Chiral Symmetry and Electromagnetic Probes

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Abstract

This is the summary of my talk, given at the 2nd RHIC II science workshop in the electro-magnetic-probes-working group. I shortly summarize some of the fundamental physical questions, related to chiral symmetry, which can possibly be addressed by measurement of electromagnetic probes.

1 QCD and Chiral Symmetry

Due to the asymptotic freedom of QCD [Mut87], i.e., the fact that the renormalized running coupling becomes large at small scattering-momentum transfers, we cannot describe the observed color-neutral bound states of quark-antiquark pairs (mesons) or three quarks (baryons), utilizing the usual methods of perturbation theory.

To make contact with hadronic observables [DGH92, RW00], one uses the chiral symmetry of QCD in the light-quark sector, i.e., for u- and d- (to less accuracy also s-) quarks to formulate effective hadronic models like the σ model. Chiral symmetry is the transformation of the quark fields with an $\mathrm{SU}(2)_V \times \mathrm{SU}(2)_A$ [or $\mathrm{SU}(3)_V \times \mathrm{SU}(3)_A$] flavor rotation:

$$\psi \rightarrow \exp[-\mathrm{i}(\vec{\alpha}_V + \gamma_5 \vec{\alpha}_A)\vec{T}]\psi, \tag{1}$$

where $\vec{T}$ are the 3 (8) generators of SU(2) [SU(3)] in flavor space. This is a symmetry of the QCD Lagrangian

$$\mathscr{L}_{\text{QCD}} = -\frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a + \bar{\psi}(\not{D} - \hat{M})\psi \tag{2}$$

in the limit of vanishing quark masses $\hat{M} \rightarrow 0$. Here, $F_a^{\mu\nu}$ are the (non-Abelian) field-strength tensors of the 8 gluons, $D_\mu = \partial_\mu + \mathrm{i} g A_\mu^a \lambda^a/2$ the covariant derivative [λ^a Gell-Mann matrices, the 8 generators of (color) $\mathrm{SU}(3)_c$], and $\hat{M}$ the mass matrix of the quarks (acting in flavor space).

In the limit $\hat{M} \rightarrow 0$ (the "chiral limit"), the Noether currents,

$$\vec{j}_V(x) = \bar{\psi}\vec{T}\gamma^\mu\psi, \quad \vec{j}_A(x) = \bar{\psi}\vec{T}\gamma_5\gamma^\mu\psi, \tag{3}$$

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corresponding to the vector- and axial-vector transformations (1) respectively, are conserved. With the small explicit breaking due to the (current) quark masses, the axial-vector current is not exactly conserved. This is known as partial conservation of the axial-vector current (PCAC).

In the vacuum and at low temperatures and densities, chiral symmetry is spontaneously broken from $SU(2)_V \times SU(2)_A$ to $SU(2)_V$ [from $SU(3)_V \times SU(3)_A$ to $SU(3)_V$], i.e., even in the chiral limit the ground state of QCD is not invariant under the full chiral group, but only under the $SU(2)_V$ [$SU(3)_V$] subgroup. The QCD vacuum is not invariant under axial-vector rotations, while the underlying dynamics (encoded in the Lagrangian) is as stated before. Thus, the vacuum is degenerate, because each $SU(2)_A$ [$SU(3)_A$] transformation of any given vacuum state (i.e., state of minimal energy) results in another state with the same energy. This leads to the existence of 3 (8) massless pseudoscalar Nambu-Goldstone bosons, which are identified with pions, building an iso-triplet (pions, kaons and η, building an flavor-SU(3) octet) [Gol61, NJL61]. Since the chiral symmetry is also slightly broken explicitly by the quark masses, the Goldstone bosons are not exactly massless.

On the level of quark- and gluon-degrees of freedom, the spontaneous symmetry breaking is due to the quark condensate, i.e., $\langle \bar{\psi}\psi \rangle \neq 0$. The masses of the pseudo-Goldstone bosons are determined by Ward-Takahashi identities of chiral symmetry (PCAC). To leading order this results in the Gell-Mann-Oaks-Renner (GOR) relation [GMOR68]

$$m_\pi^2 F_\pi^2 = -(m_u + m_d) \langle \bar{u}u \rangle , \tag{4}$$

where F_π is the pion-decay constant, $F_\pi \simeq 93$ MeV. We also assumed $\langle \bar{u}u \rangle = \langle \bar{d}d \rangle$, which holds true in the SU(2) model, since isospin symmetry is valid to a high degree of accuracy (but not, because the pertinent quark masses are equal, but because they are small [Wei96])[1]. Since QCD is asymptotically free, at high enough temperatures and/or densities, one expects a restoration of the chiral symmetry, because the interactions become weaker, and the chiral condensate melts. Lattice-QCD calculations [Kar02] indeed show that the chiral symmetry is restored, and that this is closely related to the "deconfinement transition", where quarks and gluons rather than hadrons become the relevant degrees of freedom. These calculations determine the critical temperature for the chiral phase transition to be $T_c \simeq 170$ MeV.

