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MESON PRODUCTION WITH VARIOUS PROBES*

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Meson production is the most important final state in hadronic reactions. In order to exploit the full physics potential, different production channels for as many as possible mesons have to be investigated, analyzed and interpreted in a consistent way. Besides electromagnetic reactions with real and virtual photons, hadronic interactions, using pions and protons as well as light or heavy nuclei, are used for pseudoscalar (π, η, η'), scalar (a_0, f_0), and vector-meson (ρ, ω, ϕ) production. A number of examples, focusing on the complementarity of the different probes, are given.

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1. Introduction

Probing sub-structure of the nucleon can proceed in a number of different ways: one of the most important ones is the investigation of its excited states (nucleon resonances: N^*, Δ, Y^*). Excitation energy can be "implanted" into nucleons by many different probes: photons, pions, protons *etc.* The excited nucleon in most cases de-excites by emission of single or multiple mesons–photon de-excitation is only a very tiny fraction of the total decay probability.

Due to the short lifetime of nucleon resonances (typically 10^{-23} s) and the corresponding large widths (of the order of 100 MeV) the spectroscopy of excited states is quite complicated. Thus it is necessary to exploit filters for example to selectively study N^*-resonances only. In addition the investigation of the same excited state by different probes helps to establish its characteristics.

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In order to perform such detailed investigations, dedicated N^*-programs have started at different labs worldwide (*e.g.* ELSA, GRAAL, Jlab) and others have plans to go in this direction (*e.g.* COSY, GSI, MAMI). In the following a few examples are given to demonstrate the necessity and importance to pursue these complementary studies.

2. Δ-resonance

The $\Delta(1232)P_{33}$-resonance was the first nucleon resonance to be discovered. Fermi and collaborators found this state in the early 50's in πN-scattering [1]. The interpretation as an excited nucleon resonance with spin 3/2 was put forward soon after its discovery by Brueckner [2]. Being an isospin 3/2-state, it comes in 4 charge-states: Δ^{++}, Δ^{+}, Δ^{0}, and Δ^{-}.

In pion scattering and charge exchange, all 4 charges states are accessible in principle, but the Δ^{+} and Δ^{-} require a reaction with a neutron which is only available as a bound target nucleon:

$$\begin{aligned} \pi^+ p &\to \Delta^{++} \to \pi^+ p\,, \\ \pi^+ n &\to \Delta^{+} \to \pi^+ n, \pi^0 p\,, \\ \pi^- p &\to \Delta^{0} \to \pi^- p, \pi^0 n\,, \\ \pi^- n &\to \Delta^{-} \to \pi^- n\,. \end{aligned}$$

A much easier way to study the single positively charged Δ-state is to use real or virtual photons on a proton target:

$$\gamma p \to \Delta^{+} \to \pi^+ n, \pi^0 p\,.$$

Thus, in order to study for example the magnetic moments of the different Δ's, complementary reactions have to be used. While $\mu(\Delta^{++})$ is known to be about $4.5\mu_N$ from UCLA- and SIN-data on π^+p bremsstrahlung (*i.e.* $\pi^+ p \to \Delta^{++} \to \gamma\pi^+ p$) [3], only recently calculations have been published to determine $\mu(\Delta^{+})$ from radiative pion photoproduction ($\gamma p \to \Delta^{+} \to \gamma\pi^0 p$) [4]. Corresponding experimental investigations are being made now by the TAPS-collaboration [5].

Many properties of the Δ-resonance have been investigated in pion-induced reactions. More recently, photon-induced single pion production has been used to determine the so called EMR, R_{EM}, which is the amplitude-ratio for Δ-excitation by $E2$- and $M1$-photons:

$$R_{\mathrm{EM}} = \frac{E2}{M1} = \frac{E_{1+}^{3/2}}{M_{1+}^{3/2}}.$$

The interest in this ratio is derived from the fact that the (small) $E2$-amplitude is a measure for the transition quadrupole moment, which can be interpreted in terms of a deformation of the nucleon and/or Δ-resonance [6,7].

The most recent results are:

$$R_{\mathrm{EM}} = -(2.5 \pm 0.1(\mathrm{stat.}) \pm 0.2(\mathrm{sys.}))\% \quad [6]\,,$$

and

$$R_{\mathrm{EM}} = -(3.1 \pm 0.3(\mathrm{stat.} + \mathrm{sys.}) \pm 0.2(\mathrm{model}))\% \quad [7]\,.$$

From such results for R_{EM}, an *oblate* spectroscopic deformation for the Δ^+ with a static quadrupole moment of $Q(\Delta^+) = -(0.153 \pm 0.013 \pm 0.048)$ fm^2 has been deduced [7]. (Note: although the two results for R_{EM} agree within errors, significant discrepancies in the underlying experimental data exist, in particular the cross sections for π^+- and π^0-production, which need to be clarified!)

More recently, helicity dependent partial cross sections $\sigma_{1/2}$ and $\sigma_{3/2}$ for π^+-and π^0-photoproduction have been measured in double polarization experiments (*i.e.* circularly polarized photons onto longitudinally polarized protons) from as close to threshold as possible up to the maximum available energy [8]. The aim of such measurements are a test of the GDH-sum rule and a determination of the spin-polarizability γ_0 — both of them receive the biggest contribution from the Δ-resonance.

