MESONIC DECAYS OF BARYON RESONANCES IN NUCLEI AND COMPRESSED HADRONIC MATTER*

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As any composite, complex system the nucleon exhibits a rich excitation energy spectrum. The structure of these excitations — often called resonances because of their large decay widths — can be studied in π-induced and photonuclear reactions. In experiments at the electron accelerator MAMI mesonic decays of free resonances and of resonances bound in complex nuclei have been studied with the photon spectrometer TAPS. By comparing free to bound resonances, one is sensitive to possible modifications of baryon properties within the surrounding nuclear environment. An ensemble of mutually interacting baryon resonances can be generated in the central zone of relatvistic heavy ion collisions as demonstrated in systematic studies of meson production at the heavy ion synchrotron SIS, utilizing TAPS and other detector systems.

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Introduction

In the 60's Friedman, Kendall and Taylor *et al.* [1] discovered quarks and gluons as constituents of the nucleon in their pioneering inelastic electron scattering experiments. First experimental evidence for an internal structure of the nucleon was, however, provided already in the 50's by the observation of the lowest excited non-strange state of the nucleon, the Δ-resonance [2]. As any composite system the nucleon can be excited to a rich excitation energy spectrum determined by the interactions among the constituents. The excited states of the nucleon decay predominantly by the strong interaction with lifetimes of the order of $5{\cdot}10^{-24}$s corresponding to decay widths of around 100 MeV. Due to this large spread in energy these states are often referred to as baryon resonances. As illustrated in Fig. 1 all resonances

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have a strong branching into the nucleon+meson (mostly pion) channel. The excited states of the nucleon are characterized by their isospin I, spin J and mass and are further labelled according to the relative angular momentum l of the nucleon and the emitted meson ($l = 0, 1, 2 \ldots \cong$ S,P,D...) in the exit channel. While π-emission ($I = 1$) is possible from $I = 1/2$ as well as $I = 3/2$ states, isospin conservation in strong interactions restricts η-emission ($I = 0$) into the groundstate to decays of $I = 1/2$ resonances.

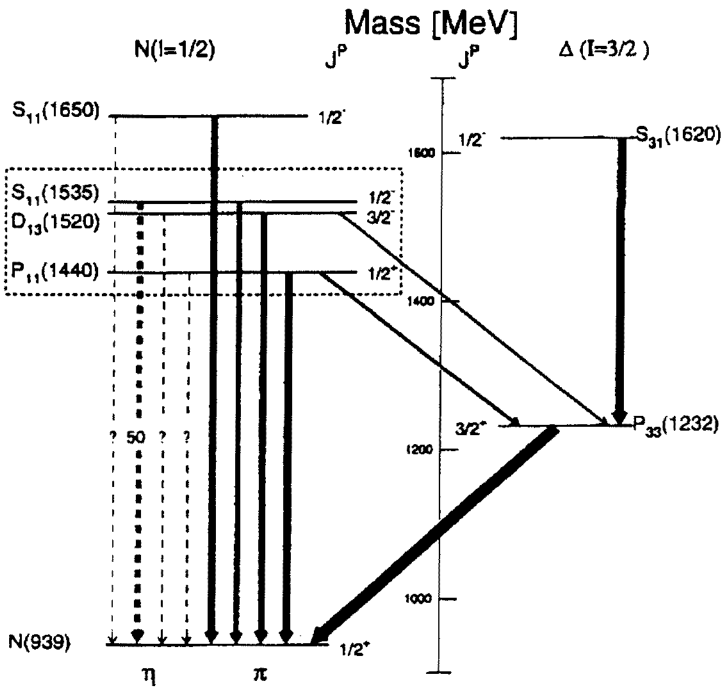

Fig. 1. The excitation energy spectrum of the nucleon up to a mass of 1.7 GeV/c^2. Decay modes are indicated.

One of the puzzling features of ($I = 1/2$) resonances is the strong ($\approx$50%) branching of the $S_{11}(1535)$ resonance into the $N\eta$ channel while the resonance with the same quantum numbers at 1650 MeV/c^2 only has an η-branching ratio of $\approx$1%. This observation is related to details of the baryon structure and only recently model calculations have been performed [3, 4] which may provide a quantitative description of these measured branching ratios. Experimentally, this selectivity can be exploited to tag excitations of the $S_{11}(1535)$ resonance by the observation of η-mesons, which is difficult in the π-channel in view of several overlapping, π-emitting resonances.

