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Baryon Structure

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Abstract

The detailed investigation of the baryon structure is of fundamental importance for the understanding of the structure of QCD in the non-perturbative regime. First, a brief review on the theoretical and experimental situation of baryon spectroscopy is given. Then, the radial structure of baryons, related to the ground state form factors and the baryonic compressibility, is discussed. An experiment has been performed at Saturne in which for the first time a compression of the nucleon is observed, exciting the P_{11}(1440 MeV) resonance (Roper resonance) by α-particles. The analysis of the data indicates that this excitation covers a large fraction of the available monopole strength in the nucleon. The derived compressibility is discussed as well as the consequence for other fields, as nuclear medium effects on baryon properties, high density phenomena in nuclear collisions as well as colour transparency. In the last point the spin-flip structure of the P_{11}(1440 MeV) resonance is discussed. The possibility to determine isoscalar spin-flip strength by polarized deuteron scattering is contrasted with first preliminary results from photon-induced reactions studied at Mainz which indicate a non-negligible M1 excitation of the Roper resonance.

1. Introduction

The structure of baryons may be viewed as an intrinsic three quark structure with strong gluon exchange contributions giving rise to a polarization of sea quarks. Since the baryon structure can be regarded as bound and low lying excited states of quantum chromodynamics (QCD), it is of fundamental interest to investigate the baryon properties in detail. The present situation of the theoretical description is rather difficult. The non-abelian nature of the colour gauge group $SU(3)_c$ of QCD makes the calculation of self energies and bound state properties a difficult problem. Therefore, in general the baryon structure is discussed in simplified models. The oldest and quite successful model is the constituent quark model[1] in which three quarks are placed in a harmonic oscillator potential. Relativistic extentions of this model are also discussed in the literature[2]. Other models are the bag model[3] and the Skyrmion model[4]. The latter is well suited to describe the dynamical problem of N^* resonances, e.g. in π-nucleon scattering. Further, string models as well as an algebraic approach[5] have been applied.

These models are based on rather different formalisms and lead to quite different pictures of the structure of the nucleon. For example, the constituent quark model treats the valence quarks only. Sea quark effects which are important to satisfy chiral symmetry are neglected. Topological soliton models consider the baryon as a bosonic field which corresponds to a treatment of the meson cloud arising from the polarization of the sea quarks. In this model the quark degree of freedom is eliminated. In hybrid models, like the chiral bag model[6] and the chiral quark model[7], both valence and sea quark effects are taken into account. The above mentioned models give quite different predictions for the properties of baryon resonances which have to be tested in specific experiments using both electromagnetic and hadronic probes. So far, in all these models no satisfactory description of low and high energy properties of baryons have been reached. Certainly, it is a challenge for future work to establish the connection of the different models to QCD or to derive predictions directly from QCD.

The experimental situation may be summarized as follows: There are old data (mostly from the sixties) on electromagnetic form factors, structure quantities, resonances in π-N and K-N reactions, excitation of resonances by hadronic and electromagnetic probes. For crucial tests of baryon models these data are not sufficient. There is a new generation of data to come from new machines, with
electrons: ELSA, MAMI, NIKHEF, CEBAF,
hadrons: SATURNE, COSY.

Because of the complexity of the baryon structure it is absolutely necessary for reliable tests of baryon models to have as much experimental information as possible. Therefore, it is indispensable to perform complementary experiments with hadronic and electromagnetic probes. It appears very attractive to use selective probes in which the scalar, vector or tensor character of the interaction is enhanced.

2. Radial structure of baryons

One of the most basic properties of baryons is the radial structure. Its static properties can be studied in elastic processes of hadrons and leptons. Dynamical properties of the size degree of freedom can be studied in inelastic processes exciting compression (or radial) modes. These are related to the compressibility of the system. Experimental possibilities for the study of radial properties are provided by the longitudinal field in electron scattering. Using hadronic probes, a scalar field exists which can be strongly enhanced in specific reactions, e.g. in the scattering of α-particles due to the quantum numbers (I=0,S=0). This may allow to study the "scalar"(spin scalar and isoscalar) structure of baryons.

The energy of a possible radial mode (excitation of a P_{11} resonance with large monopole matrix element) is critically dependent on the basic parameters of the different baryon models, e.g. it depends on the confining potential in the constituent quark model[2]. Using a harmonic potential, the lowest radial mode corresponds to a quark excitation from the 1s to the 2s shell with an energy of $2\hbar\omega$ which is about 1 GeV. In bag models the radial mode depends on the bag size. Models have been proposed[8-10], in which the radial mode is generated by the oscillation of the bag surface. In Skyrmion models[11] the monopole mode represents the lowest N^* resonance with an excitation energy of about 400 MeV. The large difference in the prediction of the radial mode in the simple constituent quark and the Skyrmion model is related to the size of the nucleon and may reflect the fact that the features of the sea quark or meson induced density are quite different from those of the valence quarks. In the hybrid descriptions of the chiral bag and the chiral quark model the baryon density may be split up into two contributions, one due to the valence quark wave function (concentrated in the interior) and the other due to quark-antiquark polarisation located more at the baryon surface. In these models one expects therefore two compression modes, one due to compression of the surface and the other dominant in the interior. From this one may be able to get information on the radius of the valence quark distribution, this would be in conflict with the Chesire cat principle[12].

The radial mode of excitation of the nucleon can be viewed as a density vibration of the system (fig.1). In the first phase the nucleon is compressed going along with a shrinking of its radius. Then in the dilatation phase one or two pions are emitted and the nucleon decays back into the ground state. If the total monopole sum rule strength (discussed below) is concentrated in this state, then the compressibility K can be determined. K represents the curvature of the energy density $E(\rho)$ around the minimum ρ_o, with $K = [9\rho^2 \frac{d^2E}{d\rho^2}]_{\rho=\rho_o}$. The compressibility can be related directly to the excitation energy E_x of the compression mode by $E_x = (\frac{\hbar^2 \cdot K}{m \cdot <r^2>})^{1/2}$ (see the discussion below). Because of this, it is an experimental challenge to find this mode of excitation in baryonic systems. As it corresponds to an excitation without transfer of angular momentum, spin and isospin, it is related to the excitation of P_{11} resonances (for I=1/2 and J=1/2 baryons).

