin ring of nuclear surface contributes to the single-step (K^- , π^-) reaction at 0° .
- Fig. 13 : Energies of the proton hole in nuclei as deduced from (p, 2p) experiments (Jacob and Maris 1973).
- Fig. 14 : $^{12}_{\Lambda}\text{C}$ excited states and their configurations (Brückner et al 1975).
- Fig. 15 : Schematically shown transformation of the nuclear ground state into the strangeness analogue state. The energy $\Delta V_{n\Lambda}$ is needed for the $n \rightarrow \Lambda$ transformation.
- Fig. 16 : Beam-telescope identified stopped K^- . The P1-P5 are plastic scintillator counters; \check{C}_1 and \check{C}_2 are threshold Čerenkov counters. The gamma-rays from the target are selected by the correct time of flight measured by P₄ and the NaI counter (Bamberger et al 1971, 1973).
- Fig. 17 : Prompt gamma spectra coincident with stopped K^- in ^6Li and ^7Li targets (Bamberger et al 1971, 1973).
- Fig. 18 : Level scheme of $^4_{\Lambda}\text{H}$ and $^4_{\Lambda}\text{He}$.
- Fig. 19 : a) The most important contributions to the Λ -N potential;
b) π^0 exchange responsible for charge-symmetry-breaking effects.

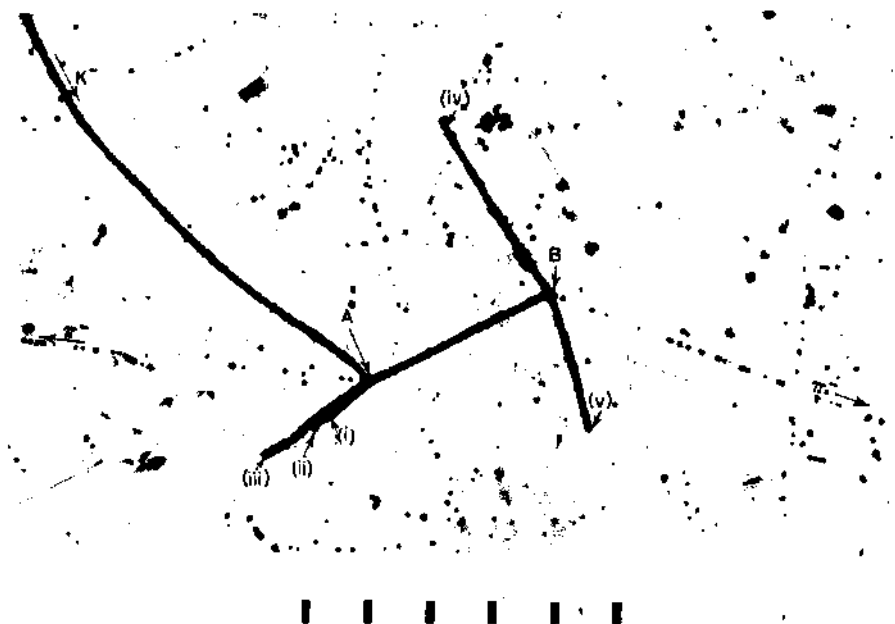


PLATE 11-13

Ilford K5 emulsion.

FOWLER (1958).