This presentation is structured as follows: We will begin by discussing the properties of free baryon resonances and presenting recent results on the photo-excitation and η-decay of the $S_{11}(1535)$ resonance. Subsequently we will address the question to what extent baryon resonances preserve their identity and whether their properties are modified in the nuclear medium. In a third step we will extend our discussions to an ensemble of mutually interacting, excited nucleons generated in the collision zone of relativistic nucleus-nucleus collisions. The composition of this form of hadronic matter and the consequences for particle production will be presented. Finally an outlook will be given on future experiments in the field of baryons and mesons utilizing new facilities and instrumentation.

1. The properties of free baryon resonances

The general features of the excitation energy spectrum of the nucleon and the properties of most baryon resonances have been determined from pion elastic and inelastic scattering. The baryon spectrum can be fairly well accounted for by *e.g.* the constituent quark model, according to which quarks are confined in a three-dimensional spin-independent harmonic oscillator potential. For a more detailed description of the excitation energy spectrum a spin-dependent quark-quark interaction has to be included which — depending on the model — is mediated by *e.g.* one-gluon exchange or the exchange of pseudoscalar mesons as discussed by Riska [3] in a contribution to this conference and in [4, 5]. These model descriptions, which have quite some predictive power, can be tested with high precision photoproduction data which have become available with the advent of modern continuous wave electron accelerators.

As an example Fig. 2 shows the excitation function for the $p(\gamma,\eta)p$ reaction which exhibits a steep rise near the production threshold arising from the population of the $S_{11}(1535)$ resonance. Details of this measurement performed with the TAPS detector (Two Arm Photon Spectrometer) at MAMI (E_e=850 MeV) are described by Krusche [6] in a contribution to this conference and in [7]. The accuracy of the data allowed for a re-determination of the η-mass to $m_\eta = (547.12\pm0.06\pm0.25)$ MeV/c^2 consistent with a recent SATURNE measurement [8]. A Breit–Wigner fit to the data allowing for a momentum dependent width gives resonance parameters for the mass W_R=(1544±13) MeV/c^2 and width Γ_R=(200±40)MeV, consistent with the values quoted by the Particle Data Group [9].

The s-wave character of the $N(1535)$ resonance is confirmed by the completely isotropic angular distribution near the production threshold. Small deviations from isotropy at higher energies are a measure for the excitation and η-decay of the $D_{13}(1520)$ resonance. Investigating the $2\pi^0$-exit channel

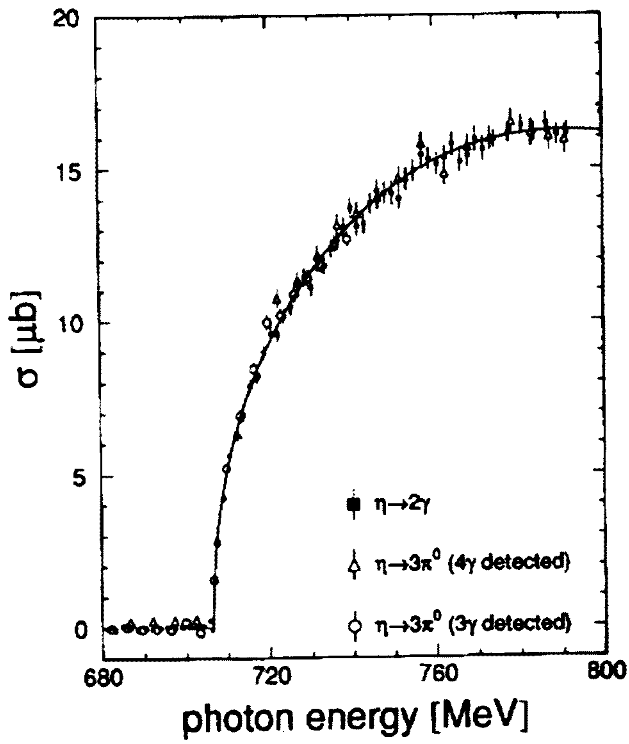

Fig. 2. The cross section for the reaction p(γ, η)p as a function of the incident photon energy. The data from different η-meson decay channels and correcteobservedd for their respective branching ratios are indicated. The figure is taken from [7].

the two-step decay of the D_{13}-resonance via $D_{13} \rightarrow \Delta\pi^0 \rightarrow N\pi^0\pi^0$ could be established by a careful analysis of correlations in a Dalitz-plot for the three particles in the final state.

