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Excitation of the Roper Resonance and Study of Higher Baryon Resonances*

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Abstract

The region of the P_{11} resonance N(1440) is investigated in inelastic α-scattering on hydrogen using α-particles from Saturne with a beam momentum of 7 GeV/c. In the missing mass spectra of the scattered α-particles two effects are observed, excitation of the projectile, preferentially excited to the Δ-resonance, and excitation of the Roper resonance. The large differential cross sections indicate a structure of a compression mode. From this the compressibility of the nucleon K_N may be extracted. The Roper resonance excitation corresponds to a surface mode which may be related to an oscillation of the meson cloud. The other monopole mode which corresponds to a vibration of the valence quarks should lie at about 800 MeV of excitation or above. This is the region of the P_{11}(1710 MeV) resonance. Therefore experiments are important to measure the monopole strength in this energy region.
Another interesting aspect is the scalar polarizability which can be extracted from inelastic dipole excitations (squeezing modes) at excitation energies above 500 MeV.

The detailed experimental study of the baryon properties presents an exciting challenge in hadronic physics for the next decade since it is related to the understanding of the structure of QCD in the non-perturbative regime. For the description of the baryon properties different theoretical approaches exist: constituent quark model[1,2], bag model[3], Skyrmion model[4], further string and algebraic models[5]. 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 only the valence quarks. Sea quark effects which are important to satisfy chiral symmetry are neglected. Topological soliton models consider the baryon as a bosonic field which corresponds only to a treatment of the meson cloud arising from the polarization of the sea quarks. In the chiral bag model[6] valence and sea quark effects are taken into account. These 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.

One of the most basic degrees of freedom is the size of the baryon. 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 radial excitation modes (isoscalar monopole states) which give information on the compressibility of the system. A candidate for a radial mode of the nucleon is the P_{11}(1440 MeV) resonance.

The energy of the radial mode (excitation of a P_{11} resonance with large L=0 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[7-9], in which the radial mode is generated by the oscillation of the bag surface. In Skyrmion models[10] 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 constituent quark and the Skyrmion model may reflect the fact that the features of the sea quark or meson induced density are quite different from those of the valence quarks.

The study of these radial excitations appears to be difficult since in proton-nucleon scattering 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 structure of the transition density which has a radial node. Therefore, excitation e.g. of the Roper P_{11}(1440 MeV) is not observed clearly in electron scattering[11]. Because of these difficulties it is important to look for selective probes which may enhance the cross sections. A favorable reaction appears to be the inelastic scattering by α-particles because in the forward scattering scalar excitations are dominant due to the structure of the α-particle. This offers the rather unique opportunity to study the scalar structure of the nucleon which includes the radial modes of excitation discussed above. Further, for scalar excitations operator sum rules exist which allow to connect the different properties almost model independent.

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. 1 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 - proton scattering at Saturne[12] a bump was observed above the π-threshold which was interpreted as coherent pion production.

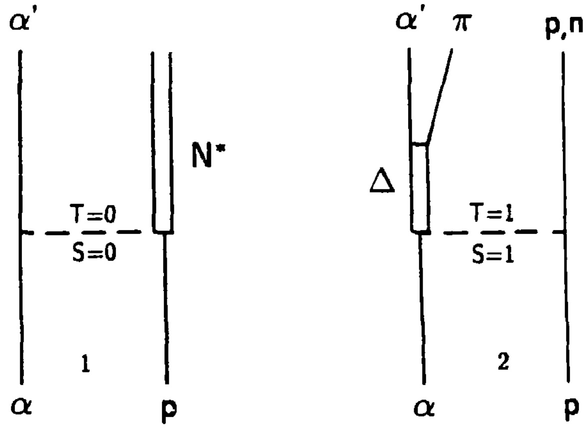

Figure 1: Graphs for target and projectile excitation contributing to the inelastic $\alpha + p \rightarrow \alpha' + X$ scattering.
1. Inelastic excitation of the target with a dominant T=0, S=0 transition in the forward scattering amplitude.
2. Projectile excitation with subsequent decay back into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

It is shown in fig. 2 that this contribution corresponds to the projectile excitation discussed here. This spectrum can be described quantitatively within a meson exchange model[13] 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.