2.1 What do we already know on excited baryons

There are three pieces of information on excited baryons, resonances observed in π-N scattering (or K-N scattering), electro- and photo-production, and hadron-production of baryon resonances.

π-N scattering: From phase shift analyses of π-N scattering detailed information exists on baryon resonances and their quantum numbers; this is important as a basis for our investigation. Here, we are interested in the P_{11} amplitudes which are given e.g. in the phase shift analysis by Cutkoski and Wang[13] in fig.2. In these amplitudes two

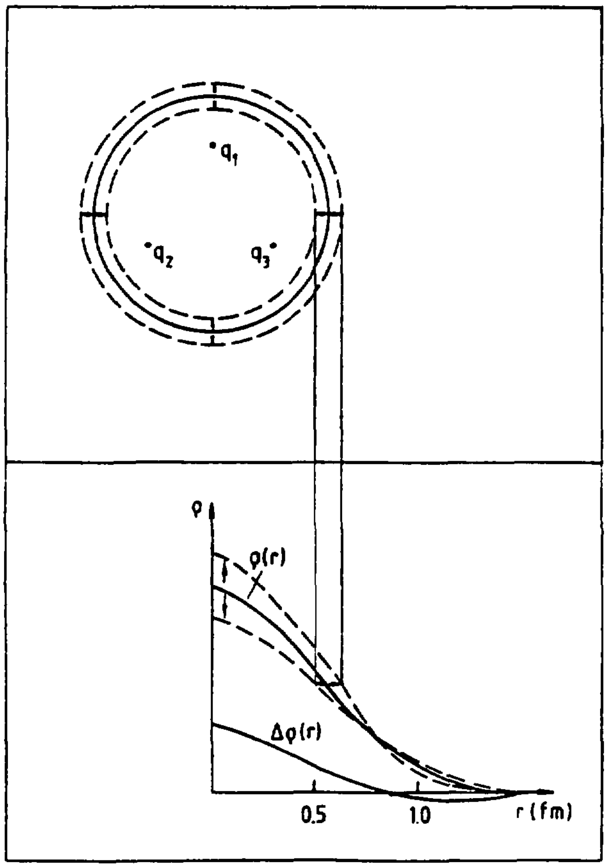

Figure 1: Character of the compression mode. Upper part: radius, lower part: density profile. Both the compression and the dilatation phase are shown in relation to the ground state density $\rho(r)$.

resonances are apparent, $N^*(1440$ MeV), called the Roper resonances, and $N^*(1710$ MeV). At the centroid energy of the first resonance the imaginary amplitude has a maximum and the real amplitude goes through zero. The second resonance appears as an interference structure with the high energy tail of the first resonance. Here it should be noted that the Roper resonance shape is quite different from that of a Breit-Wigner form with a rather steep low energy slope and a rather long fall off towards higher energies.

Electro-production: The inclusive data which exist from experiments at SLAC (see ref.14) indicate three resonance regions (see fig.3). The first resonance is entirely due to Δ excitation, the second resonance region corresponds to N^* excitation of the D_{13} and S_{11} resonances centered at 1520 MeV. The third resonance region is centered

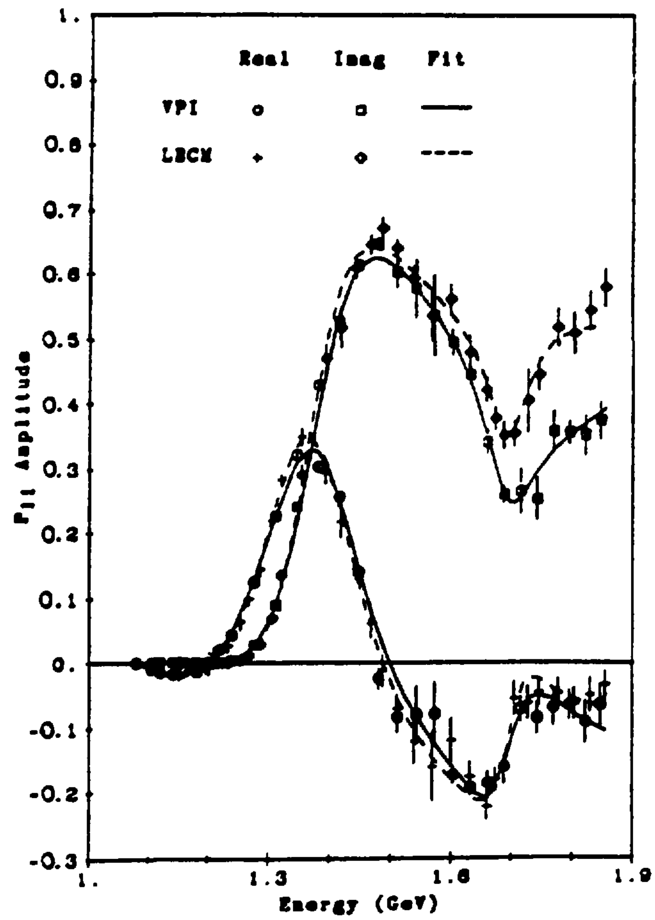

Figure 2: Real and imaginary P_{11} amplitudes from π-N phase shifts.

at 1680 MeV and is dominated by the F_{15} resonance. Under these resonances there are large background contributions which can contain other resonances. However, no evidence is found for the Roper resonance excitation.
In photo-reactions a radial excitation as discussed here is not possible.

Hadron-production: In hadron excitation of resonances the situation is somewhat different. Proton-proton scattering at high energy is dominated by Pomeron exchange, preferring excitation of isoscalar structure. Therefore the Δ resonance is only weakly excited (19 GeV/c p-p scattering data[15] from CERN are given in fig.3). The second and third resonance region is seen quite similarly as in electron scattering. In the p-p data an indication for excitation of the Roper resonance is seen, however, an unambiguous analysis of this excitation is not possible.