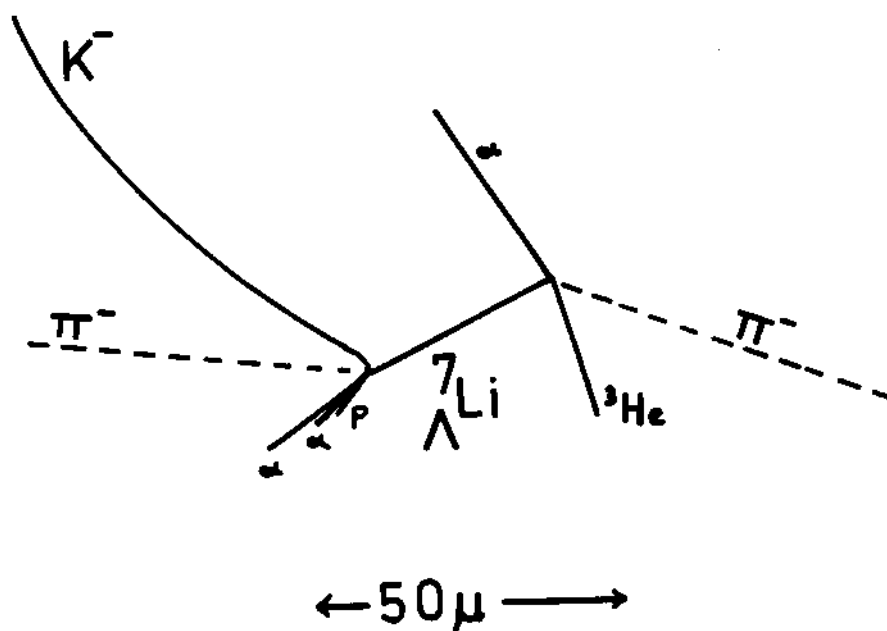


Fig. 1

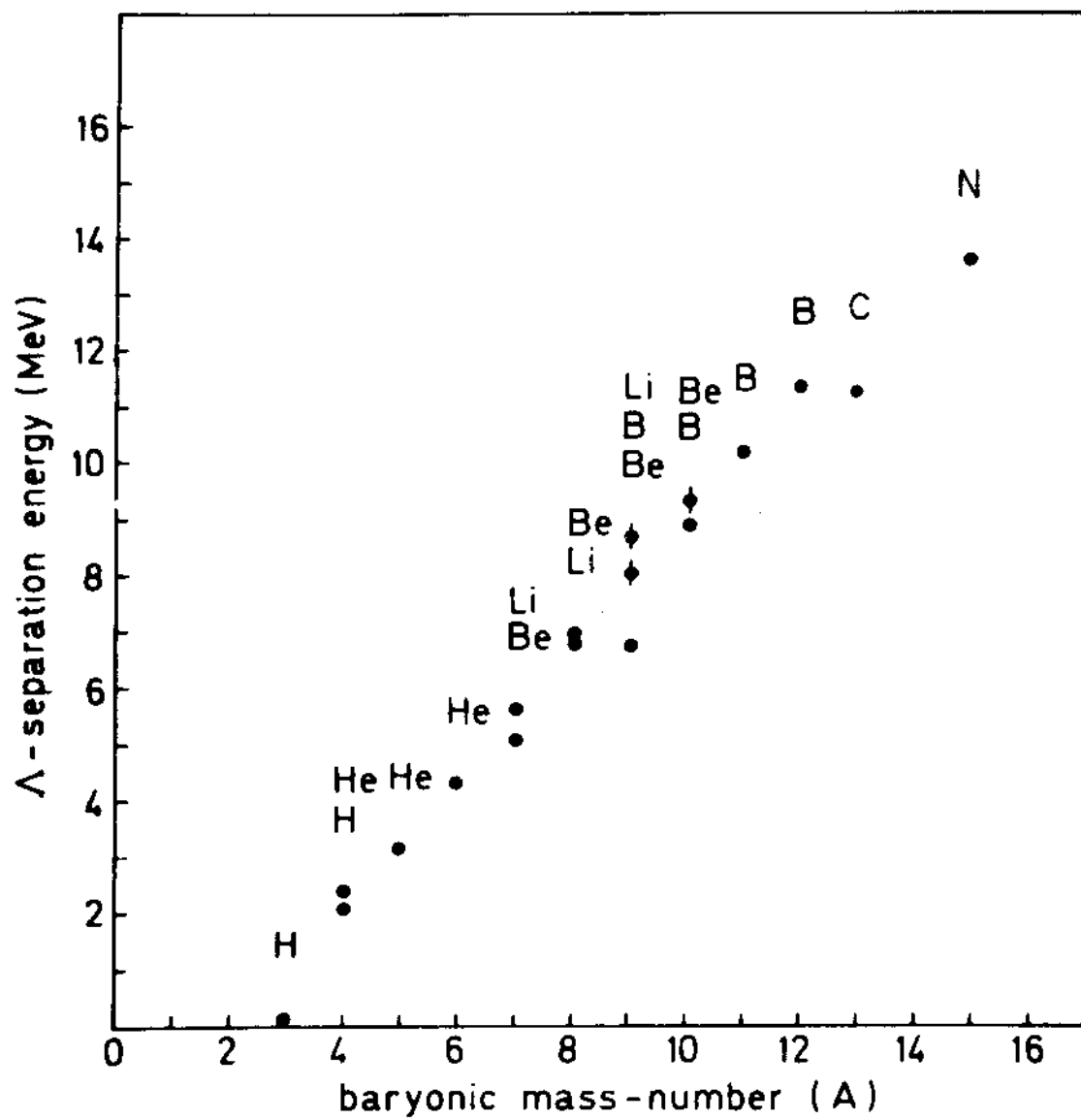


Fig. 2

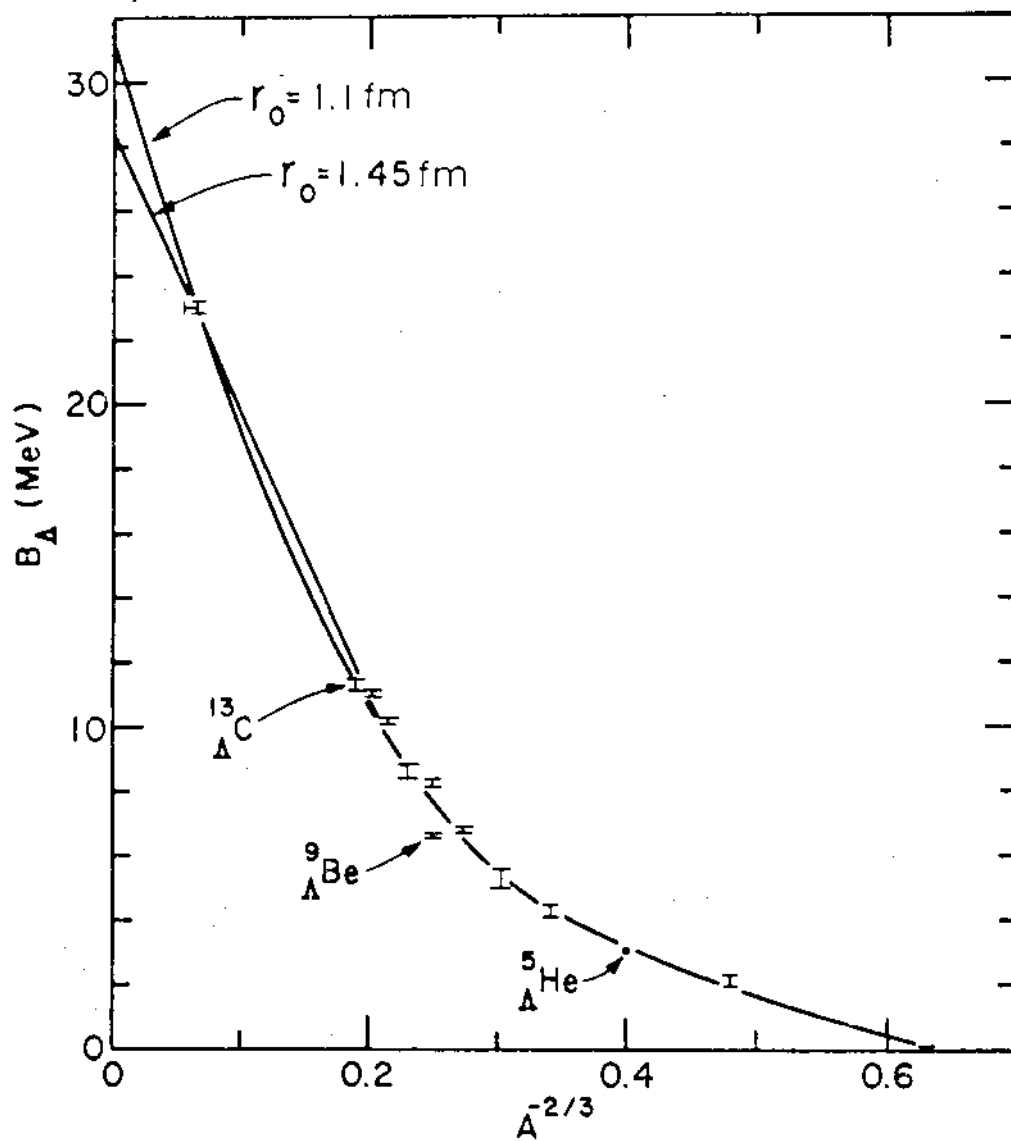