To investigate the region of the Roper resonance P_{11}(1440 MeV), which is a candidate for a radial excitation of the nucleon, we studied α-p scattering at a beam momentum of 7 GeV/c which is close to the maximum momentum for Saturne. Scattered α-particles were measured in the SPES IV magnetic spectrometer. A spectrum of the missing energy Ω (Ω=E_i-E_f) is given in fig. 3 measured at a very small scattering angle of 0.8 degree. This shows a very strong rise of the yield at the pion-threshold and a pronounced structure above 500 MeV. The contribution due to projectile excitation is indicated by the solid line. Above the π-threshold 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. It is interesting to note that, at the smallest angle measured, this excitation is sufficiently large to produce a bump in the inclusive spectrum. In order to see the details of this structure, the difference spectrum - in which the projectile excitation

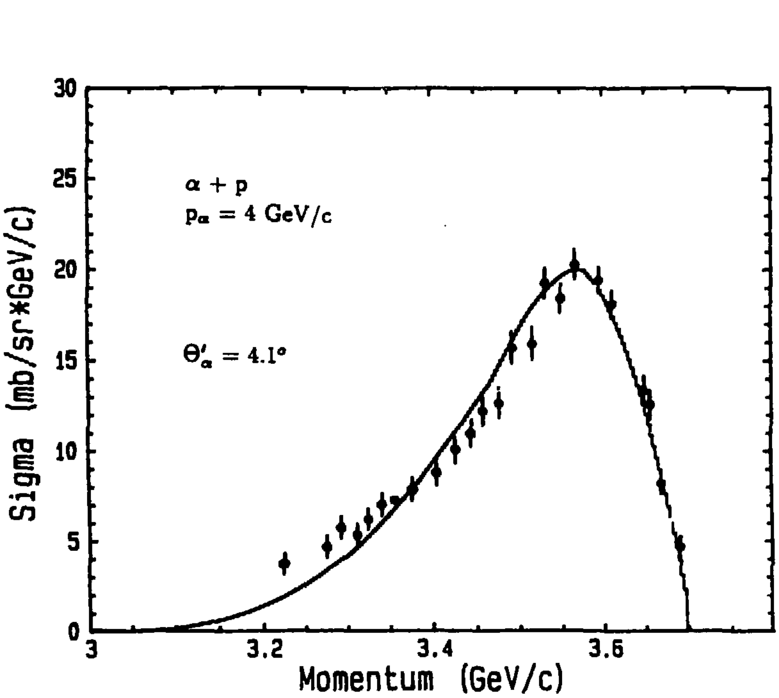

Figure 2: Momentum spectrum of inelastic scattered α-particles on hydrogen measured at an α-momentum of 4 GeV/c. The data are from ref. 2.

contribution is subtracted from the measured spectrum - is shown in the lower part of fig. 3. This shows a pronounced bump in the Roper resonance region which falls off rapidly towards larger values of Ω. Above 0.9 GeV the yield is rather flat. This is the region of the D_{13}(1520 MeV) and S_{11}(1535 MeV) resonances which can be excited in inelastic α-scattering by L=1 transfer.

In the experimental spectra in fig.3 the monopole strength peaks at a value of Omega which corresponds to an excitation energy of 410-420 MeV with a width of about 120 MeV. Due to the momentum transfer dependence of the α-particle form factor, which has to be taken into account, the strength is shifted to lower values of Omega. To obtain the monopole strength function, the form factor dependence has to be unfolded. This is only known for small momentum transfers[14]; the extrapolation gives rise to uncertainties in the extracted resonance parameters. Our estimates give a shift of only 30-50 MeV in the peak energy and a 30-60 MeV increase in the resonance width, indicating a P_{11}-resonance at a mass of about 1400 MeV with a width of about 160-170 MeV. The energy is rather low in comparison with the average energy from π-N phase shift analyses[15,16]. Amplitudes of recent π-N phase shift analyses[16] are given in fig.4. The zero position in the real amplitude and the maximum in the imaginary part are located at a mass of about 1440 MeV. The discrepancy of this with the center of the monopole strength in our data may be due to the following effects: there could be a background problem in the π-N phase shifts because the P_{11} amplitudes are relatively small. Another problem could arise from the α-particle form factor which is