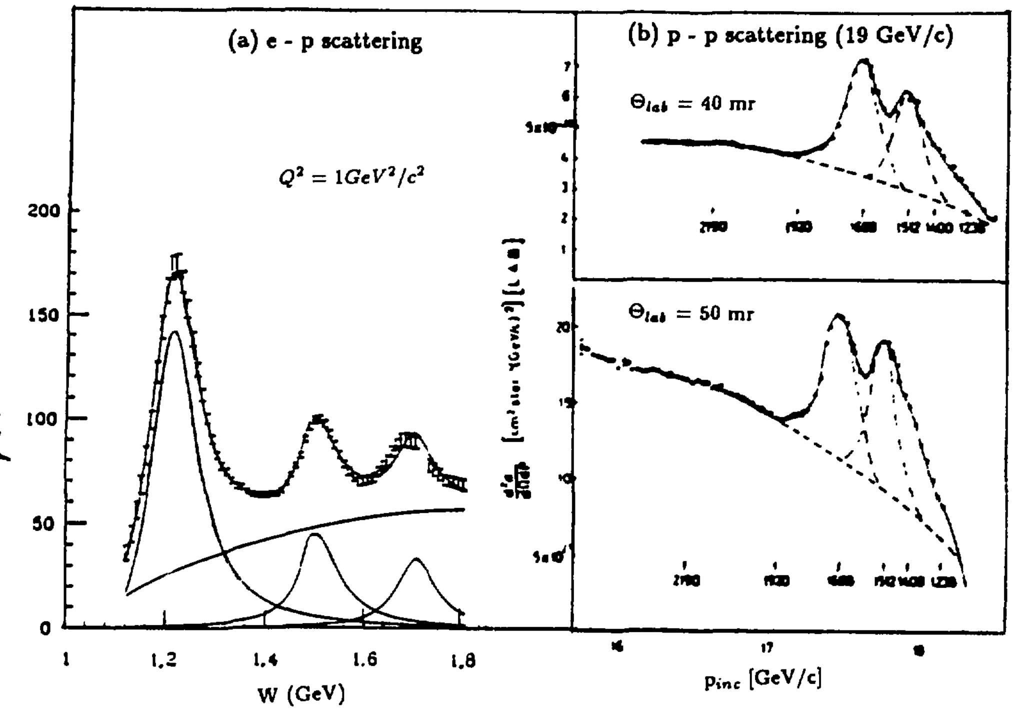

Figure 3: Spectra of baryon resonance excitation from (a) electron scattering (data from SLAC) and from (b) p-p scattering (CERN data).

It has to be concluded that the study of these radial excitations appears to be rather difficult, also in proton-nucleon scattering in the few GeV region, where the excitation spectrum is dominated by spin-isospin modes. Further, because of their particular structure, these modes are rather weakly excited in electromagnetic interactions. With real photons P_{11} resonances can be excited only by a magnetic dipole operator which does not correspond to radial excitation. By virtual photon excitation purely longitudinal excitation of P_{11} resonances is possible, but there are strong cancellation effects in the differential cross sections due to the fact, that the N^* radial wave function is orthogonal to that of the ground state. Because of these difficulties it is important to look for selective probes which may enhance the cross sections for these particular excitations.

2.2 Selective hadronic reactions

There exists the possibility to study the excitations of interest rather purely by using selective hadronic reactions. The first example is the (^{3}He,t) reaction[16] studied at SATURNE. The difference in the quantum numbers of projectile and ejectile allow

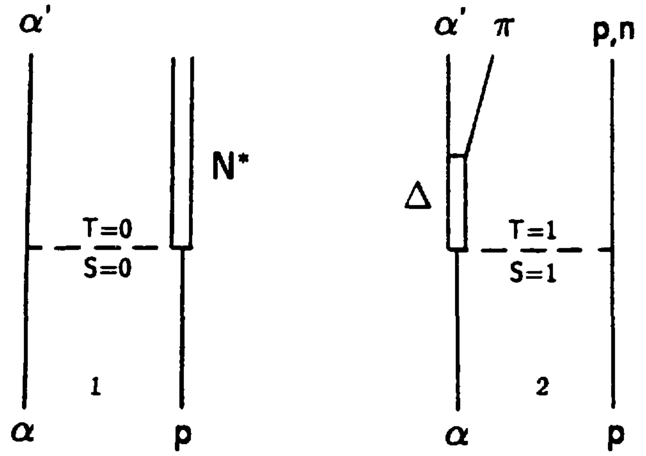

Figure 4: Graphs for target and projectile excitation contributing to the inelastic $\alpha + p \rightarrow \alpha' + X$ scattering.
1. Inelastic excitation of the target with a dominant T=0, S=0 transition in the forward scattering amplitude.
2. Projectile excitation with subsequent decay back into the α ground state by π-emission. This is dominated by a T=1, S=1 transition giving rise to Δ excitation.

for the proton only the excitation of the Δ^{++} resonance. In our case the excitation of the nucleon with α-particles is of interest. Due to the quantum numbers of the α-particle only pure spin scalar and isoscalar transitions are possible. This offers the rather unique opportunity to study the scalar structure of the nucleon including the radial mode in fig.1. For these scalar excitations operator sum rules exist which allow to connect the different properties almost model independent. For deuteron projectiles also spin-flip excitations are possible, thus allowing also the study of the spin structure of the Roper resonance.

In the investigation of these hadronic reactions there are complications due to the fact that both the target as well as the projectile may be excited during the scattering process. For the $\alpha + p \rightarrow \alpha' + X$ reaction this is demonstrated in fig.4 in which different graphs for target and projectile excitation are shown. Whereas for α-p scattering the target Δ excitation should be small, there are no selection rules which inhibit Δ excitation of the projectile. By emission of a pion this excitation decays favorably back into the α-particle ground state observed in the detector. For this process we expect large forward angle cross sections comparable to charge exchange reactions. If further the ground state decay branch $B_o : \alpha_\Delta \rightarrow \alpha_{g.s.} + \pi$ is sufficiently large (10-20%) then this contribution of projectile excitation should be observed in the inclusive spectra. Actually, in older studies of α-p scattering at SATURNE[17] a bump was observed above the π-threshold which was interpreted as coherent pion production. It is shown