Fig. 3

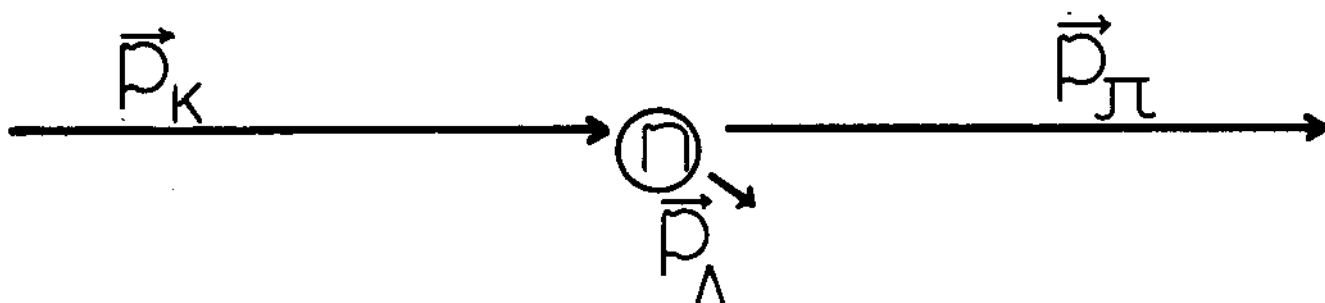


Fig. 4

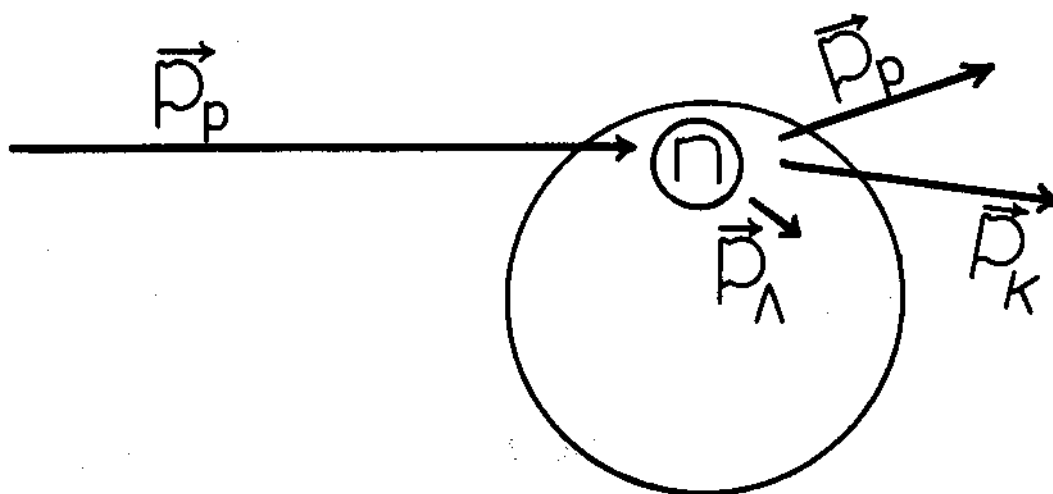


Fig. 5

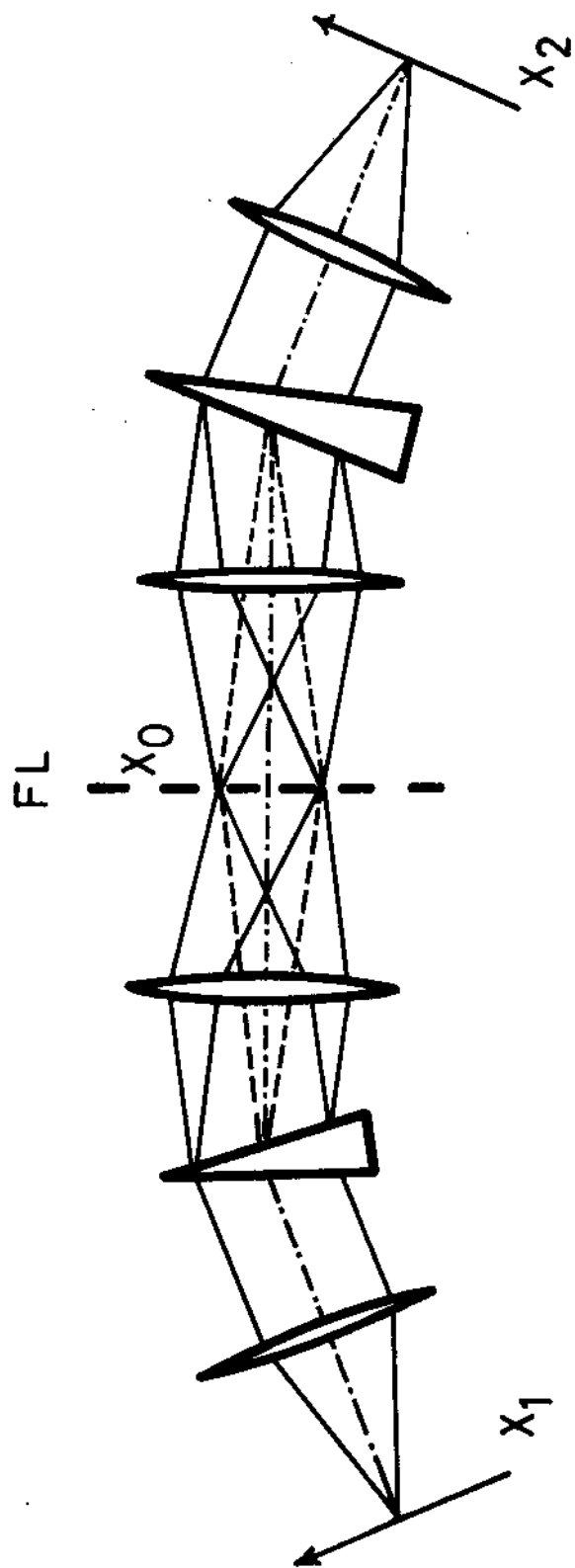