Thus, the spectral properties of hadrons in the medium are expected to undergo significant modifications compared to the vacuum. For the observation of such medium modifications in relativistic heavy-ion collisions (rhic's), the most promising probes are leptons and photons, which interact only electromagnetically with the surrounding medium.

Thus, to probe in-medium modifications of low-mass vector mesons (like ρ, ω, and ϕ), in recent years the dilepton spectra from their decay inside the medium where studied intensively, both theoretically (for a recent review, see [RW00]) and experimentally [A$^+$95, W$^+$95, A$^+$98], where a significant enhancement of the dilepton spectrum in the invariant-mass region from about 200 MeV to 1 GeV compared to the expected yield from the corresponding pp-collision rates.

[1] One should keep in mind that GOR-type relations are derivable from chiral-symmetry considerations alone, i.e., the fact that they apply to the pseudo-Goldstone bosons of the approximate chiral symmetry, while it cannot be concluded that all baryon masses are generated by the slight explicit breaking of chiral symmetry. Rather, it is known that, e.g., the nucleon obtains its mass from the anomalous breaking of scale (dilatation) invariance and the corresponding trace anomaly through the presence of a gluon condensate, $\langle F_{\mu\nu}^a F_a^{\mu\nu} \rangle \neq 0$. The spontaneous breaking of chiral symmetry nevertheless explains the mass splitting of the chiral partners (see. Fig. 1).

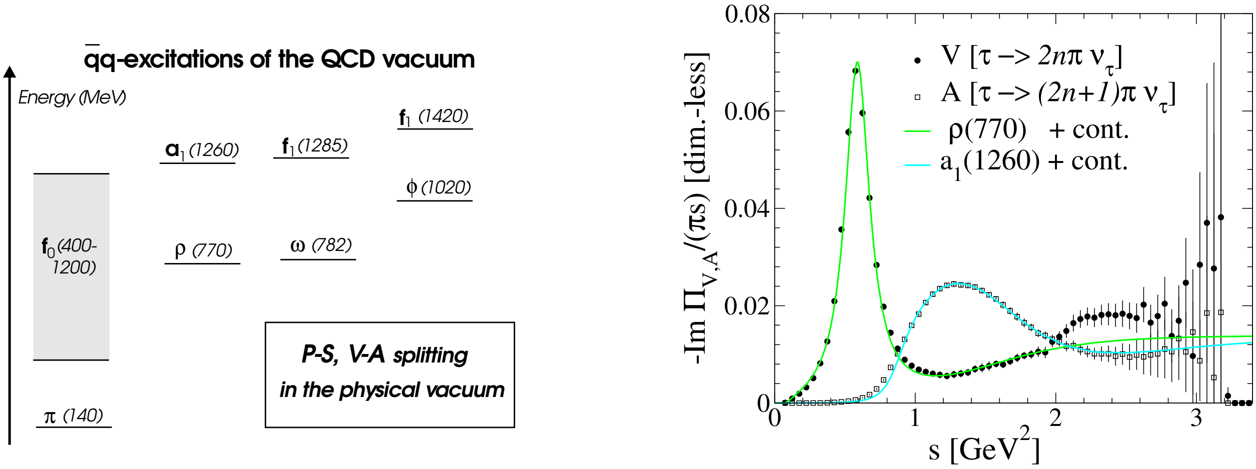

Figure 1: Left panel: The mass splitting of scalar and pseudoscalar and vector-axial vector chiral-partner mesons in the vacuum. Right panel: The current-current-auto-correlation functions, experimentally assessed through the spectra of τ-lepton decay to an even number of pions and an odd number of pions, corresponding to the vector-current- and the axial-vector-current correlator respectively. The spectra are fitted with ρ- and a_1 spectral functions from phenomenological hadronic models and a perturbative QCD continuum contribution [Rap03].