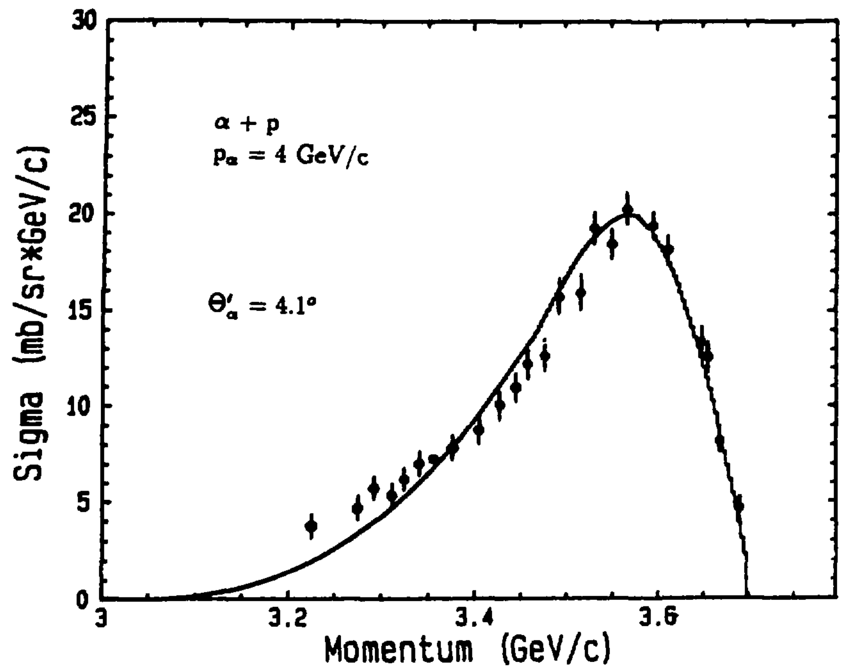

Figure 5: Momentum spectrum of inelastic scattered α-particles on hydrogen measured at an α-momentum of 4 GeV/c. The data are from ref.17.

in fig.5 that this contribution corresponds to the projectile excitation discussed here. This spectrum can be described quantitatively within a meson exchange model[18] using the impulse approximation and a ground state branching B_o of 0.3. Dependent on the non-resonant contribution this is in good agreement with the branching B_o discussed above. The appearance of this contribution in the missing mass spectra close to the pion threshold is due to the Lorentz boost in the projectile excitation. For the interpretation of our data discussed below it is important to know that the spectral shape of the projectile excitation is quite independent of the Δ resonance parameters and the detailed assumptions on the background contribution.

3. Experiment on the Roper resonance excitation

To investigate the region of the Roper resonance P_{11}(1440 MeV) α-p scattering was studied[19] at SATURNE using a beam momentum of 7 GeV/c. Scattered α-particles were measured by the Spes 4 magnetic spectrometer. A spectrum of the missing energy Ω ($\Omega = E_i - E_f$) measured at a very small scattering angle of 0.8 degree is given in fig.6. In this spectrum a very strong rise of the yield is observed at the pion-threshold, further a pronounced structure above 500 MeV is seen. The contribution due to projectile excitation is indicated by the solid line. Above the π-threshold

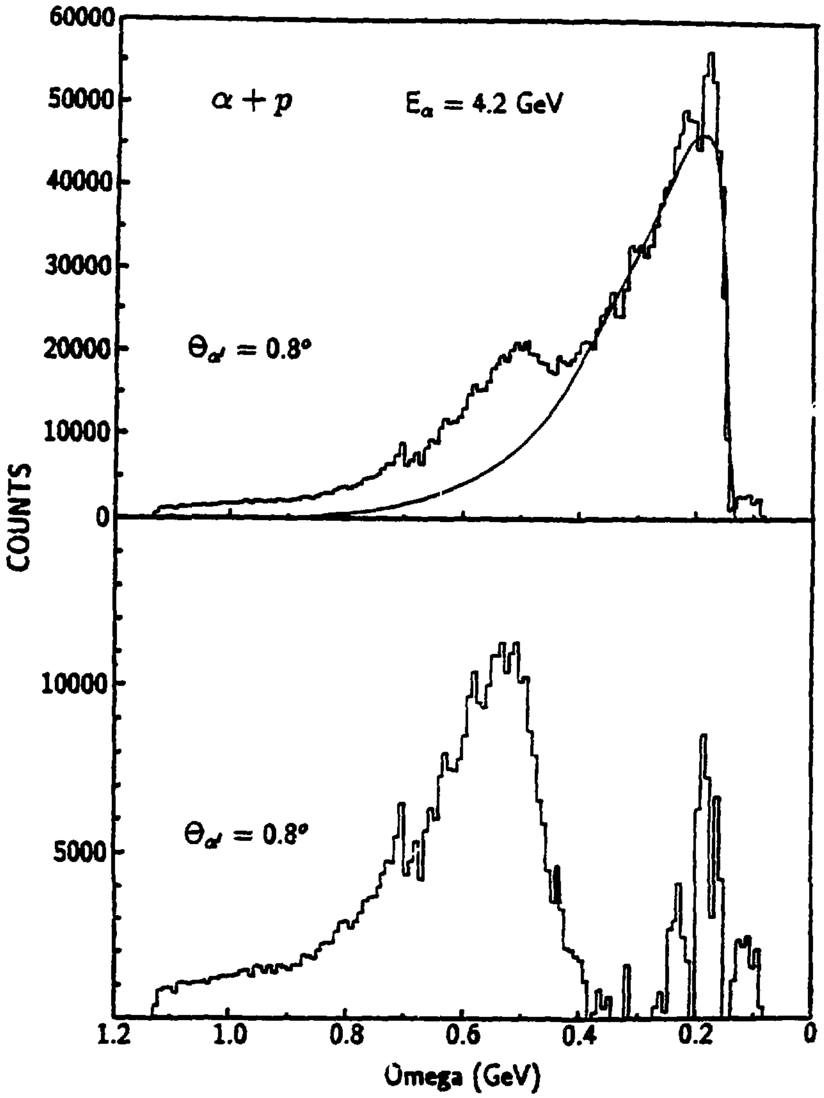

Figure 6: Missing energy Ω spectra of inelastic α-p scattering at E_α=4.2 GeV (upper part). The solid line corresponds to the spectral shape for projectile excitation. In the lower part a spectrum is shown in which the contribution due to projectile excitation is subtracted.