Fig. 6

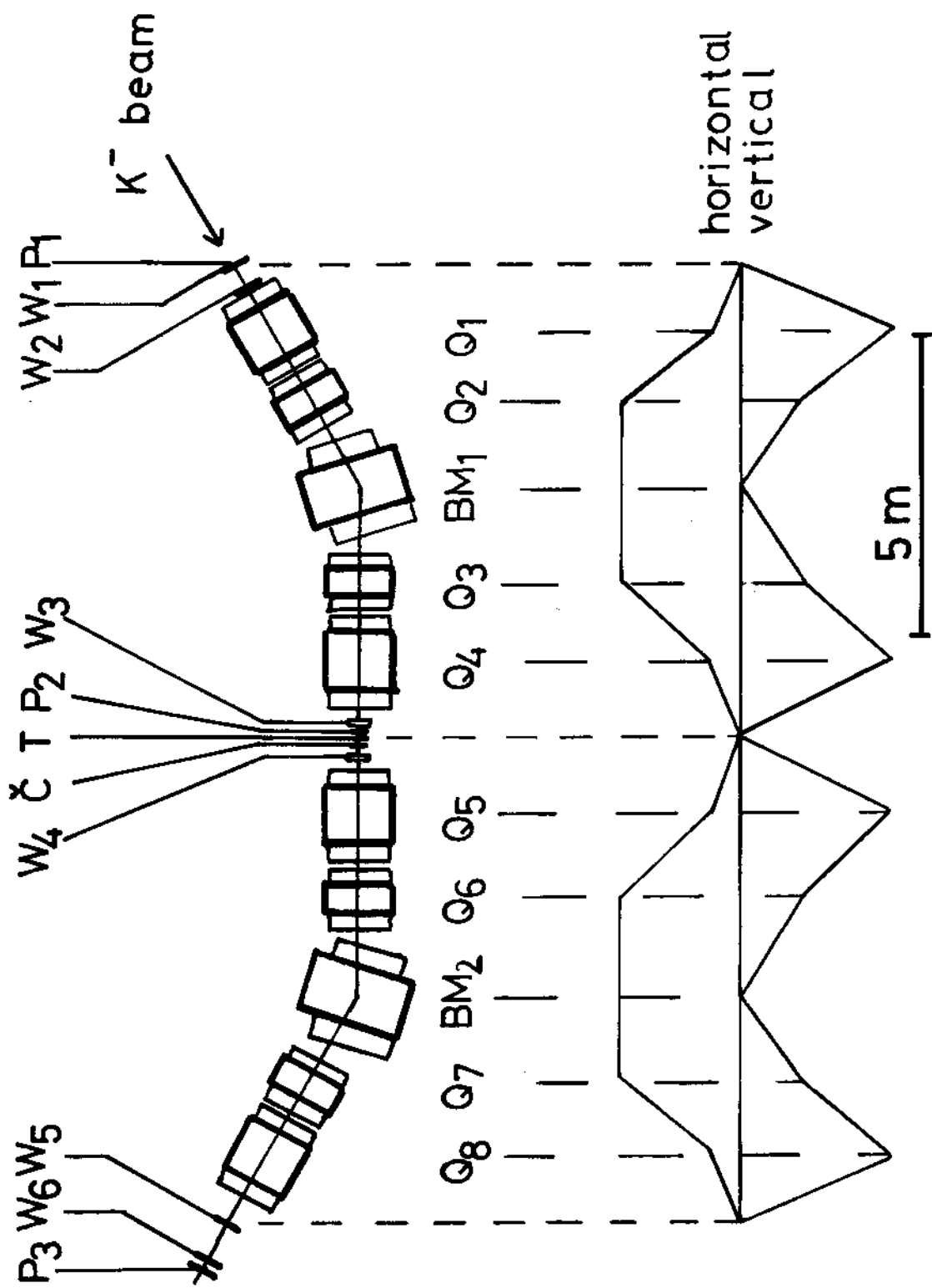


Fig. 7

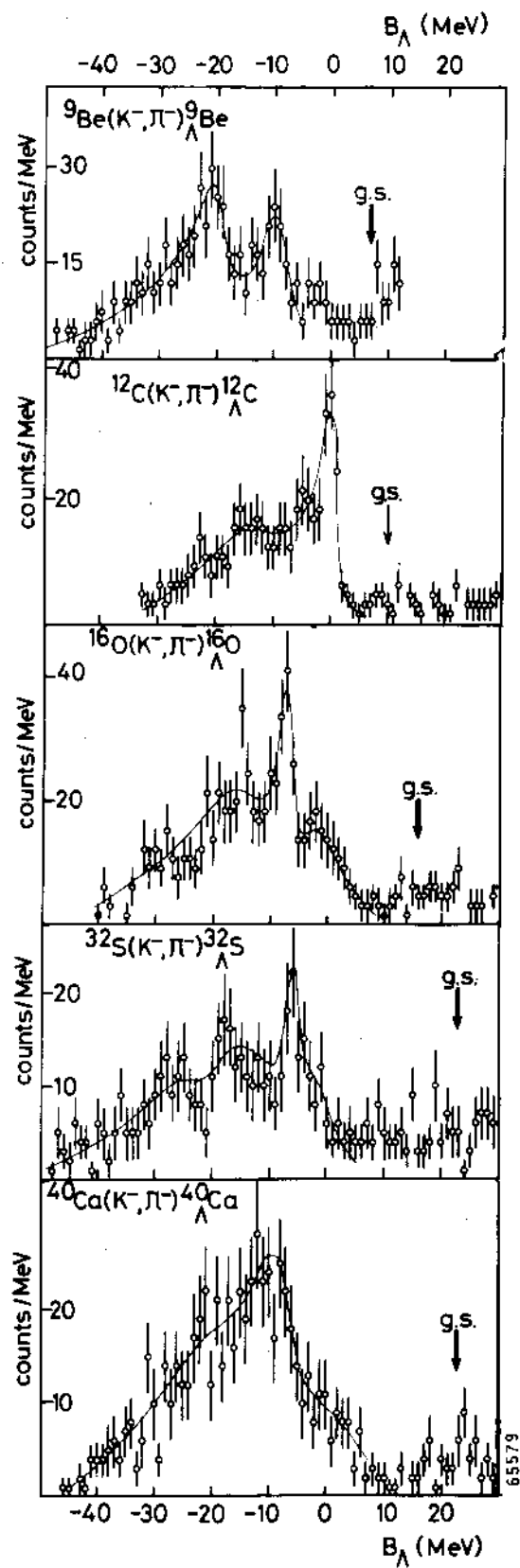
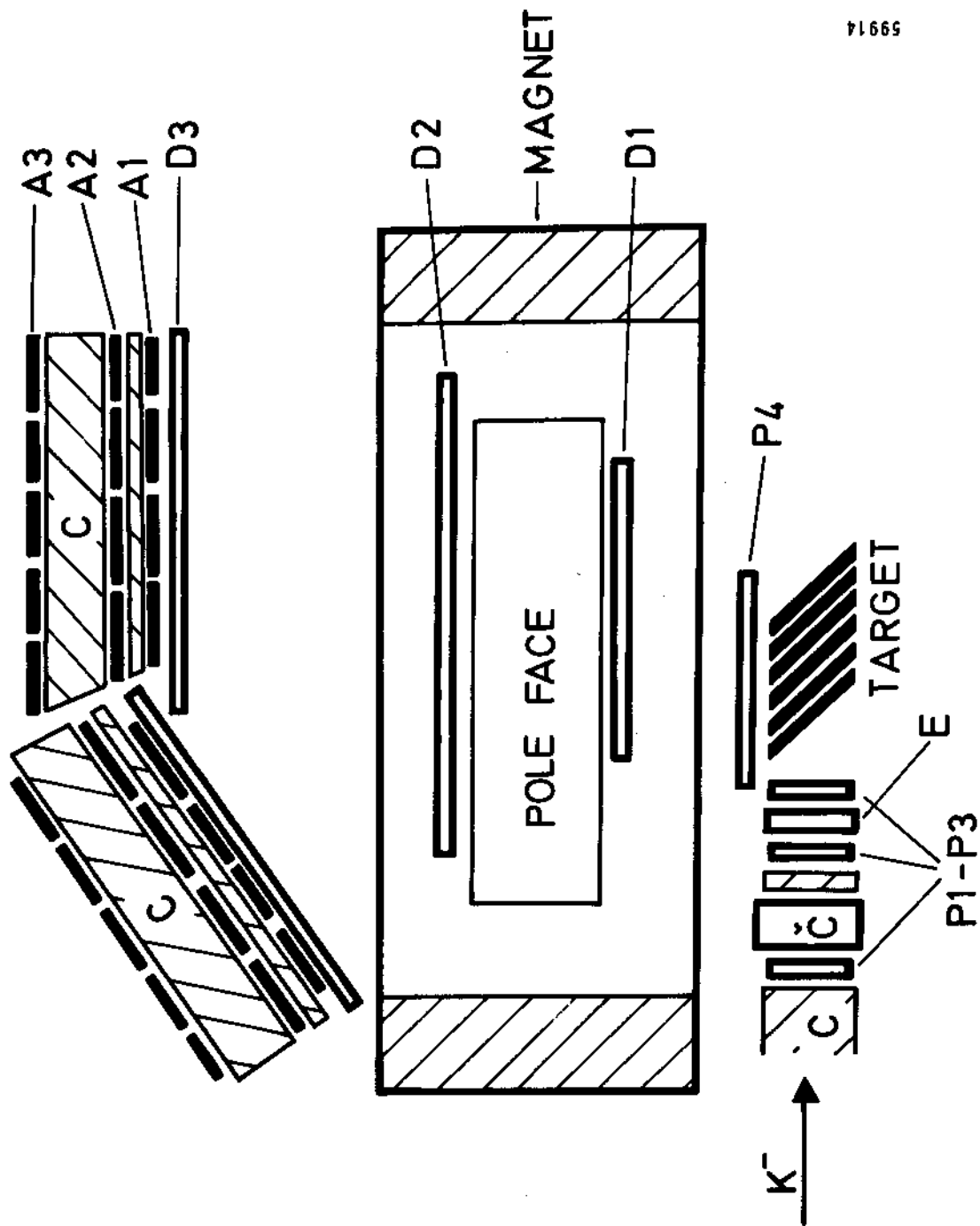