The strength of the electromagnetic coupling between the nucleon ground state and excited states is a very sensitive test for baryon models. Since the electromagnetic interaction violates isospin conservation the S_{11} excitation has to be studied on the proton and on the neutron to deduce the complete electromagnetic transition amplitude. The photo-production of the η-meson off the neutron has been extracted from a measurement on the deuteron in quasi-free kinematics. Electromagnetic coupling constants for the S_{11}(1535)

resonance derived in this way [6, 10] are in rather good agreement with quark model predictions.

This is only an illustration for the richness and high quality of baryon resonance data recently obtained at high duty factor electron accelerators. Measurements of this kind will be extended to higher baryon resonances at *e.g.* the accelerators ELSA (E_e=3 GeV) and CEBAF (E_e=6 GeV) as well as at the high momentum π-beam soon available at GSI [11].

2. The properties of baryon resonances bound in nuclei

The availability of high precision data on free baryon resonances forms the basis to learn how these properties are modified when excited nucleons are embedded in the nuclear medium. It might be naively expected that any resonance structure would be broadened in a nucleus due to Fermi motion, collisional broadening ($N^*N \to N^*N$) and additional decay modes (*e.g.* $N^*N \to NN$) that are not available for free baryon resonances. Resonance excitations in nuclei may, however, also be narrowed by medium effects due to Pauli blocking of final states, *e.g.* the decay $\Delta \to N\pi$ is prohibited if the final state of the nucleon is occupied.

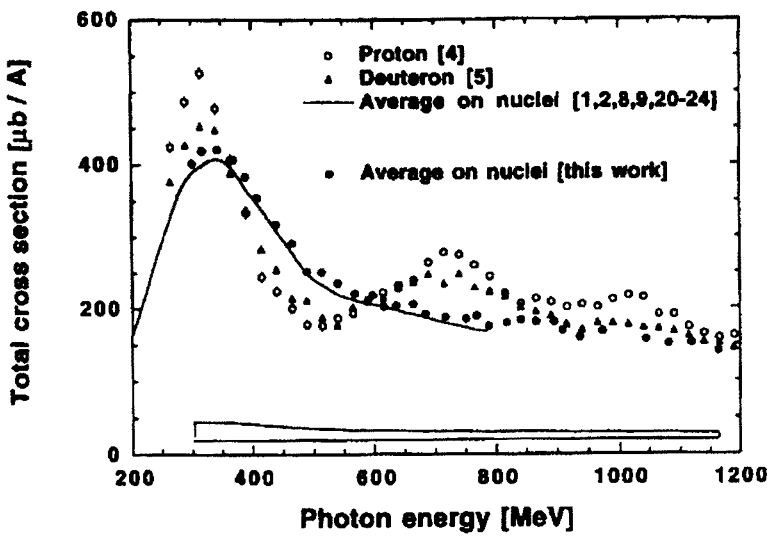

Fig. 3. The cross section per nucleon for photon absorption on various nuclei compared to the elementary cross section on the nucleon. The band at the bottom indicates the systematic uncertainties. The figure is taken from [12].

The first question is whether excited nucleons preserve their identity within complex nuclei. Fig. 3 shows a comparison of photo-absorption data on the nucleon and on nuclei demonstrating convincingly the existence of Δ's in nuclei. The Δ-structure is clearly visible, broadened by about 30% with a centroid shifted to higher energies by about 30 MeV compared to the proton data. In contrast, little if any evidence for discrete higher resonance structures can be extracted from the data on nuclei. One has to keep in mind, however, that the structure in the proton data at 700 MeV arises from several overlapping resonances and that the increase in cross section between 500 and 700 MeV is not due to a higher resonance but to the opening of new reaction channels, *e.g.* double pion production, largely dominated by charged pion production via the so-called Kroll–Ruderman Δ-term. Consequently, it is difficult to deduce quantitative information on the in-medium properties of higher resonances from inclusive data such as photo-absorption.