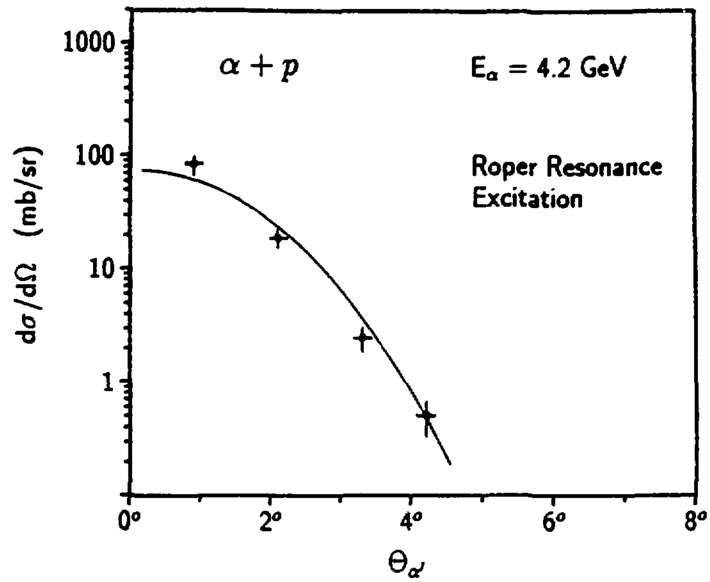

Figure 7: Differential cross sections for excitation of the P_{11} resonance. The solid line shows the calculated shape for monopole excitation.

the shape of the spectrum is quite well reproduced by the projectile contribution. However, at larger values of Ω there is a significant excess yield indicating a strong excitation of the Roper resonance region. In order to see the details of this structure, a spectrum - in which the projectile excitation contribution is subtracted from the measured spectrum - is shown in the lower part of fig.6. This shows a pronounced bump in the Roper resonance region which falls off rapidly towards larger values of Ω.

Differential cross sections are given in fig.7. They show a very steep angular dependence characteristic of monopole transitions. Estimates using simple scaling assumptions of experimental monopole cross sections indicate that the large yields obtained for the Roper resonance excitation imply a large fraction of the possible monopole sum rule strength. From this it appears possible to determine a first experimental number for the nucleon compressibility.

Projectile excitation, which is dominated by the Δ resonance[18], presents also a monopole (L=0) excitation, however, of spin-isospin structure. Therefore, the angular distribution should be quite similar for both cases. This is observed experimentally[19].

3.1 Comparison of the resonance form with π-N scattering

It is of interest to investigate whether in the α-spectra the same N*(1440 MeV) resonance is observed as in the π-N phase shift amplitudes. In fig.6 the yield above 0.9 GeV is rather flat. This may be due to more damped processes and instrumental background. If a high energy background from these effects is subtracted, the monopole strength peaks at a value of Ω which corresponds to an excitation energy of 410-420 MeV with a width of about 120 MeV. In the composite baryonic reaction in question the spectrum is cut by the α-particle form factor; therefore the dominant strength is apparent at lower values of Ω. To obtain the monopole strength function, the form factor dependence has to be unfolded. The spectrum is well described using a Breit-Wigner resonance form modified by the phase space of one and two pions and using the α-p form factor derived from elastic α-p scattering.

The tranformation into the total energy frame is given in fig.8. Unfolding the α-particle form factor yields the resonance shape given by the solid line. This curve should be compared with the total P_{11} resonance cross section in π-N scattering. The closed and open points in fig.8 correspond to the π-N phase shifts from the reanalysis by Hoehler et al.[20] which is consistent with the phase shifts given by Cutkosky and Wong[13]. The rise of the P_{11}(1440 MeV) resonance is in excellent agreement with our results. Above 1.4 GeV the deduced strength function has larger uncertainties due to the fact that the experimental spectrum at the corresponding values for Ω is already cut off significantly by the α-particle form factor. Nevertheless, we can state that there is excellent agreement of the Roper resonance form deduced from π-N phase shifts and from our data.

3.2. Description of α-scattering in the framework of the folding model

To determine the monopole strength, an effort has been made to analyse the differential cross section in a folding approach. In this model the elastic and inelastic scattering is described consistently using optical potentials which are obtained by folding the projectile and target densities with an effective interaction between the constituents of target and projectile. This may arise from scalar meson (σ) or two gluon exchange. However, a certain amount of ω exchange cannot be excluded. The differential cross sections of elastic scattering are sensitive to the scalar radius of projectile and target. To extract this "scalar" radius of the proton a consistent description of elastic α-p and α-α scattering has been performed shown in fig.9. The data[21] are well described at small momentum transfer yielding a scalar mean square radius $< r_p^2 >$ of 0.66$\pm$0.06 fm^2. This is consistent with the hadronic radius extracted from high energy experiments by Povh and Hüfner[22].

For the inelastic excitation a monopole transition density was used which was derived from a macroscopic compression of the system[23] (Taylor expansion of the compressional amplitude). We found that the absolute inelastic cross sections in fig.7 are sensitive only to the monopole matrix element and not to the details of the transition density.