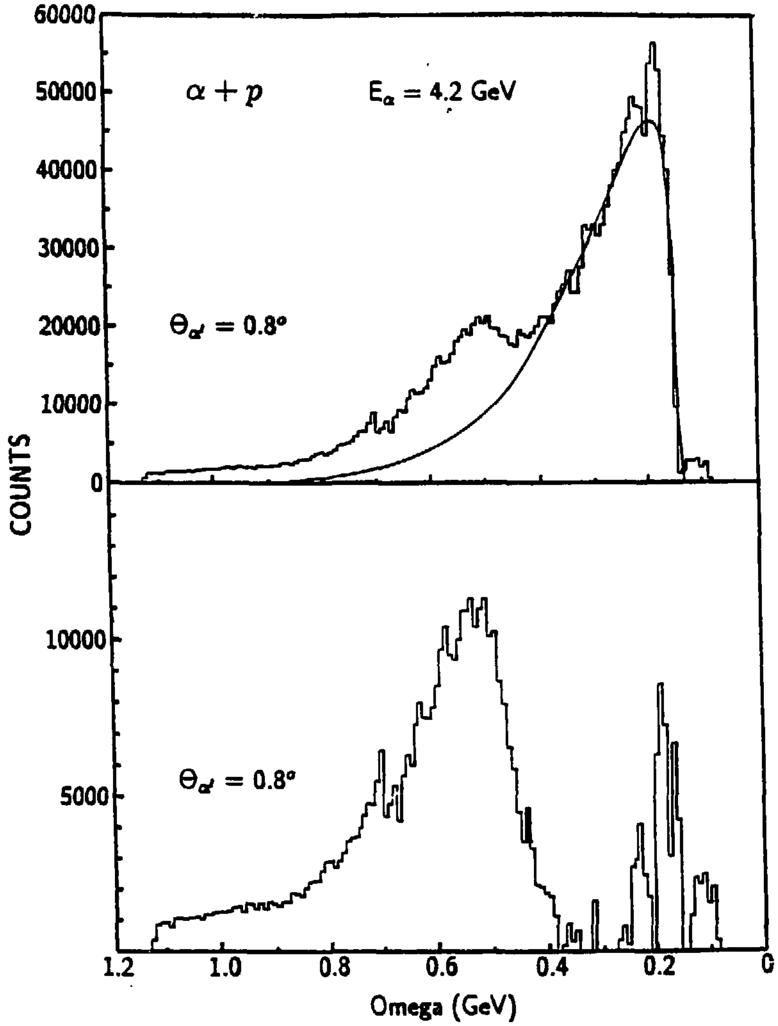

Figure 3: Missing energy Ω spectra of inelastic α-p scattering at E_α=4.2 GeV (upper part). The solid line corresponds to the spectral shape for projectile excitation. In the lower part the difference spectrum is shown.