In pion-induced reactions, recent developments have concentrated on a detailed investigation of mass and width of Δ^{++} and Δ^0, respectively, in order to investigate isospin breaking in the Δ^{++}–Δ^0-system. Besides electromagnetic contributions, the mass difference between *up* and *down* quarks is supposed to be responsible for a difference $\Delta m = m(\Delta^{++}) - m(\Delta^0)$ and/or $\Delta\Gamma = \Gamma(\Delta^{++}) - \Gamma(\Delta^0)$. While Δm is found to be small, $\Delta\Gamma$ is different from zero (7–9 MeV, depending on the model used in the analysis) [9].

3. $S_{11}(1535)$-resonance

The decay pattern of the $S_{11}(1535)$ is exceptional because it exhibits a very large fraction into the ηN-channel: $\Gamma_\eta/\Gamma = 30$–55 % [3]. This means that η-production tags the S_{11}-resonance; unfortunately, the η-meson is somewhat too massive, so that the low-mass part of the S_{11}-resonance can not decay into the ηN final state. Nevertheless η-production has been used to investigate this resonance in different reaction channels, for example:

$$\begin{aligned} \pi^- p &\to S_{11}^0 \to \eta p\,, && [10] \\ \gamma p &\to S_{11}^+ \to \eta p\,, && [11] \\ pp &\to S_{11}^+ p \to \eta pp\,. && [12] \end{aligned}$$

Actually it is still debated whether the $S_{11}(1535)$ is a genuine nucleon resonance, since no evident structure is found in partial wave analyses ("speed plots") at the corresponding energy [13] and the suggestion has been made that it may be generated as a quasibound $K\Sigma$-state [14].

Experimentally it is found that η-production near threshold is dominated by s-wave. In photoproduction, both the energy dependence of the total cross section and the isotropic angular distributions assert this assumption [11]. The excitation function and differential cross sections for η-production in proton–proton collisions can also be reproduced by s-wave production, if pp final-state interactions are taken into account [12]. More recently, other reaction channels have been identified: (a) in photoproduction experiments with linearly polarized photons (photon asymmetry) and polarized targets (target asymmetry), contributions from other nucleon resonances have been deduced ($D_{13}(1520)$ with a branching ratio (BR) of about 0.8% and $F_{15}(1580)$ with BR $\sim$ 0.15%) (for a combined analysis see [15]) (b) in pp-reactions the importance of ρ-exchange has been inferred from non-isotropic angular distributions [16].

If η-production is studied on nucleons bound inside nuclei, a number of interesting new aspects can be investigated:

- neutron

$$\begin{aligned} pn &\rightarrow d;\gamma np\,, \quad [17] \\ \gamma n &\rightarrow \eta n\,, \qquad [18] \end{aligned}$$

  using a deuteron target,

- bound $S_{11}(1535)$ $\gamma A \rightarrow \eta A\,,\quad [19]$,

- non-S_{11} contribution $\gamma A \rightarrow \eta A\,,\quad$ [20] in "coherent production", if A is an even–even nucleus like ^{4}He.

In fact, η-production on a neutron can also be tagged by using π^+-beams:

$$\pi^+ n \rightarrow \eta p\,,$$

which could possibly be exploited at the new pion beam of GSI [21].

η-production in pn-reactions close to threshold with deuterons in the final state at CELSIUS has ruled out the previously inferred strong threshold enhancement, but shows an increased cross section compared to two-body phase space, indicating the presence of strong FSI. Photoproduction experiments on light nuclear targets (d, ^{4}He) also show such an enhancement [22] — its interpretation is not settled yet. On the other hand, inclusive η-photoproduction on heavy nuclei did not show any significant change of the S_{11}-resonance besides trivial nuclear effects (Fermi-motion, binding energy, FSI).

4. Other resonances

One of the mysterious nucleon excitations is the so called "Roper-resonance" $P_{11}(1440)$, which — although not directly observed in experimental spectra — is a well established 4-star resonance [3]. Because of its quantum numbers identical to the nucleon ground state it is sometimes also referred to as the nucleon breathing mode [23].

It has a branching ratio of 5–10 % into $N(\pi\pi)^{I=0}_{s-\mathrm{wave}}$ [3] which makes it an ideal candidate to be observed in $(\pi^0\pi^0)$-production, for example:

$$\begin{aligned} \pi^- p &\rightarrow \pi^0\pi^0 n\,, \\ \gamma p &\rightarrow \pi^0\pi^0 p\,. \end{aligned}$$

According to recent calculations the contribution of the Roper-resonance to double pion photoproduction is small — the main contribution seems to come from sequential decay of the $D_{13}(1520)$-resonance via the intermediate Δ [24]. (It should be mentioned that older calculations suggested that P_{11} was the major contribution [25]. This calculation did, however, not reproduce the observed peak structure around 700 MeV.) Since a sizeable fraction of the inclusive cross section for $\pi^- p \rightarrow X$ is associated with the $P_{11}(1440)$-resonance [26], it would be very interesting to study pion-induced $2\pi^0$-production. First results have already appeared [27].

η'-photoproduction has recently been studied at the ELSA using the SAPHIR-detector [28]: a structure in the excitation function has been observed, which has been assigned to the excitation of an intermediate N^*-resonance $S_{11}(1897)$ [29]; interestingly if such a resonance is assumed, no other reaction mechanism is necessary to explain the $pp \rightarrow pp\eta'$ cross section at threshold, if FSI is taken into account.

5. Outlook

The investigation of nucleon resonances is an important but complicated issue of hadron physics, which tries to understand the structure of baryons and mesons and thus hopes to solve the "puzzle of unseen quarks" — as T.D. Lee once phrased it [30]. Ambitious programs have started at different labs and it can be safely predicted that significant progress will be achieved during the next years. *Mesons* in the final state are the carriers of information so we certainly will hear much about this in future MESON200X Conferences in Cracow!

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