The inelastic cross sections can be related to operator sum rules which allow a quite model independent analysis. Assuming a monopole transition operator in the simple form r^2, two sum rules[24] are important, the energy weighted sum $m_1 = \Sigma_i E_i <$

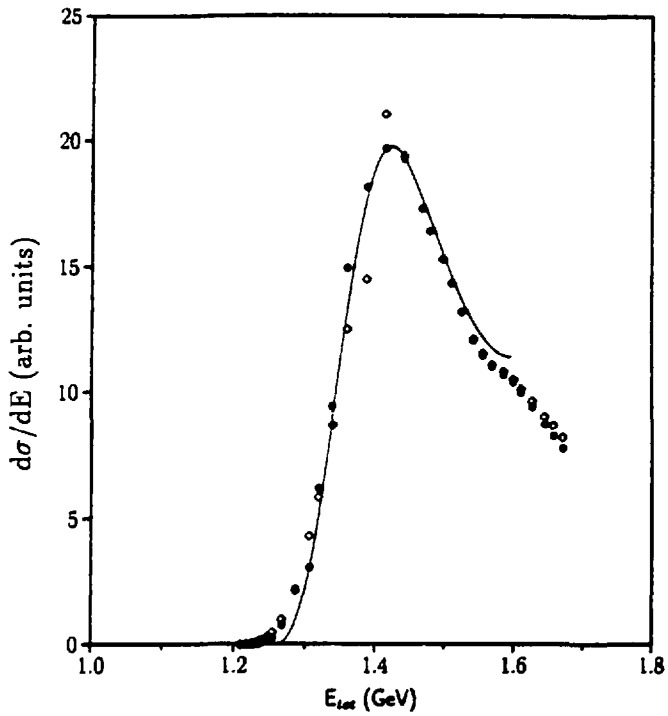

Figure 8: Total energy dependence of the cross section. Unfolding the α-p form factor gives rise to the monopole strength function given by the solid line. This is compared to the π-N P_{11} phase shifts deduced by Hoehler et al.

$f_i|r^2|i>^2$ and the energy inversely weighted sum $m_{-1} = \Sigma_i \frac{1}{E_i} < f_i|r^2|i>^2$ (where $< i|$ and $< f_i|$ represent ground and excited state wave funtions, respectively, with their energies E_i). For the nucleon the sum rule limits are given by

$$m_1 = 18(\hbar^2/m_N) < r_N^2 > . \tag{1}$$

and

$$m_{-1} = 6 < r_N^2 >^2 /K_N \tag{2}$$

where m_N is the mass and $< r_N^2 >$ is the rms radius of the scalar density. K_N is the compressibility which may be defined for spherical systems by $K_N = r^2[\frac{d^2(E/A)}{dr^2}]_{E=E_o}$, this is consistent with the definition in sect.2.

From the model independent sum rule m_1 the maximum monopole transition matrix element can be obtained

$$< r^2 >_{tr}^{max} = \sqrt{\frac{18 \cdot \hbar^2 \cdot < r_N^2 >}{m_N \cdot E_x}}. \tag{3}$$

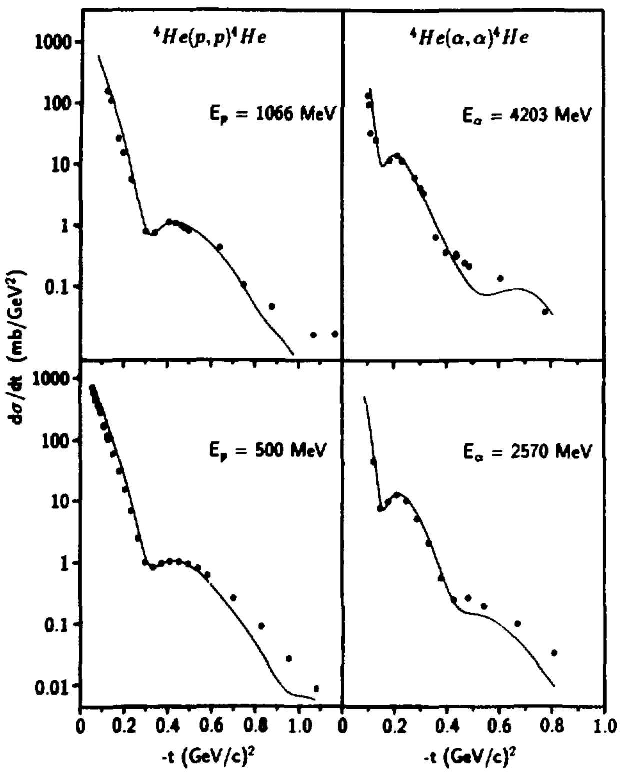

Figure 9: Differential cross sections for elastic α-p and α-α scattering. The solid line corresponds to the folding model calculation discussed in the text.

The experimental data are consistent with $< r^2 >_{tr} = 0.9$ fm^2 which corresponds to about 80 % of the energy weighted sum (3). This indicates that almost all the monopole strength in the nucleon is concentrated in the N*(1440 MeV) resonance.

A transition density which describes the sum rule strength and the data consistently requires a density form which is peaked at the surface, supporting an interpretation of the Roper resonance excitation as a compressional mode of the nucleon surface. The interior is hardly affected, its compression should require a much higher excitation energy. These conclusions appear to support the chiral bag and chiral quark model, with the monopole excitation in question corresponding to the compression of the mesonic cloud.

It is interesting to derive a value of the nucleon compressibility K_N from the experimental data. The ratio m_1/m_{-1} is related to the excitation energy of the compression modes by $m_1/m_{-1} = E_x^2$. This leads to

$$K_N = (m_N/3\hbar^2)\, E_x^2 < r_N^2 > . \qquad (4)$$

This gives an experimental estimate of $K_N = 1.4 \pm 0.3$ GeV. The errors are due to the uncertainties in the extraction of the excitation energy, the monopole matrix element as well as the energy of the remaining monopole strength.

Values of the compressibility can be derived from the different models. For the constituent quark model a value of K_N of 3 GeV is obtained using a harmonic oscillator with $\hbar\omega = 500$ MeV. More complicated versions of this model, as e.g. discussed in ref.2 give a lower compressibility. Estimates from the MIT bag are discussed in ref.25 and give K_N in the order of 0.9–1.2 GeV. From the Skyrmion model K_N in the order of 0.8–1.0 GeV is deduced. Thus, as expected from the above discussion, the extracted value of K_N lies in between the values from different models.

Experimentally, there is the exciting problem of the second monopole mode in which the compression is more in the interior of the nucleon. From the sum rule estimates it is likely that this monopole excitation lies in the P_{11}(1710 MeV) resonance. In the π–N data in fig.4 this resonance is clearly seen and has a significant branching to the nucleon ground state[13]. Therefore, a monopole component to this resonance appears quite possible.