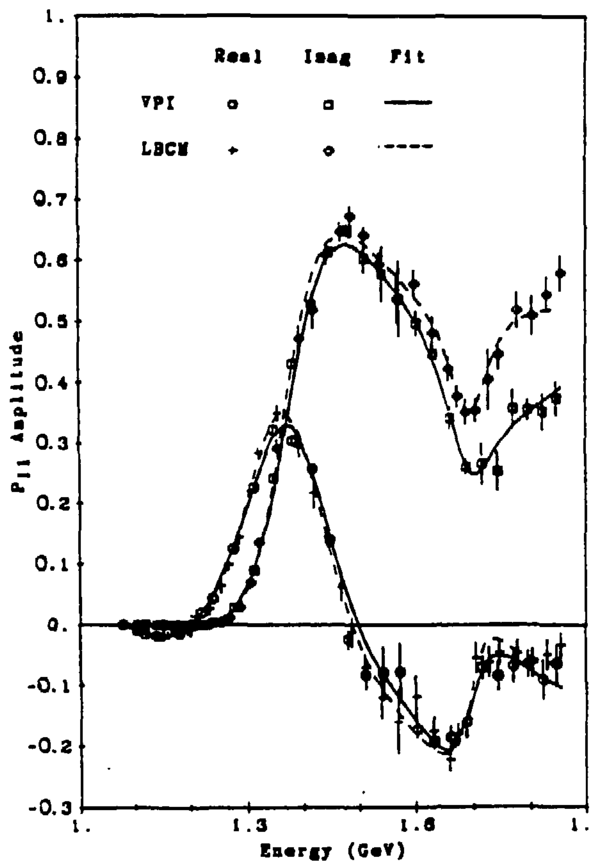

Figure 4: Real and imaginary amplitudes of π-N phase shifts.

not known sufficiently well at large momentum transfers. It might also be possible that only the lower part of the Roper resonance has a strong monopole matrix element. This would indicate a change of the properties across the resonance.

Differential cross sections are given in fig.5. They show a very steep angular dependence characteristic of monopole transitions. Estimates using simple scaling assumptions of experimental monopole cross sections[17] indicate that the large yields obtained for the Roper resonance excitation imply a large fraction of the monopole sum rule strength.

Projectile excitation, which is dominated by the Δ resonance[13], presents also a monopole (L=0) excitation, however, of spin-isospin structure. Therefore, the angular distribution should be quite similar for both cases. A somewhat flatter angular distribution for projectile excitation is expected due to the emission of a pion.

To obtain the monopole sum rule 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 obtained by folding the projectile and target density with an effective interaction arising from scalar meson (σ) and gluon exchange. For the elastic channel the nucleon ground state density was used whereas for the inelastic excitation a transition density has been derived consistent with scalar sum rules. In fig.6 differential cross sections for elastic α–proton scattering are given which are well described by the potential approach using a scalar mean square radius of about 0.60 fm^2.

The scaling of the inelastic cross sections as well as the properties of compression modes are related to operator sum rules which allow an almost model independent analysis. Assuming a monopole transition operator in the simple form r^2, two sum rules are important, the energy weighted sum $m_1 = \Sigma_i E_i < f_i|r^2|i >^2$ 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). Assuming a one density system the sum rule limits are given for our case by

$$m_1 = 2(\hbar^2/m_o) \cdot N < r_N^2 > \quad (1)$$

and

$$m_{-1} = 2 \cdot N < r_N^2 >^2 / K_N. \quad (2)$$

where m_o is the mass of the particles in motion, N is the particle number, and $< r_N^2 >$ relates to the rms radius of the scalar nucleon density which is not well known. K_N is the nucleon compressibility which may be defined for spherical systems by $K = r^2 \cdot \frac{d^2(E/A)}{dr^2}$; this corresponds to the curvature in the equation of state of the system at the minimum (ground state energy).

It is interesting to derive a value of the nucleon compressibility K_N from 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

$$K_N = (m_o/\hbar^2)\ E_x^2\ < r_N^2 > \ . \quad (3)$$

This formula has been discussed in detail for the excitation of the giant monopole resonance in nuclear systems[18] and can be applied also for the nucleon in first approximation. In eq.(3) N cancels out but is important in the energy weighted sum which gives the monopole matrix element.