Fig. 8



59914

Fig. 9

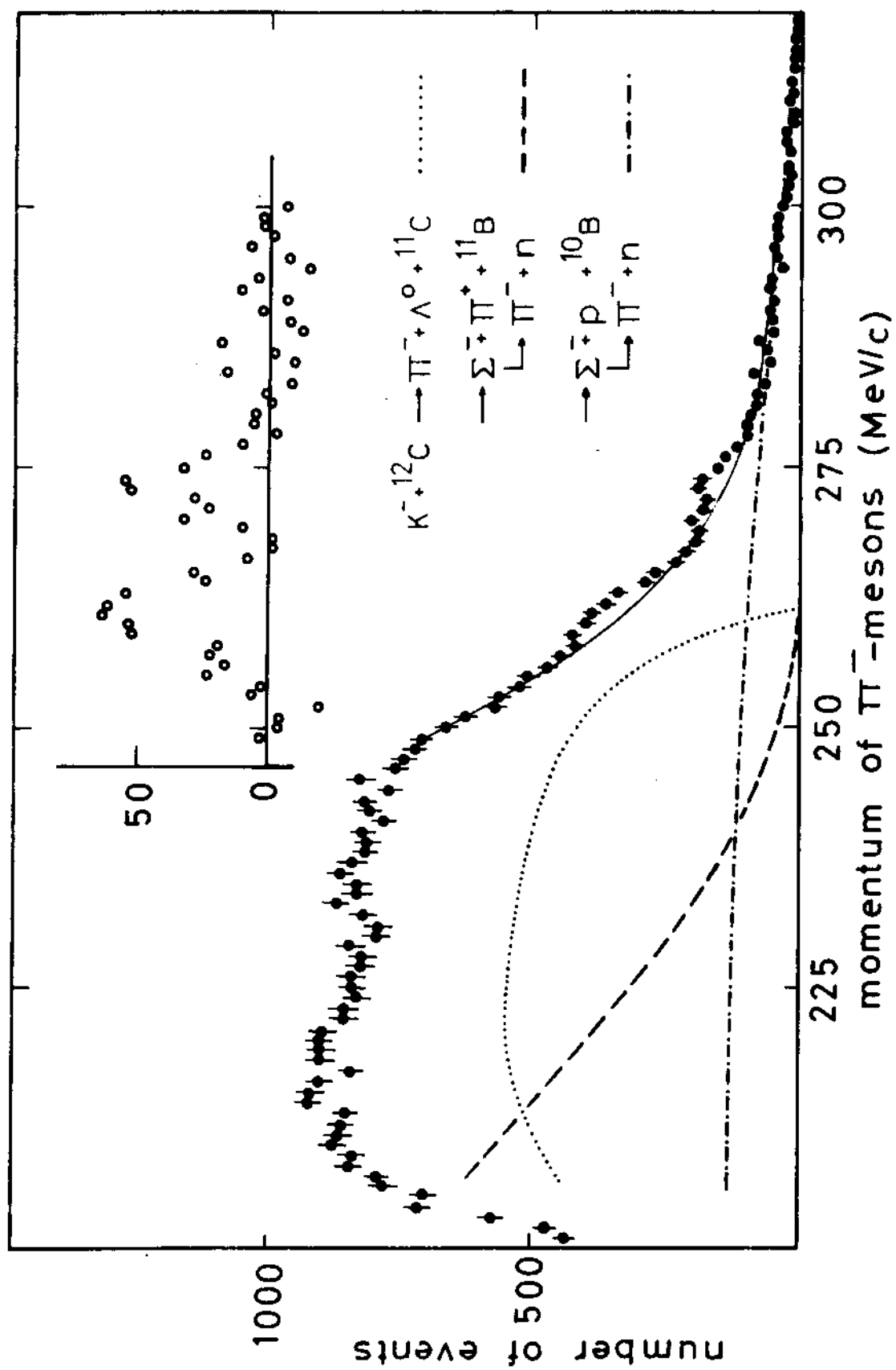
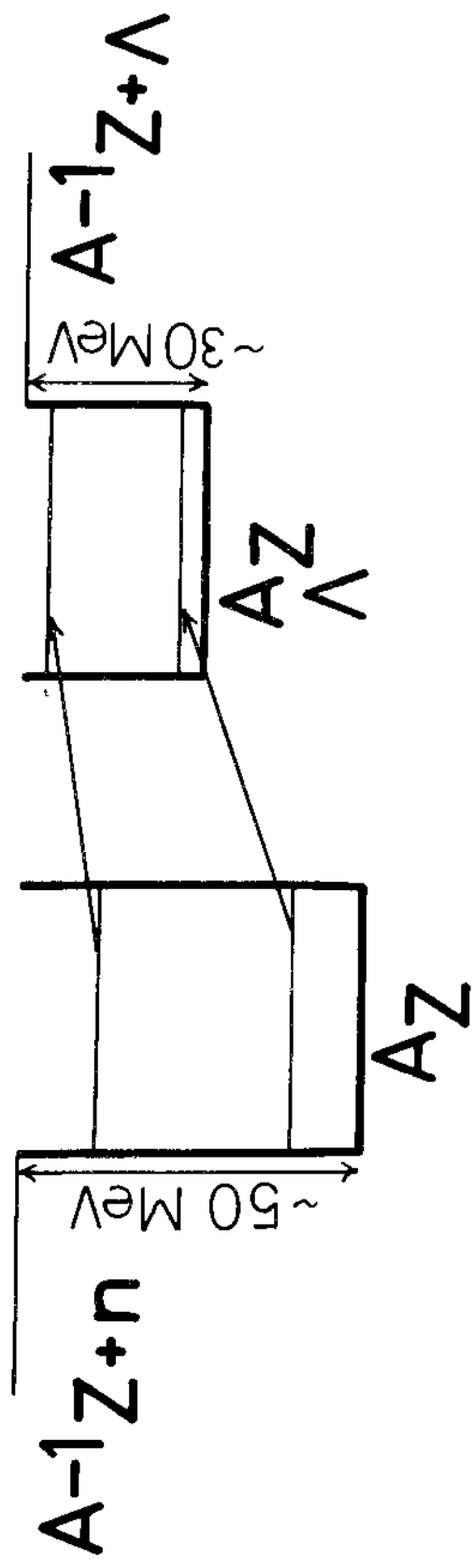