The study of the inelastic excitation of this resonance has to be performed in an exclusive experiment in which also the decay of the resonance is measured. This is necessary, because the monopole strength is smaller than in the Roper resonance excitation, further in the region of the P_{11}(1710 MeV) resonance there are other baryon resonances of higher multipolarity which might be strongly excited. Therefore, the decay angular distribution of emitted particles has to be used to extract the multipole components. Experiments are planned at SATURNE and COSY. At SATURNE these experiments will be realized at Spes 4, with a new large angle detector around the target. In the proposed experiments at COSY the associated strangeness decay channel is chosen to enhance the signature of the P_{11}(1710 MeV) resonance. Other new possibilities of such experiments are the study of scalar polarizability effects in the nucleon.

4. Relation to other problems

The finite compressibility deduced from our experiment may have interesting consequences in other fields discussed below.

Nuclear medium modifications on nucleon properties (swelling or shrinking): The radius of a nucleon in a nucleus is directly related to the scalar structure and can be investigated if it is possible to study the Roper resonance in nuclear systems. Experiments similar to that in sect.3 have been already started on targets of Deuteron and Carbon. Preliminary results indicate that the P_{11} resonance can be observed in these systems. The details of its shape will shed light upon the importance of medium modifications.

High density phenomena in nuclear physics: There are two interesting aspects, ultrarelativistic heavy ion collisions and the structure of neutron stars. Concerning the first aspect it is expected that in the initial phase of the heavy ion reaction a system of high density is formed, characterized by the equation of state of nuclear matter. In this equation of state it is generally assumed that the nucleons are incompressible. The finite size and compressibility of the nucleon have the consequence that at a density of about twice the nuclear matter ground state density the nucleons will start to get compressed; therefore the nuclear equation of state should go over into an equation of state of baryons. In consequence a strong production of excited baryons is expected giving rise to a subsequent increase of mesonic yield.

In neutron stars we consider nuclear systems of rather stable high densities (5-10 times the nuclear ground state density). Here, the effect of the compressibility of the nucleon should be very important in creating a large flux of baryons and mesons at high speed which can carry a large fraction of the energy in the interior of the star. This effect should be taken into account in the calculation of the dynamics of these systems.

Colour transparency: Under certain favorable conditions the structure of QCD may give rise to an enhancement of the transparency of baryons travelling through nuclear matter. A necessary condition for this phenomena is, that a small nucleon is formed which interacts weakly with the nuclear medium. The probability to find a small nucleon is related to the coupling of the nucleon ground state to the radial modes of excitation discussed above. The fact, that the first radial excitation of the nucleon is quite low, in the order of 500 MeV, appears to be favorable for an eventual observation of a transparency increase.

4. Spin-structure of the Roper resonance

So far we were dealing with the radial (L=0) structure of the P_{11}(1440 Mev) resonance. The full structure of this interesting resonance contains also a spin-flip matrix element, this may give insight into the coupling of the compression to the spin degree of freedom in baryons.

The investigation of the spin-structure of this resonance is possible with hadronic and electromagnetic probes. With hadronic probes the spin-flip matrix element can be studied in inelastic deuteron scattering. Here, in addition to the pure radial excitation which should be similar to α-scattering, an isoscalar spin-flip matrix element can be determined. Simple estimates show that the measurement of the vector and tensor polarisation with polarised deuterons is well suited for this investigation. Such experiments are proposed for SATURNE.

A complementary study relates to the magnetic dipole excitation (M1) of the P_{11} resonance in photon induced reactions, a long standing problem discussed in the literature[26]. Now, new information has been obtained from recent experiments at MAMI. In the $(\gamma, 2\pi)$ reaction the cross section is dominated by the Born terms (essentially π emission plus Δ resonance excitation). However, also contributions

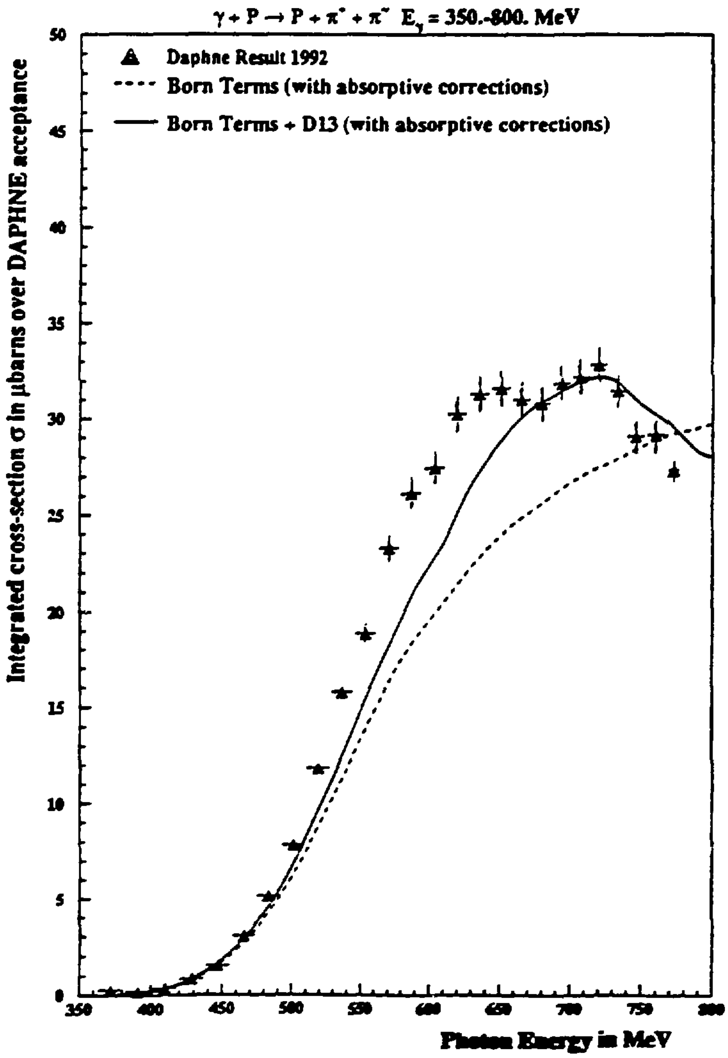

Figure 10: Integrated cross section as a function of the photon energy for the reaction $\gamma + p \to p + \pi^+ + \pi^-$. The data are from ref.27.