An exclusive reaction like η-production via the $S_{11}(1535)$ resonance appears more suitable to answer this question. Quasifree photo-production of η-mesons has been studied for a series of nuclei [13]. The results are shown in Fig. 4 in comparison to a model analysis with proper treatment of Fermi

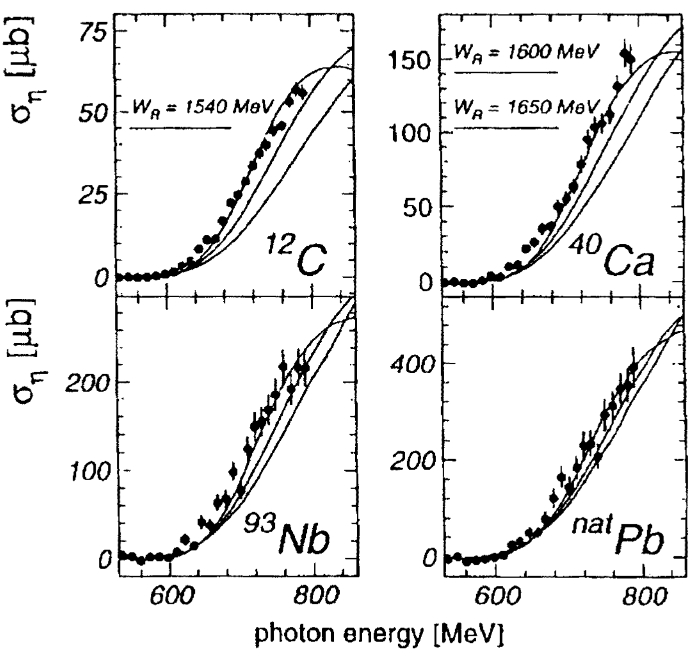

Fig. 4. The cross section for the reaction $A(\gamma,\eta)X$ on C, Ca, Nb, and Pb targets [13] as a function of the incident photon energy in comparison to model calculations of Carrasco [14]. The different curves represent calculations for different assumed resonance masses.

smearing, Pauli blocking and the final state interaction of η-mesons [14]. The model calculation reproduces the mass and energy dependence of the cross section rather well. Possible in-medium shifts of the resonance position have been investigated within this model analysis but the best agreement with the data is found for the free resonance mass (≈ 1540 MeV/c^2). Within the energy range covered in this measurement no dramatic change in the resonance width is observed either, leaving little room for strong medium effects.

The effect of η-absorption and S_{11}-propagation in the medium has been studied within the framework of BUU-simulations [15] usually applied to describe relativistic heavy ion reactions (see chapter 3). This analysis shows that η-mesons produced within the nuclear volume are absorbed and can consequently not be observed while η- mesons leaving the nucleus originate from S_{11}-decays near the surface at an average baryon density of $\rho_B \approx 0.5\rho_0$ and suffer little rescattering.

Summarizing this chapter, it appears difficult to draw quantitative conclusions on medium modifications of resonances above the Δ from inclusive measurements such as photo-absorption. A study of the $S_{11}(1535)$ resonance in the exclusive η-production reaction demonstrates that this resonance preserves its identity in the nuclear medium with little if any changes in resonance parameters at least for baryon densities corresponding to one half of the nuclear matter density.

3. Ensemble of mutually interacting baryon resonances

In the previous chapters we have discussed the properties of single baryon resonances either free or bound in nuclei. We will now focus on a scenario characterized by a large number of co-existing, mutually interacting baryon resonances. This special form of hadronic matter — often referred to as resonance matter [16] — can be formed in relativistic nucleus-nucleus collisions as has been demonstrated in systematic studies of meson production in such reactions. The space-time evolution of such a collision process is illustrated in three time steps of 10 fm/c each in Fig. 5 which depicts the result of a transport model calculation with the IQMD-model [17]. For a short time interval of about 10 fm/c a compressed collision zone is formed with baryon densities of about three times normal nuclear matter density in a small volume of about 100 fm^3. The system subsequently explodes in a collective expansion due to the repulsive interaction among nucleons at small distances. The initial kinetic energy of the two colliding nuclei in the entrance channel is converted into collective and thermal energy and also partially stored in the internal degrees of freedom of the nucleons, *i.e.* resonance excitations. Meson production studies thus allow the fraction of nucleons excited during the high density phase of the nuclear collision to be determined. Both aspects, the dynamics of the exploding collision zone and meson production, are being studied at the heavy ion synchrotron SIS at GSI.