Fig. 10



neutron \rightarrow lambda

Fig. 11

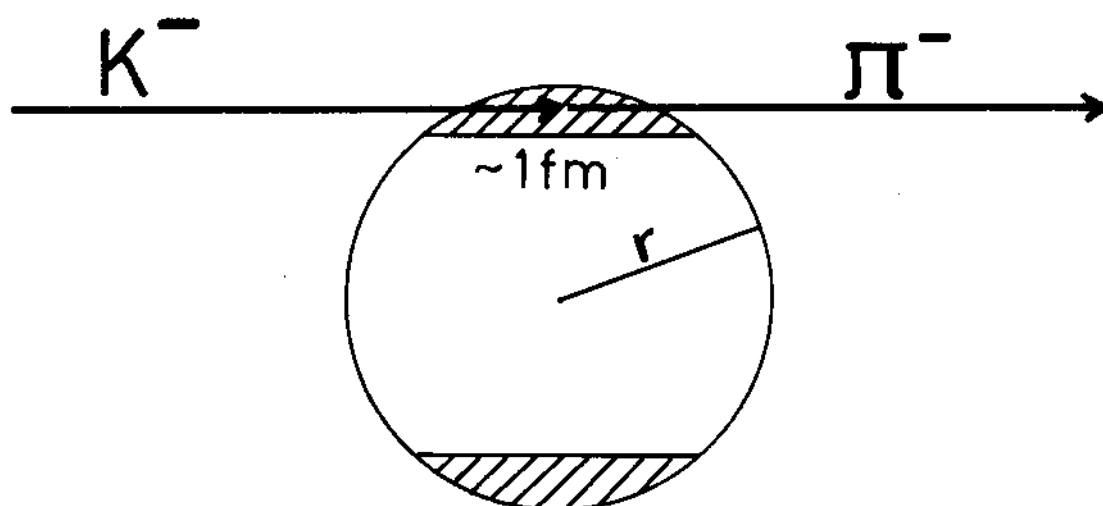


Fig. 12

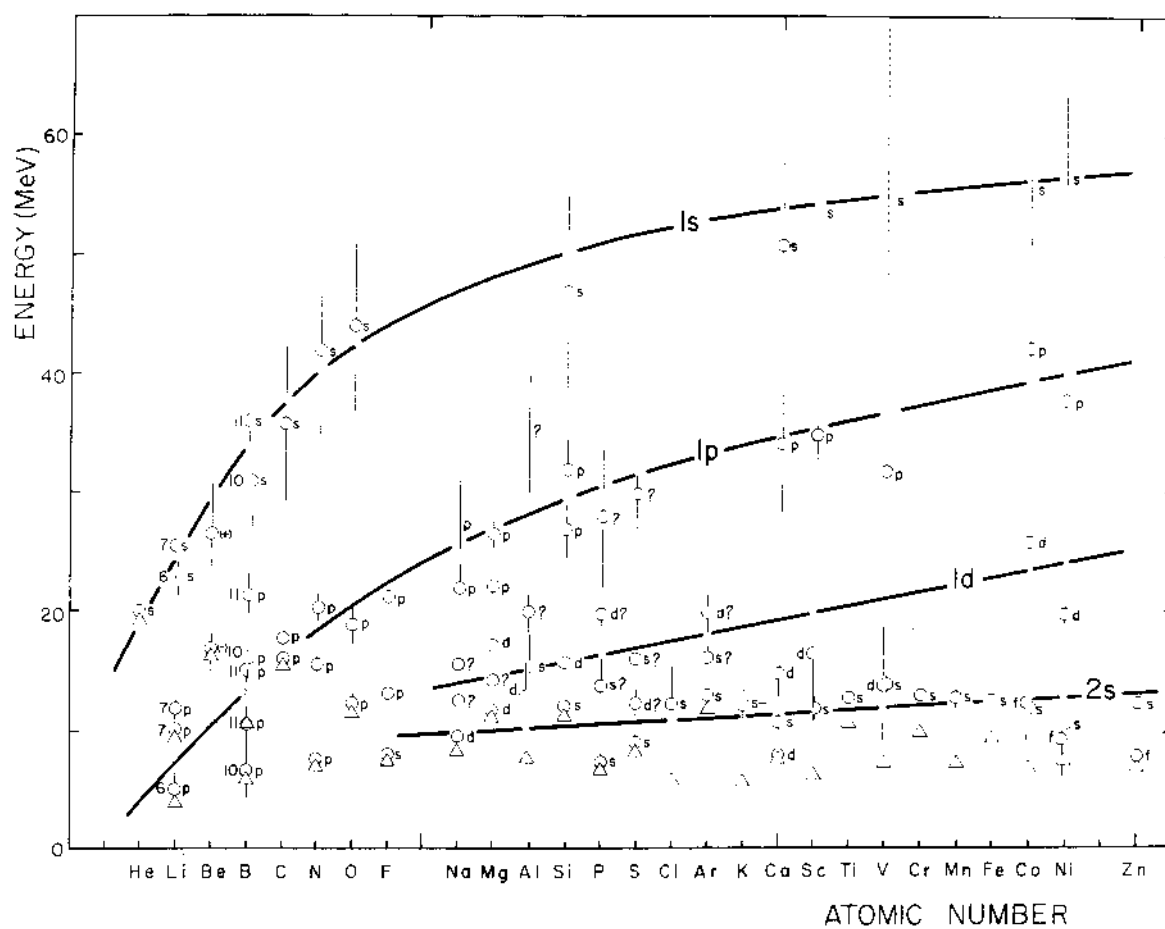


Fig. 13

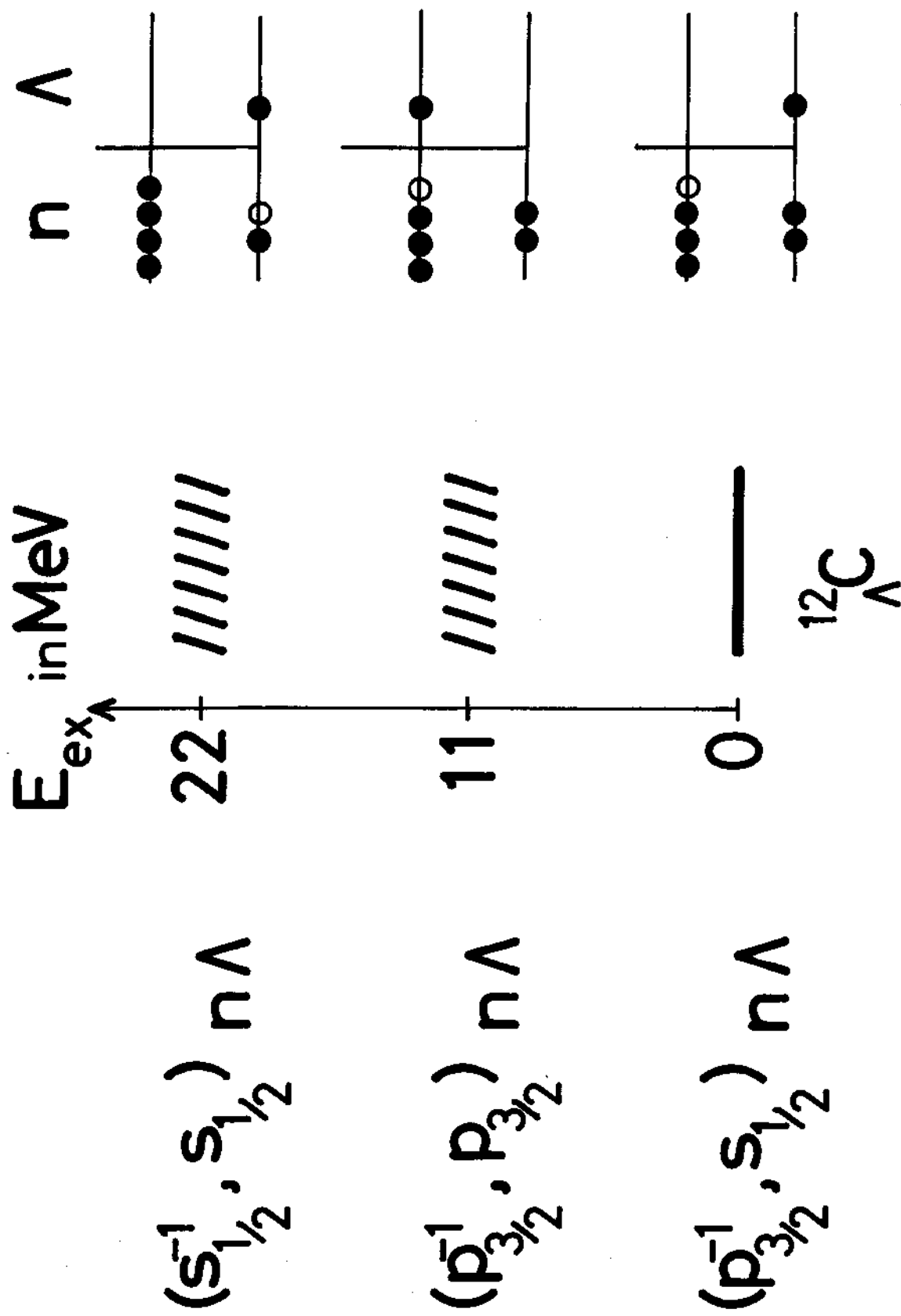
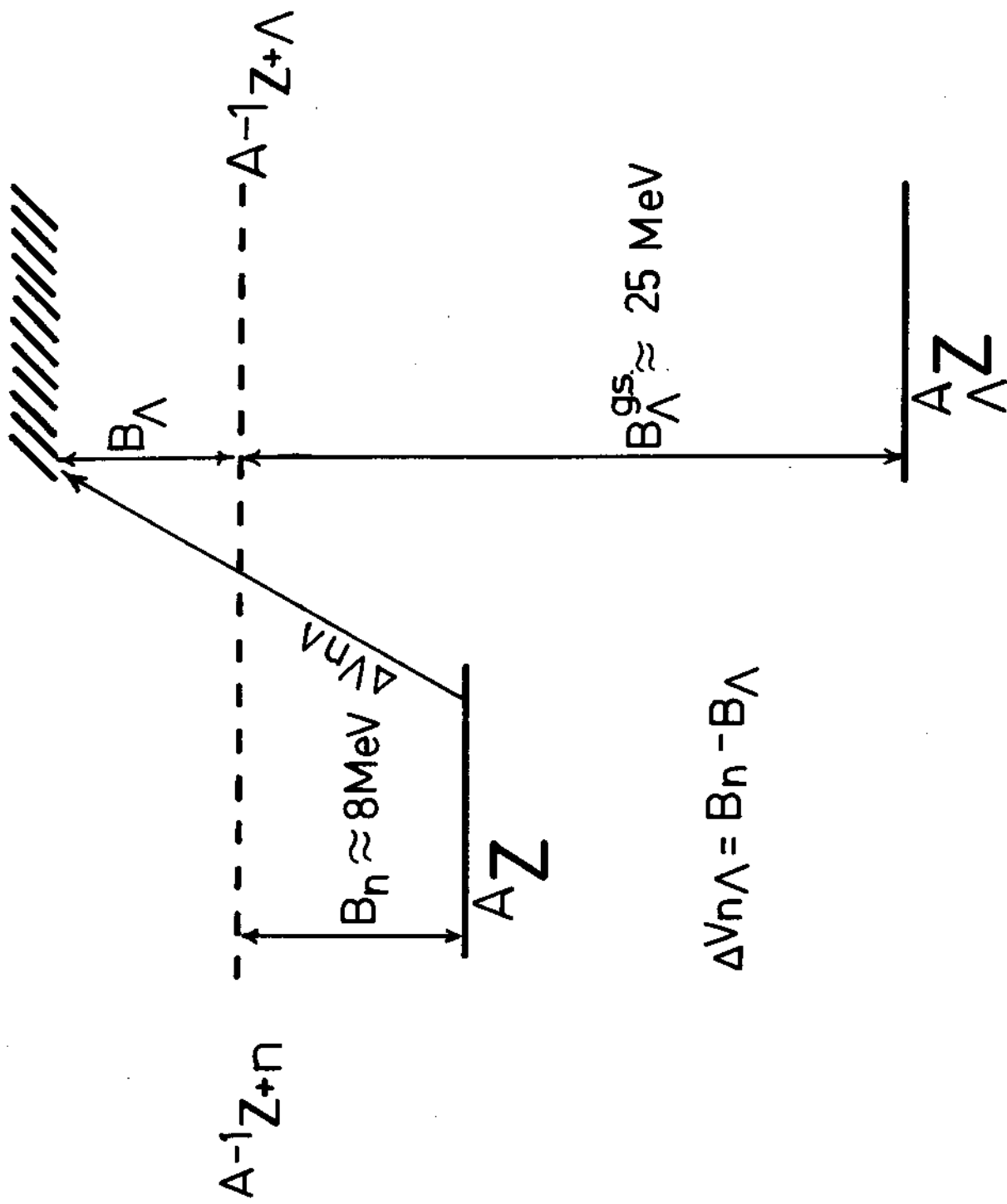