Because the vector mesons carry the quantum numbers of the photon, the dilepton (as well as the single-photon) decay spectra are closely related with the (retarded) propagators of the mesons, and these are determined by the vector-current correlator:

$$\begin{aligned}
\Pi^{<}_{V\mu\nu}(q) &= \int \mathrm{d}^4x \exp(\mathrm{i}q\cdot x) \left\langle J^{(V)}_{\mu}(0) J^{(V)}_{\nu}(x) \right\rangle_T = -2n_B(q_0)\,\mathrm{Im}\,\Pi^{(\mathrm{ret})}_{\mu\nu}(q), \\
\frac{\mathrm{d}N_{e^+e^-}}{\mathrm{d}^4x\mathrm{d}^4k} &= -g_{\mu\nu}\frac{\alpha_{\mathrm{em}}^2}{3q^2\pi^3}\,\mathrm{Im}\,\Pi^{(\mathrm{ret})}_{\mu\nu}(q)|_{q^2=M^2_{e^+e^-}}, \\
q_0\frac{\mathrm{d}N_{\gamma}}{\mathrm{d}^4x\mathrm{d}^3\vec{q}} &= \frac{\alpha_{\mathrm{em}}}{2\pi^2}g^{\mu\nu}\,\mathrm{Im}\,\Pi^{\mathrm{ret}}_{\mu\nu}(q)|_{q_0=|\vec{q}|}.
\end{aligned} \tag{5}$$

Chiral symmetry relates the vector- and axial-vector quantities by the Weinberg-sum rules [Wei67]. In our context, the most interesting is the second one:

$$F_\pi^2 = -\int_0^\infty \frac{\mathrm{d}p_0^2}{\pi p_0^2}[\mathrm{Im}\,\Pi_V(p_0,0) - \mathrm{Im}\,\Pi_A(p_0,0)], \tag{6}$$

where Π_V and Π_A are three-dimensionally longitudinal components of the vector- and the axial-vector current correlator respectively. This sum rule directly links an order parameter of the chiral symmetry breaking (the pion-decay constant, F_π) to the current correlators, and thus (together with other Weinberg sum rules) one concludes that in the restored phase, the current correlators (and thus the spectral functions of the corresponding vector- and axial-vector-meson chiral partners) must coincide. E.g., the ρ-meson spectral function should become degenerate with the a_1-meson spectral function at high enough temperatures $T \geq T_c$ (and/or densities).

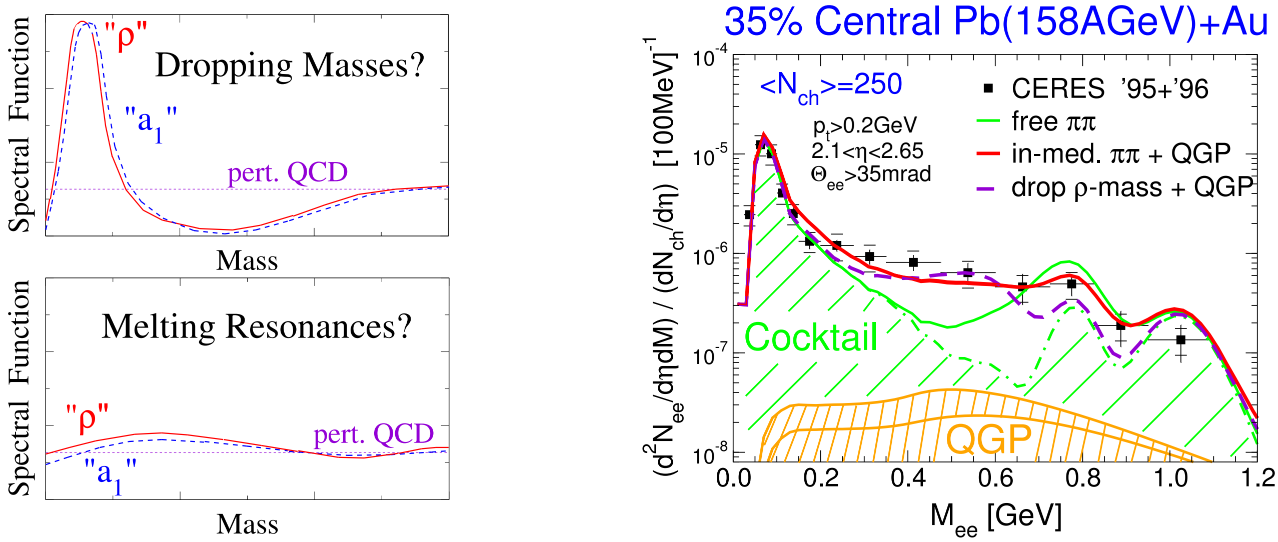

Figure 2: Left panel: The two scenarios of chiral-symmetry restoration of the vector-axial-vector meson spectral functions ("dropping masses" or "melting resonances"). For details, see the main text. Right panel: Low-mass dilepton rates, measured by the CERES collaboration, compared to model calculations, based on the two scenarios of chiral-symmetry restoration.