Fig. 5. The space-time evolution of a central relativistic nucleus-nucleus collision (Au+Au at 2 AGeV) simulated within the IQMD-model [17].

The study of collision dynamics performed with the FOPI detector can be summarized as follows: central nucleus-nucleus collisions, *e.g.* Au + Au in the energy range of 150-1000 AMeV lead to a collective almost radial expansion of the collision zone. About 50% of the initially available kinetic energy in the entrance channel is converted into this collective motion [18] reaching expansion velocities of about 30% of the velocity of light at 1AGeV. This scenario is consistent with achieving baryon densities of 2–3 times normal nuclear matter density in the compression phase of the heavy ion reaction before the explosion of the collision zone sets in. During the expansion nuclear fragments are formed by clusterization.

The remaining about 50% of the total available energy go into thermal motion and resonance excitation, *i.e.* meson production. To estimate the fraction of nucleons in excited states during the high density phase of the heavy-ion reaction one may exploit the correlation of measured meson multiplicities M_π, M_η with the abundance of respective resonances in the high density phase. Transport model calculations indicate [19] *e.g.*, that after onset of the reaction the sum $(N_\Delta + N_\pi)$ of Δ-resonances and pions is almost constant as a function of time. With $N_\pi \rightarrow M_\pi$ and $N_\Delta \rightarrow 0$ for t$\rightarrow \infty$ one gets $(N_\Delta + N_\pi)_{\rho=\mathrm{high}} \approx (N_\Delta + N_\pi)_{\rho=0} = M_\pi$. Consequently, to the extent that the number of pions within the compressed collision zone is as low as suggested in Fig. 7 the measured pion multiplicity M_π is directly related to the resonance abundance at high baryon densities. There is, however, an additional complication: how does one determine which resonances

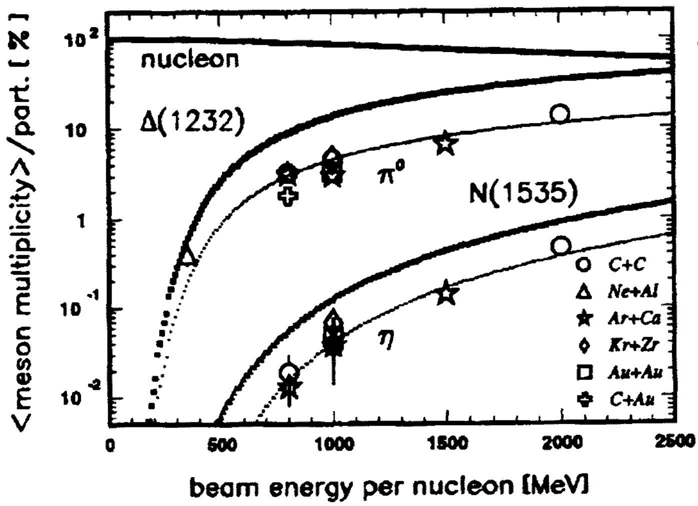

Fig. 6. Population probabilities of the $\Delta(1232)$ and $S_{11}(1535)$ resonances deduced from the π^0- and η-multiplicities measured for different collision systems and bombarding energies [20–22]. The curves are the result of a thermal model calculation [22].

are populated? Energetically it is the easiest to populate the lowest excited state, the $\Delta(1232)$ resonance, which decays by π-emission. Higher lying resonances also contribute to the π-yield. Their population is, however, much weaker and consequently in first approximation, *i.e.* with an accuracy of about 30% the observed π-yield is indeed a measure for the excitation of the $\Delta(1232)$ resonance. A clean signature for the excitation of a higher lying resonance is the detection of η-mesons. As demonstrated before they originate almost exclusively from the decay of the $S_{11}(1535)$ resonance, *i.e.* if we observe an η-meson we know that the $S_{11}(1535)$ resonance has been populated.