Fig. 14



$$\Delta V_{n\Lambda} = B_n - B_\Lambda$$

Fig. 15

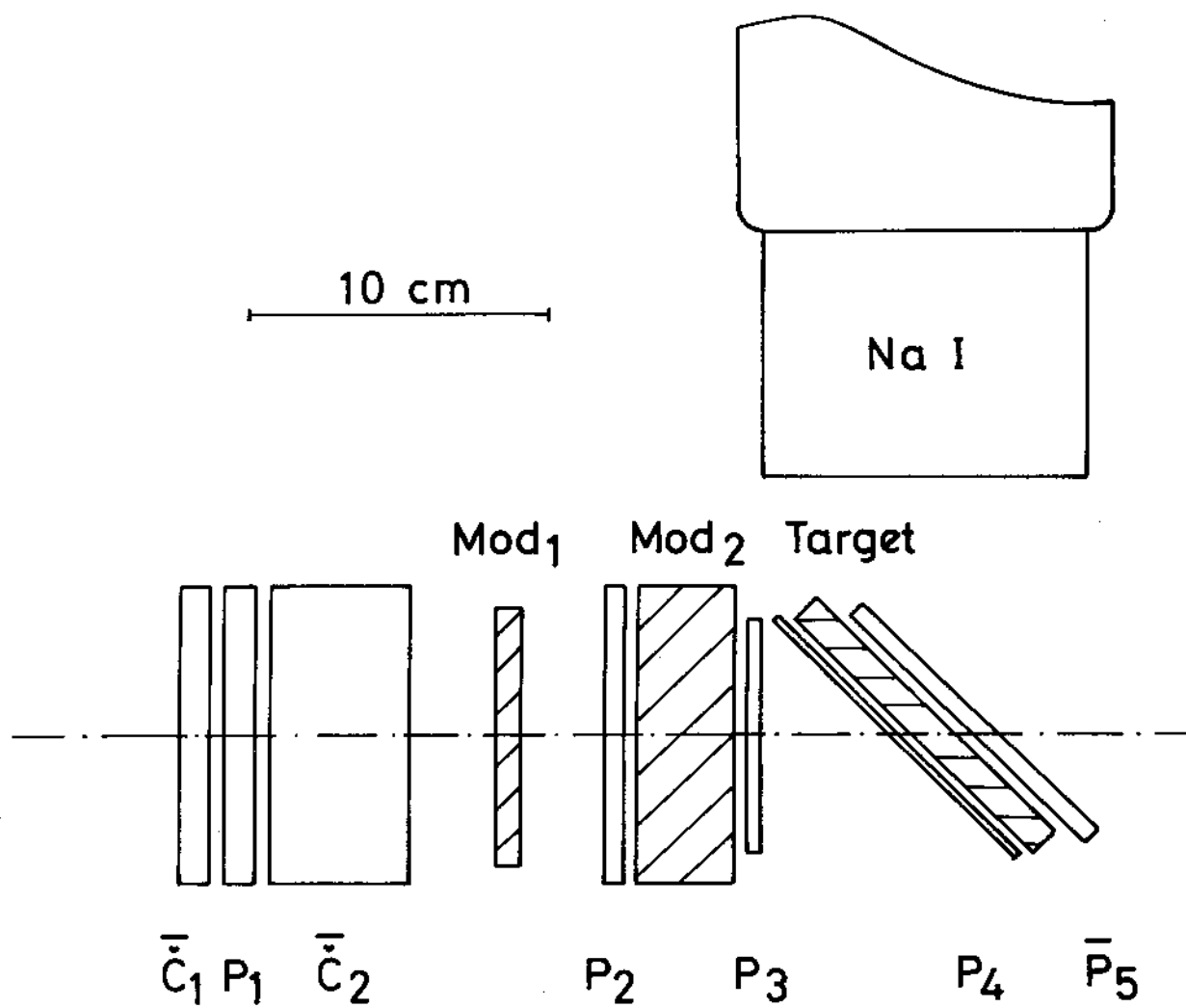


Fig. 16