To assess in-medium modifications of hadrons at higher temperatures and/or densities, one necessarily has to use phenomenological hadronic models. These models are only equivalent on the mass shell due to low-energy theorems of chiral symmetry, but differ off mass shell, and at higher finite temperatures and densities, the off-shell properties of the hadrons become important. Model-independent statements, based on chiral symmetry alone, can only be made in the low-temperature/density limit.

One finds mainly two different scenarios for the nature of the restoration of chiral symmetry: Based on mean-field theories, a "dropping-mass scenario" was conjectured [BR91, LKB96]. Within this model, with increasing temperature the peak positions of both the vector- and the axial-vector current correlators are shifted to lower invariant-mass values. Such a behavior is also found within hidden-local-gauge-symmetry models, where chiral symmetry appears in the vector manifestation [HY03, Sas05].

Within phenomenological hadronic models for the vector mesons, one predicts a "melting-resonance scenario" (see [RW00] and references therein): While the masses of the vector mesons stay more or less constant, the vector-meson spectral functions become broader with increasing temperature, approaching the perturbative-QCD-continuum limit above the critical temperature (see left panel of Fig. 2).

As one can see from the right panel of Fig. 2, which shows low-mass dilepton rates, measured by the CERES collaboration at the SpS, one cannot distinguish between the "dropping mass" and the "melting resonance" scenario. The investigation of the mechanism behind chiral-symmetry restoration of hadron-spectral functions is not only an interesting question in itself, but may help to answer the more fundamental question of the "origin of (hadronic) mass": If the main mass-generation mechanism is through the trace anomaly (i.e., the gluon condensate), one expects the masses to change less, compared to the case that the origin of mass is purely due to the explicit chiral symmetry breaking (related with the quark-condensate as an order parameter), because due to lattice-QCD calculations the gluon condensate is expected to persist up to much higher temperatures than the quark condensate [Kar95]. In fact, since the gluons are chiral singlets, they are not related to chiral symmetry, and thus the gluon condensate needs not to vanish at the chiral phase transition point.

2 Challenges for experiment (and theory)

For future RHIC(-II) experiments, for the above given reasons, it is of high interest to assess spectral properties of chiral-partner hadrons, in the context of electro-magnetic probes especially in the vector- and axial-vector channel.

As a complement to the dilepton measurements in relativistic heavy-ion collisions, an experiment addressing the a_1-spectral function through invariant-mass $\pi^{\pm}$-γ spectra is promising. From the review of particle physics [E$^+$04], we find that the a_1 might be a quite clean source for $\pi\gamma$-invariant-mass spectra, since the partial width for the process $\Gamma_{a_1 \rightarrow \pi\gamma} = 0.64$ MeV, compared to that for the ρ-meson of $\Gamma_{\rho \rightarrow \pi\gamma} = 0.07$ MeV. In the $\pi\gamma$ channel, the ω decays only to $\pi^0\gamma$, not to $\pi^{\pm}\gamma$. "Background" sources, decaying to charged-pion-photon pairs are the a_2 ($\Gamma_{a_2 \rightarrow \pi\gamma} = 0.3$ MeV) and the $\pi(1300)$ (partial width for this channel yet unknown).

Recently, an experiment by the TAPS collaboration at ELSA [Trn05] was successful in measuring the in-medium modifications of ω mesons for the first time. Here π^0-γ-invariant-mass spectra where taken from scattering of photons off a liquid-hydrogen- and a niobium target. As expected, from the lH_2 target no medium modifications of the ω were seen, while the difference-spectrum (see left panel of Fig. 3) between the Nb and the hydrogen-target shows a peak at $M = 722$ MeV (with a width of 55 MeV, which is reported to be dominated by the experimental resolution).

For the heavy-ion case, the question remains, whether one can probe really the properties of the a_1 under "hot" conditions, i.e., reconstruct the invariant-mass π-γ spectra from a_1 decays from the interior of the fireball or whether the signal is destroyed by rescattering of the pion. Then one could see only decays of a_1 mesons in the less dense boundary zone of the fireball, from where the pion escapes without further reinteractions with the medium, and one would not probe its spectral properties under the interesting conditions. Nevertheless, the RQMD-based simulations, presented by P. Fachini at this workshop, seem to encourage further studies in this direction.