The photon spectrometer TAPS has again been used for such studies [20–22]. Taking the known branching ratios of resonance and meson decays into account the population probability of the Δ-resonance and the $S_{11}(1535)$ resonance have been deduced (see Fig. 6) for different collision systems over a wide range of bombarding energies.

The curves in Fig. 6 are the result of an attempt to describe the observed resonance populations in terms of a thermal model [22], *i.e.* it is assumed that a thermal and chemical equilibrium among nucleons and baryon resonances is reached in the high density phase of the heavy-ion collision while part of the initial kinetic energy (≥ 20 %) goes into collective degrees of freedom, *e.g.* flow. The success of this description illustrates that it appears possible to determine the hadrochemical composition of the compressed hadronic matter formed in relativistic nucleus-nucleus reactions. Depending on the incident heavy-ion energy the temperatures deduced within this model range from about 80 to 130 MeV.

Chemical equilibrium among nucleons and baryon resonances implies interactions among the constituents, *i.e.* cycles of resonance excitations and decays via the $\Delta N \rightleftharpoons NN$ and $\Delta \rightleftharpoons N\pi$ processes. As illustrated in Fig. 7, this regeneration of resonances allows a sizable resonance abundance to be maintained [23] over times much longer than the lifetime of an individual nucleon resonance ($\approx$ 1–2 fm/c) up to the point where the system starts to expand. With decreasing baryon density the resonance regeneration rate drops rapidly and resonance decays become dominant.

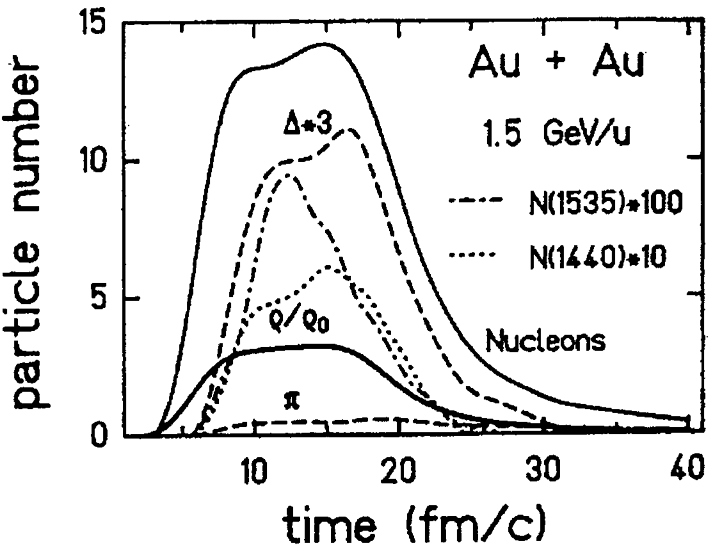

Fig. 7. Time evolution of the number of baryons in various resonance channels and the total baryon density in the central cell (radius 2 fm) of the reaction volume, obtained in a BUU-transport model calculation [23].

Evidence for interactions among nucleons and baryon resonances is also provided by enhanced sub-threshold heavy meson and antiproton yields. While the threshold for K^+ production in free nucleon-nucleon collisions is E_{thr}^{NN} = 1.6 GeV, K^+ mesons are produced with cross sections in the 100μb range [24] at incident heavy-ion energies as low as 1 AGeV. As discussed by Senger [25] in a contribution to this conference a detailed analysis of the spectra measured by the KaoS group within the QMD-model [26] shows that multi-step processes involving interactions of baryon resonances play an important role. A Δ-resonance formed in a first nucleon–nucleon collision may react with a third nucleon. Due to the higher mass of the Δ the second collision step is more energetic, making K^+ production energetically possible; hereby the energy of three nucleons is pooled for the production process. According to the analysis of the Tübingen group [26] even $\Delta\Delta$ interactions give a sizeable contribution to the observed K^+-spectrum. Analoguous experimental results and corresponding theoretical interpretations have been reported for antiproton production [27].