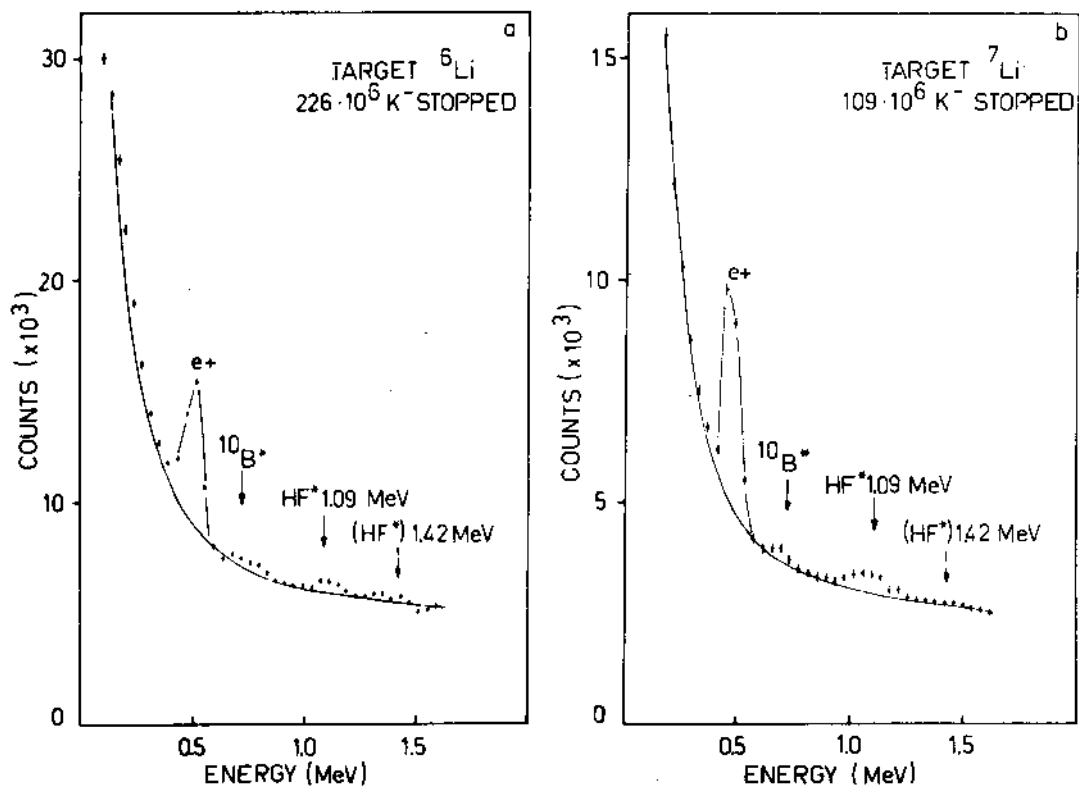


Fig. 17

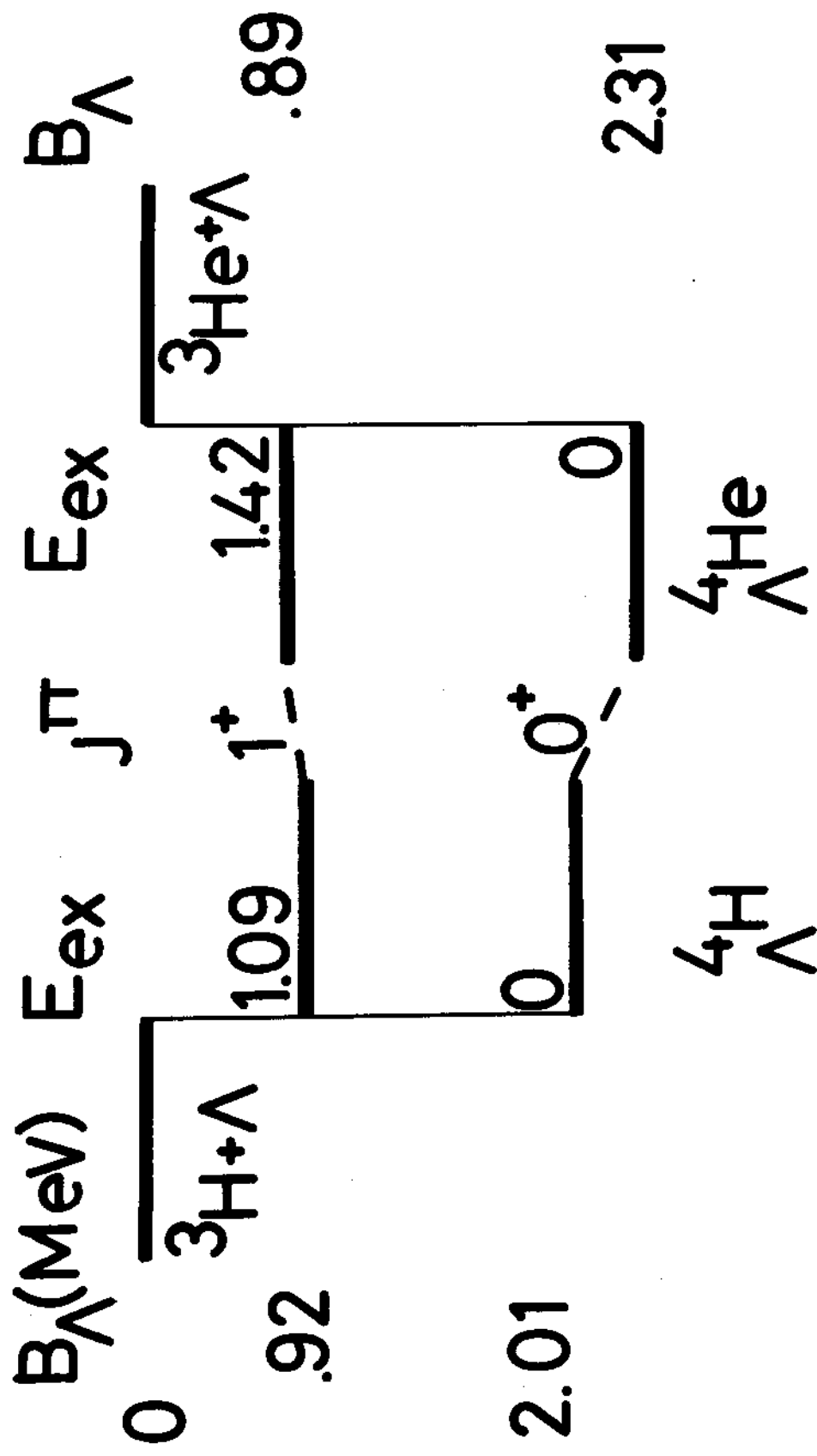


Fig. 18

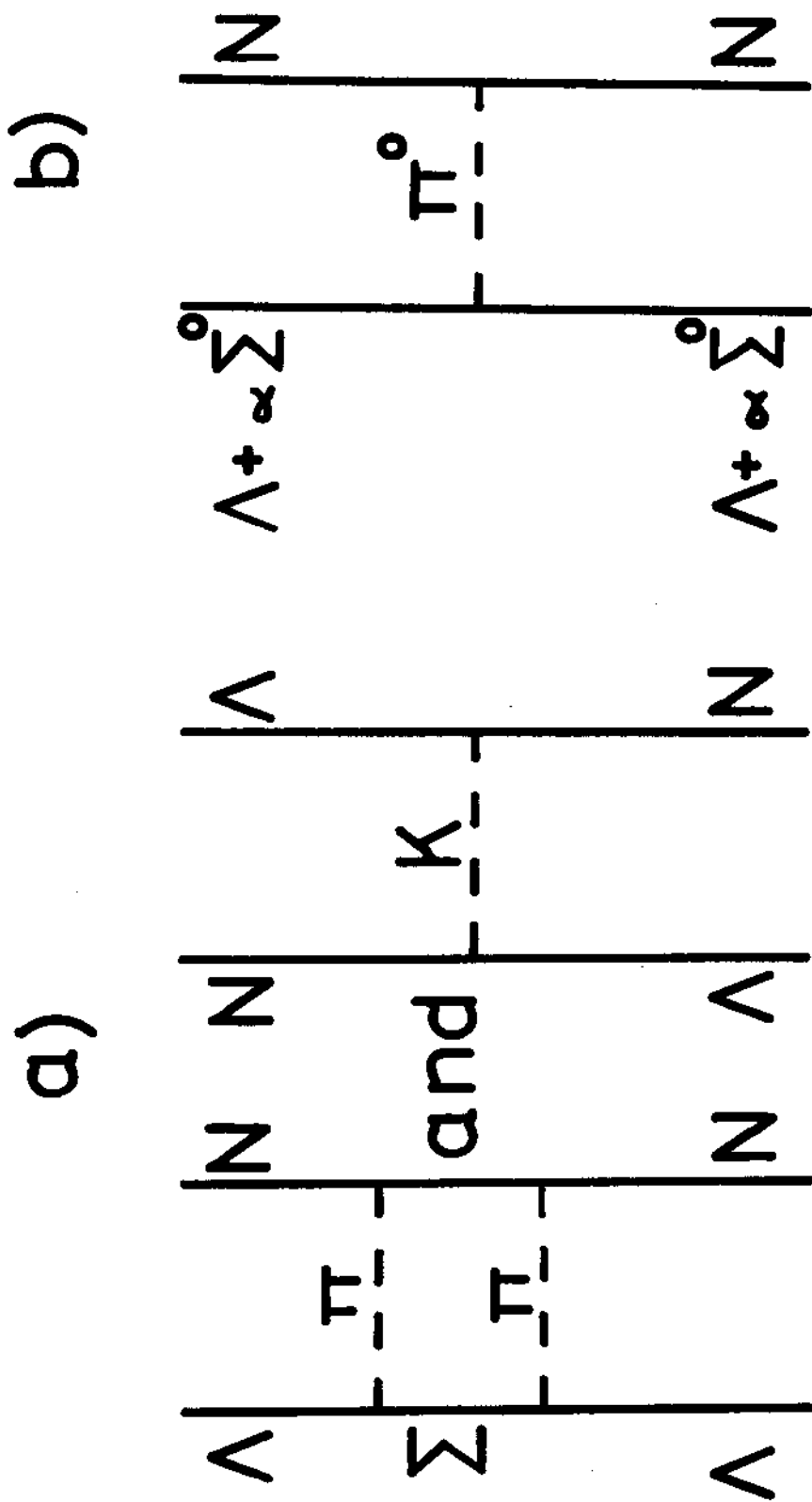


Fig. 19