In the constituent quark model m_o relates to the constituent quark mass m_q. However, in this model the ground state rms radius is directly related to the oscillator constant by the virial theorem giving rise to a nucleon radius which is far too small, ($< r_N^2 > \sim 0.37$ fm^2). Therefore, the radial properties can only be understood by the inclusion of sea quark or mesonic effects. The inclusion of this gives rise to two contributions in the sum rules m_1 and m_{-1}, a volume and a surface contribution due to the valence and sea quarks, respectively. The immediate consequence of this is that two compression modes should exist, a low energy mode (oscillation of the meson induced surface density) at an excitation energy of about 400 MeV which resembles the collective mode in the Skyrme model. The other mode is at high energy and corresponds to the monopole mode in the constituent quark model. Therefore, the monopole mode observed in our experiment should correspond essentially to a vibration

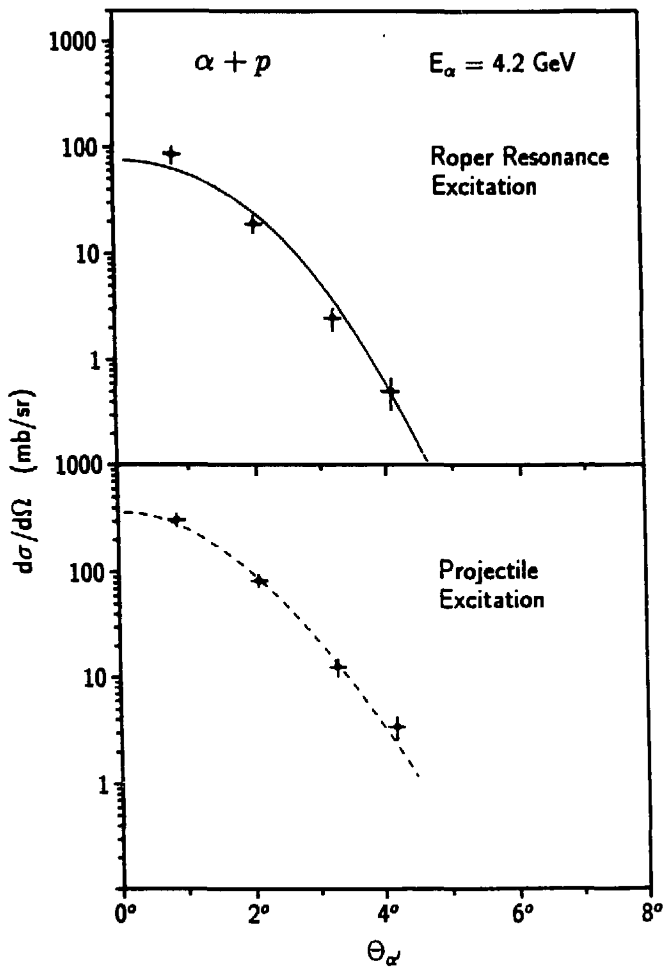

Figure 5: Differential cross sections for excitation of the P_{11} resonance excitation (upper part) and of the projectile (lower part). The solid line shows the calculated shape for monopole excitation.