4. Outlook: the quest for chiral symmetry restoration

The above discussion has demonstrated the link between the physics at electron and heavy ion accelerators. In the regime of available energies $\approx$ 0.2 - 2.0 GeV the excitation of baryon resonances plays a key role in the reaction dynamics. Furthermore, medium modifications in the nuclear environment to hadronic properties are an additional common topic.

Heavy ion reaction studies performed up to now have provided information on the density, temperature and composition of hadronic matter formed in relativistic heavy-ion collisions. This prepares the ground for testing theoretical considerations which predict precursor phenomena for chiral symmetry restoration at elevated densities and temperatures. Chiral symmetry is a fundamental symmetry of Quantum-Chromodynamics, the theory of strong interactions, which is broken under normal conditions. Calculations within the NJL-Model predict [28] a partial restoration of chiral symmetry with increasing density and temperature reflected by a decrease of the chiral condensate $< q\bar{q} >$ (Fig. 8). Experimental signatures may include shifts in vector meson masses. Vector mesons, at least the ρ-mesons, are sufficiently short-lived (τ_ρ = 1.3 fm/c) to decay within the transient hot and compressed collision zone produced in a relativistic nucleus-nucleus reaction. Furthermore, vector mesons can decay into dilepton pairs which leave the interaction zone undisturbed by strong final state interactions, thus allowing a determination of the vector meson mass upon decay from an invariant mass analysis using the lepton four-momentum vectors. Studies of this kind are part of the physics program of the dilepton spectrometer HADES presently being set up at GSI by a European collaboration [29]. Details of the detector system are described by Salabura [30] in a contribution to this conference.

Since precursor phenomena for chiral symmetry restoration, *i.e.* shifts of vector meson masses, have been predicted to occur already at normal nuclear matter density [28], experiments have been proposed to measure the ω-mass in nuclei via recoilless production of ω-mesons in a π-induced

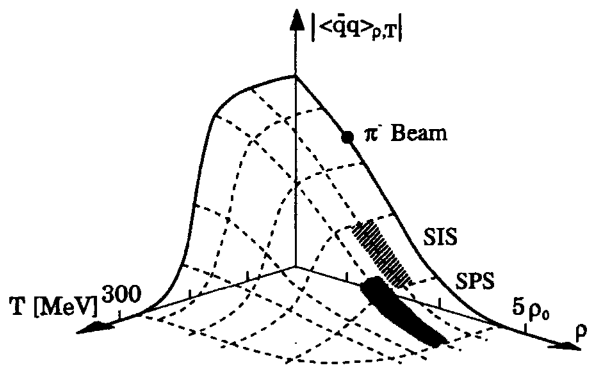

Fig. 8. The chiral condensate calculated within the Nambu and Jona-Lasinio model as a function of temperature and baryon density [28]. The density and temperature regimes reached with π- and heavy-ion beams are indicated.

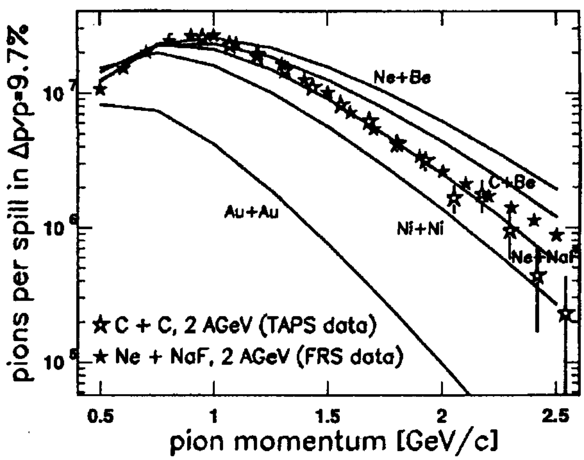

Fig. 9. Expected $\pi^{\pm}$-intensities in a momentum bin of Δ p/p = 9.7 % at the HADES detector position (28 m behind the production target) for different target-projectile combinations. The full data points represent a π^{-} spectrum measured at the FRS in the reaction Ne + NaF at 2 AGeV [27, 32].The open data points are derived from a π^0-transverse momentum spectrum measured in the system C+C at 2 AGeV [22] assuming isotropic emission from a mid-rapidity source.

reaction (for details see the contribution of Schön [31] to this conference). In contrast to heavy-ion reactions with a collision zone exploding after about 10-15 fm/c the ω-meson produced recoilfree via the $p(\pi^-,\omega)$n reaction on a bound proton can experience the interaction within the nuclear medium throughout its full lifetime ($\tau_\omega = 23$ fm/c). This experiment is going to be performed with HADES employing the π-beam available at GSI from 1998 [11].

