RADIAL EXCITATION OF THE $P_{11}(1440 \text{ MeV})$ RESONANCE AND
THE COMPRESSIBILITY OF THE NUCLEON

H. Peter MORSch
Institut für Kernphysik, Forschungszentrum Jülich
D-5170 Jülich, Germany
and
Laboratoire National SATURNE
CE Saclay, F-91191 Gif-sur-Yvette Cedex, France

Invited contribution presented at the
International Nuclear Physics Conference
26.7 - 1.8.1992, Wiesbaden, Germany

Centre National de la Recherche Scientifique
Commissariat à l'Energie Atomique
Invited contribution presented at the International Nuclear Physics Conference
26.7. - 1.8. 1992, Wiesbaden, Germany

Radial Excitation of the P_{11}(1440 MeV) Resonance and
the Compressibility of the Nucleon*

H. Peter Morsch

Institut für Kernphysik, Forschungszentrum Jülich
D-5170 Jülich, Germany
and
Laboratoire National Saturne
F-91191 Gif-sur-Yvette Cedex, France

Abstract
The excitation 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 which the compressibility of the
nucleon K_N is deduced to be 1.4 ± 0.3 GeV.

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 model1, bag model2,
Skyrion model3, further string and algebraic models4 as well as combined models, like
the chiral bag5. These models are based on rather different concepts for the structure of
the nucleon and give different predictions for certain properties of baryon resonances.

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
excitations) 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 study of these radial excitations appears to be difficult since in proton-nucleon scat-
tering the excitation spectrum is dominated by spin-isospin modes. Further, because
of their particular structure, these modes are weakly excited in electromagnetic interac-
tions. 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.
Figure 1: Graphs for target and projectile excitation contributing to the inelastic $\alpha + p \to \alpha' + X$ 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 $\alpha$ ground state by $\pi$-emission. This is dominated by a $T=1$, $S=1$ transition giving rise to $\Delta$ excitation.

In the analysis 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 $\alpha + p \to \alpha' + X$ reaction this is demonstrated in fig. 1 in which different graphs for target and projectile excitation are shown. Whereas for $\alpha$-p scattering the target $\Delta$ excitation should be small, there are no selection rules which inhibit $\Delta$ excitation of the projectile. By emission of a pion this excitation decays favorably back into the $\alpha$-particle ground state observed in the detector. For this process we expect large forward angle cross sections if the ground state decay branch $B_0$ is sufficiently large (about 20%). In fact, this contribution describes well the old $\alpha$-proton scattering spectra from Saturne$^6$.

To investigate the region of the Roper resonance $P_{11}(1440$ MeV), $\alpha$-p scattering was studied at an $\alpha$ beam momentum of 7 GeV/c which is close to the maximum momentum for Saturne. Scattered $\alpha$-particles were measured in the SPES IV magnetic spectrometer. A spectrum of the missing energy $\Omega$ ($\Omega=E_e-E_f$) is given in fig. 2 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 the projectile excitation is indicated by the solid line. Above the $\pi$-threshold the shape of the spectrum is quite well reproduced by the projectile contribution. However, at larger values of $\Omega$ there is a significant excess yield indicating a strong excitation of the Roper resonance region. In order to see the details of this structure, the difference spectrum - in which the projectile excitation contribution is subtracted from the measured spectrum - is shown in the lower part of fig. 2. This shows a pronounced bump in the Roper resonance region which falls off rapidly towards larger values of $\Omega$. Above 0.9 GeV the yield is rather
Figure 2: Missing energy $\Omega$ spectrum of inelastic $\alpha$-p scattering at $E_\alpha=4.2$ GeV (upper part). The solid line corresponds to the spectral shape for projectile excitation. In the lower part the difference spectrum is shown.

flat. This is the region of the $D_{13}(1520$ MeV) and $S_{11}(1535$ MeV) resonances which can be excited in inelastic $\alpha$-scattering by $L=1$ transfer.

In the experimental spectra 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 $\alpha$-particle form factor, which has to be taken into account, the strength is shifted to lower values of Omega. 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 $\pi$-N phase shift analyses. The differential cross sections show a very steep angular dependence characteristic of monopole transitions.
To obtain the monopole strength the differential cross section are analysed in a folding model approach. The inelastic cross sections as well as the properties of compression modes can be 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 $m_1 = \sum_i E_i \langle \langle r^2 | \psi_i \rangle \rangle^2$ and the energy inversely weighted sum $m_{-1} = \sum_i \frac{1}{E_i} \langle \langle r^2 | \psi_i \rangle \rangle^2$ (where $\langle \psi_i \rangle$ and $\langle \psi_f \rangle$ represent ground and excited state wave functions, respectively, with their energies $E_i$). For the nucleon this gives

$$m_1 = 18(\hbar^2 / m_N) \cdot < r_N^2 >$$

and

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

where $m_N$ is the nucleon mass 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 $K = r^2 \cdot \frac{d(E/A)}{dr^2}$; this corresponds to the curvature in the equation of state of the system at the minimum (ground state energy).

Using a scalar nucleon mean square radius $< r_N^2 >$ of 0.60 fm$^2$, deduced from elastic $\alpha$-N scattering, the differential cross section corresponds to 80% of the sum rule (1). This gives a value of the nucleon compressibility of $K_N$ of 1.4 ± 0.3 GeV. The uncertainties are due to the errors in the excitation energy, the sum rule strength and 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. Estimates from the MIT bag are discussed in ref.9 and give $K_N$ in the order of 900-1200 MeV. The Skyrmion model gives $K_N$ in the order of 800-1000 MeV. Thus, the extracted value of $K_N$ lies in between the values from different models.

In summary, a strong excitation of the Roper resonance has been observed in $\alpha$-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. To study the details of the compression exclusive experiments are planned for SATURNE and COSY. From this we hope to get a better insight into the basic properties of baryons.

* Saturne experiment performed in collaboration with:

W. Spang, F. Plouin, M. Boivin, Y. Yonnet, LNS Saclay.
R. Frascarìa, R. Siebert, E. Warde, J.P. Didelez, IPN Orsay.
B. Saghai, DPhN Saclay.
W. Jacobs, Indiana University Cyclotron Facility, USA.
P. E. Tegnér, University of Stockholm, Sweden.
P. Zupranski, Institute for Nuclear Studies, Warsaw, Poland.
REFERENCES:


8. sum rules have been discussed for the nuclear case e.g. by O. Bohigas, A.M. Lane and J. Martorell, Phys. Rep. 51 (1979) 276; and B.K. Jennings and A.D. Jackson, Phys Rep. 66 (1980) 143

Laboratoire National Saturne
91191 Gif-sur-Yvette Cedex France
Tél : (1) 69 08 22 03
Téléfax : (1) 69 08 29 70
Bifnet : SATURNE @ FRCPN 11
Télex : ENERG X 604641F