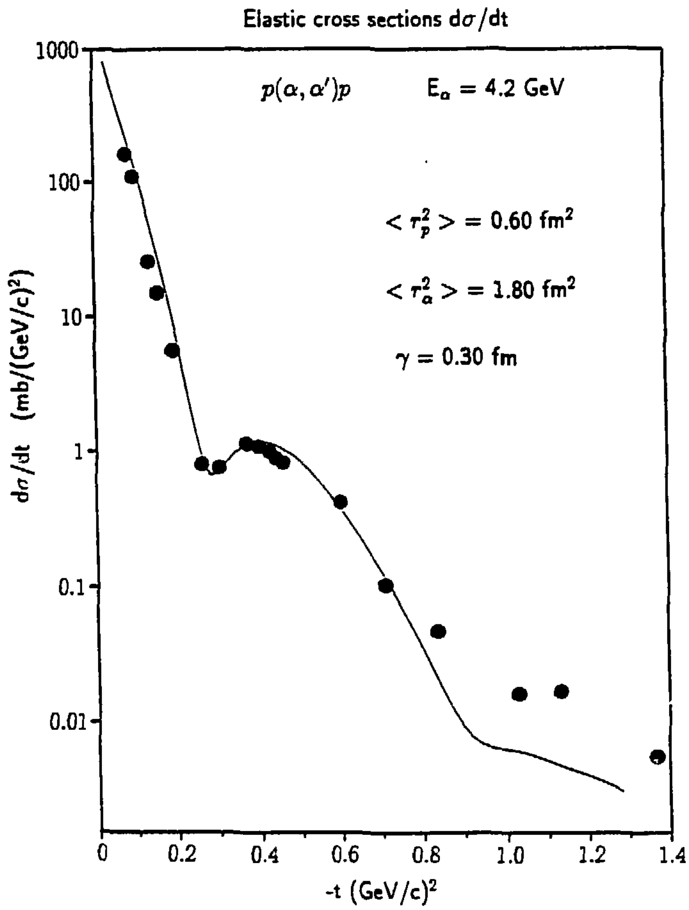

Figure 6: Differential cross sections for elastic alpha–proton scattering. The solid line corresponds to the folding model calculation discussed in the text.

of the surface density. In this approach there are clear predictions for the sum rule strength in the Roper resonance which can be compared to the differential cross section in fig.5. The shape and height of the differential cross section is well reproduced (solid line in fig.4) using a monopole matrix element $< r_{tr} >^2$ of about 0.8 fm^2 which corresponds to a sum rule strength of about 80%. This is consistent with a scalar nucleon mean square radius of about 0.60 fm^2 in good agreement with $< r_N^2 >$ deduced from the analysis of the elastic α-N scattering (fig.6). This scalar radius is quite similar to the hadronic radius of the proton extracted from high energy collisions[19].

The extraction of K_N by using eq.(3) is rather uncertain due to the fact that m_o is not known. Also it is not clear to which extent the energy weighted sum is covered. This can be improved by using a more detailed sum rule approach which takes into account explicitely valence and sea quarks. The resulting value of K_N is in the range of 1.6 – 1.8 GeV.

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 much lower compressibility. Estimates from the MIT bag are discussed in ref.20 and give K_N in the order of 900-1200 MeV. The Skyrmion model gives K_N in the order of 800–1000 MeV, respectively, if a value of $< r_N^2 >$ of 0.6 fm^2 is used (as discussed above). Thus, as expected from the above discussion, the extracted value of K_N lies in between the values from different models.

Experimentally, there is now the exciting problem of the second monopole mode which is mainly due to motion of the valence quarks. 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. 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 for the Roper resonance excitation, further in the region of the P_{11}(1710 MeV) resonance there are other baryon resonances of higher multipolarity which should be excited strongly. Therefore, the decay angular distribution of emitted particles has to used to extract the multipole components. The study of the decay channels $P_{11} \rightarrow p + \pi^o$ and $P_{11} \rightarrow p + \pi^+\pi^-$ (with dipole and isotropic angular distribution, respectively) should give clear information on the monopole component. At SATURNE these experiments may be realized at Spes 4, with a new large angle detector around the target. There are also plans for exclusive experiments with the large time-of-flight detector at COSY. Such multidetector arrangements are generally very useful for the study of many problems concerning baryon resonances.

A completely new possibility of such experiments is the study of scalar polarizability effects in the nucleon. Recently, experiments have been performed to study the electromagnetic polarizability of the nucleon. The same effects arising from the strong interaction are also of fundamental interest. One possibility is to study this effect close to the pion threshold. Such experiments are already under consideration. Further, this problem is related to the excitation of baryon resonances by scalar dipole transitions which are expected at excitation energies above 500 MeV. A very interesting by-product of such investigations would be information on the intrinsic deformation of the nucleon caused by the strange quark content.

In summary, a strong excitation of the Roper resonance has been observed in α-proton scattering which demonstrates that this resonance represents the lowest compressional mode of the nucleon. For the first time an experimental estimate of the compressibility of the nucleon has been obtained which lies between the values deduced from different models. To study 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 the basic properties of baryons.

* Saturne experiment performed in collaboration with:

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