from N^* excitation are expected, with the largest effect due to the D_{13}(1535 MeV) resonance. The interesting question is the contribution of the P_{11}(1440 MeV) resonance to the cross section. To answer this question new data have been taken for the $(\gamma, \pi^+\pi^-)$ reaction[27] with the Daphne detector, which presents a nearly 4π detector for charged particles in a cylindrical form. With the Mainz-Glasgow tagged photon beam of MAMI the energy region of photons $50 < E_\gamma < 800$ MeV was investigated. The integrated cross sections are shown in fig.10 together with theoretical calculations[28] given by the solid and dashed lines. The dashed line represents a calculation of the Born terms including absorptive corrections similar to the Lüke, Söding model[29]. The solid line includes the D_{13} resonance. There are strong interference effects between these different contributions which give a satisfactory description around 700 MeV and above. However, at lower energy an enhancement in the data is observed which is not described by this calculation. A quantitative description of the data in this region is possible by including a magnetic dipole excitation of the Roper resonance. The preliminary coupling strength extracted is about a factor three smaller than predicted in ref.30.

6. Summary

A review of some interesting new aspects of baryon spectroscopy is given. The example of radial excitation of baryons shows that exciting features of baryons exist which should be investigated by hadronic as well as electromagnetic probes. The P_{11}(1440 MeV) resonance appears to be a very interesting resonance in which the scalar structure seems to be very large. This is supported by the partial wave analysis of the $\pi N \rightarrow \pi\pi N$ reaction[31] which has a large branching into the ϵN channel. It is of large importance to study the reaction α-N discussed above in an exclusive experiment, which is already considered. For a further study of the details of the compression and other important excitation modes (like dipole modes), more exclusive experiments are planned for SATURNE and COSY. From these investigations we hope to get a better insight into some of the basic properties of baryons.

A particularly challenging problem is the electromagnetic structure of the Roper resonance. A first rather clear indication for magnetic excitation has been discussed. Even more important is the electric excitation of the radial mode which can be studied only in the longitudinal component of electron scattering. Different from α-scattering implying a strong scalar component of the force, electro-excitation of radial modes is governed by ω-exchange. Therefore, the possible observation of a weak monopole transition to the P_{11} resonance in exclusive electron scattering would clearly prove the dominant scalar structure of this excitation. Such experiments should be pursued.

A detailed theoretical understanding of the compression effects, discussed here in simplified models, is needed. This is intimately connected to the scalar part of the strong interaction which is not well understood. A full relativistic treatment of the reactions should be used going along with realistic structure model calculations for baryon excitation. The direct relation to QCD is certainly the ultimate goal in the comprehension of these effects.

I would like to end this presentation with the statement: Baryon spectroscopy with complementary probes is a challenging area of hadronic physics for the next decade.

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Answers to the questions in the PANIC session of June 30th.

A. Iyavin, University of Tel Aviv/TRIUMF

Question: A comment: We looked for a new excitation by $pp \rightarrow X^{++}n$, where the X^{++} mass lies in the region $m_p \leq m_{X^{++}} \leq m_p + m_\pi$ (allowing X^{++} to decay only weakly). The result is negative, with an upper limit for the cross section of picobarns. It is still possible that an X^o or X^+ particle exists in a mass region below m_X=1080 MeV.

Answer: I do not see any relation between your comment and my discussion of α-p scattering.

L. Kondratyuk, ITEP, Moscow

Question: Have you compared your background in the case of the Roper resonance production by α with its production on proton beam? The latter is well known and was discussed in series of papers by Boreskov, Kaidalov and Ponomarev. The dangerous point in your case is that the α formfactor cuts large masses and this can simulate a structure in background. The background is dominated by the diffraction production of πN system with Pomeron exchange between α and pion or nucleon. The background is not suppressed by the α formfactor.

Answer: We have indeed compared our α-p background (which is essentially due to projectile excitation) with N-N scattering data in the same energy region which exist from Saturne. The projectile excitation is described similarly in both cases. However, N-N scattering is more complicated due to the strong excitation of the Δ resonance in the target which dominates the spectrum. It is certainly true that the α form factor cuts the spectrum but it cannot simulate a structure in the background. The comparison with high energy p-p scattering, which you refer to, is much less evident because the nature of the background is quite different.

N.C. Mukhopadhyay, RPI

Question 1: Suppose I don't buy your theoretical analysis of the background (BW times phase space). What happens to the properties of the Roper excitation in your experiment? Can you quote a model-independent answer?

Question 2: What happens to the compressibility of the nucleon if I treat Roper as a classic hybrid (in the sense of Close et al.)? [Carlson and I have proposed a pQCD test of this idea recently]. Use your experimental information.

Answer 1: The resonance shape of the P_{11} resonance deduced in our analysis (see fig.8) is independent of the actual form we used to fit our spectrum (BW times phase space). This form was convenient and may give some insight into the physics (because the Roper resonance is not described by a BW form).

Answer 2: The compressibility is deduced from the centroid of the monopole strength (from our experiment we deduced a large fraction of the possible monopole strength in the Roper resonance). This does not give directly a physical picture of the nature of this state except for the fact that a large monopole matrix element corresponds to compression of the system. However, I believe that by our experimental observation the hybrid interpretation of a state orthogonal to the ground state with a Fock representation 3q+g can already be ruled out. Only through a mixture of the two states (representing 3q and 3q+g) a monopole matrix element can be obtained, this, however, should be rather small in the above picture.

M.M. Islam, University of Connecticut, USA

Question: My question has to do with the nucleon structure models. Your remarks on nucleon compressibility seem to indicate that a hybrid model such as the chiral bag model or the chiral quark model is perhaps more realistic. If that is so, then we have an observable; namely, the radius of the core r_c. However, the Chesire Cat Principle would say that r_c is not an observable. Do you have any comment on this?

Answer: I believe that our observation of a strong monopole transition, which has to be described by a surface vibration, is already in conflict with the Chesire Cat principle. If in further experiments a second monopole mode could be found, this would strongly speak against the validity of the Chesire Cat principle.