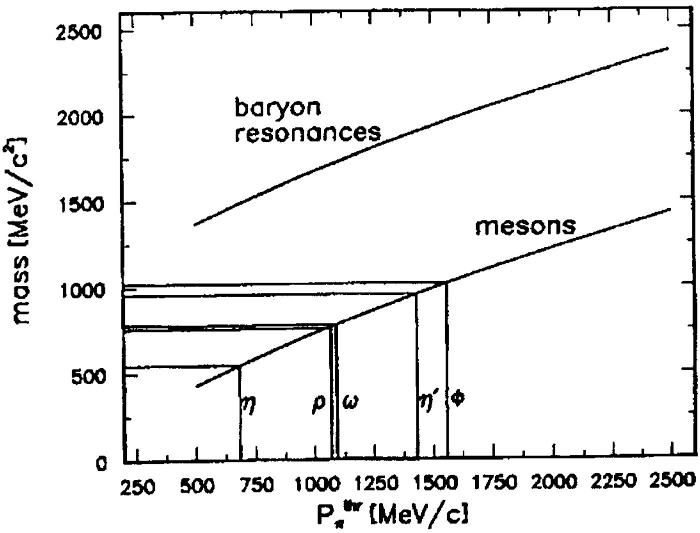

Fig. 10. π-momenta for producing pseudoscalar and vector mesons at threshold and for populating baryon resonances.

Expected π-beam intensities range from $10^7 s^{-1}$ at momenta of 700 MeV/c to 10^6 s^{-1} at 2 GeV/c (see Fig. 9). This momentum range (Fig. 10) allows the production of all pseudoscalar and vector mesons used as probes in heavy-ion collisions at SIS and also AGS energies. Furthermore, all baryon resonances up to a mass of 2 GeV/c^2 can be populated which — as discussed above — provide a crucial testing ground for nucleon structure models and play an important role in the composition of hadronic matter formed in relativistic nucleus-nucleus collisions.

The π-beam can also be used to measure elementary properties of hadrons such as electromagnetic transition formfactors of baryons and mesons via reactions such as $\pi^- N \to N e^+ e^-$ or *e.g.*, $\pi^- p \to n\omega \to n\pi^0 e^+ e^- \to n\gamma\gamma e^+ e^-$. For the latter experiment HADES has to be operated in conjunction with an electromagnetic calorimeter such as TAPS.

In general, the combination of the π-beam with detector systems like HADES, FOPI and TAPS offers almost unique possibilities for studies of hadron structures and for extending the physics described in the foregoing sections to the highest resolvable baryon resonances.

Summary

The properties of baryon resonances in three different environments have been discussed: in free space, in nuclei at normal density, and in compressed hadronic matter formed in relativistic nucleus-nucleus collisions. An illustration has been given of the high precision data on free baryon resonances obtained in recent experiments on photo-production of mesons off the nucleon. Extending these measurements to quasifree meson production off nuclei reveals that not only the Δ-resonance but also the N(1535) resonance preserve their identity in the nuclear environment (for the N(1535) at least up to 0.5 ρ_0). A system of mutually interacting baryon resonances is formed in the compressed collision zone ($\rho_B \approx 2 - 3\rho_0$) of relativistic nucleus-nucleus reactions. Systematic studies of meson production indicate that up to almost 30% of all participating nucleons are excited to resonance states at bombarding energies of 2 AGeV.

Having determined the densities and temperatures of hadronic matter in relativistic nucleus-nucleus reactions the ground is prepared for testing theoretical predictions of chiral symmetry restoration at elevated temperatures and densities. Corresponding experiments using the dilepton spectrometer HADES are in preparation. These experiments will be supplemented by measurements of vector meson masses in nuclei at normal density employing the π-beam. The planned π-beam will broaden in particular the HADES physics program and will allow the measurement of elementary properties of baryons and mesons.

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