Another promising candidate for a direct observation of chiral-symmetry restoration could be low-invariant-mass $\gamma\gamma$ spectra to probe the $\sigma(600)$ resonance. Model calculations within a chiral-quark model predict a significantly dropping mass and narrowing of the σ around T_c[2] [VKB$^+$98].

Several essential questions also have to be addressed by theory, e.g., the development and investigation of a fully chirally symmetric model of vector- and axial-vector mesons, including both chiral mesons and baryonic resonances, since the investigations of the ρ-meson properties have shown the importance of baryons for in-medium modifications of vector mesons. This is expected also to hold true at RHIC, although there one has a lower net-baryon number. Nevertheless, for the in-medium modifications

[2] For lower temperatures the mass and width are higher due to chiral-symmetry breaking; at higher temperatures, a thermal mass is built up, and the width increases again due to collisional broadening.

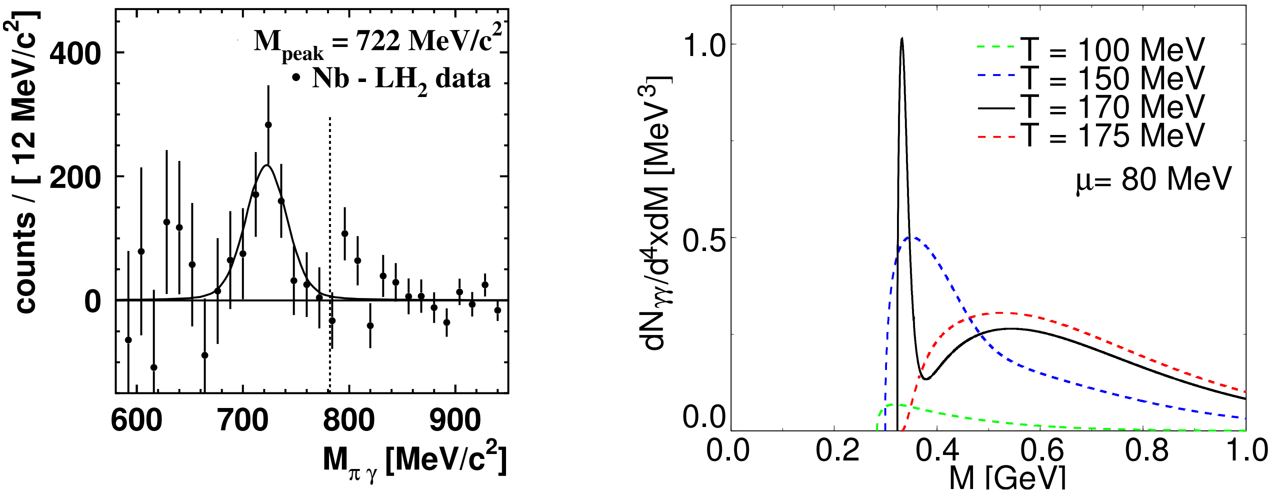

Figure 3: Left panel: The invariant-mass π^0-γ difference spectrum from the scattering of photons off a niobium and a hydrogen target. Right panel: Prediction for the in-medium modifications of the $\sigma(600)$ meson from the invariant-mass-$\gamma\gamma$ spectrum within a chiral-quark model.

of the vector mesons, the sum of baryon and anti-baryon number is the relevant quantity: Since the strong interaction is CP invariant, baryons and anti-baryons interact with mesons in the same way.

References

[A+95] G. Agakishiev, et al. (CERES Collaboration), Enhanced Production of Low-Mass Electron Pairs in 200 GeV/Nucleon S-Au Collisions at the CERN Super Proton Synchrotron, Phys. Rev. Lett. **75** (1995) 1272, URL `http://link.aps.org/abstract/PRL/v75/p1272`

[A+98] G. Agakishiev, et al. (CERES/NA45 Collaboration), Low-mass e+ e- pair production in 158-A-GeV Pb Au collisions at the CERN SPS, its dependence on multiplicity and transverse momentum, Phys. Lett. **B422** (1998) 405, URL `http://arXiv.org/abs/nucl-ex/9712008`

[BR91] G. E. Brown, M. Rho, Scaling effective Lagrangians in a dense medium, Phys. Rev. Lett. **66** (1991) 2720, URL `http://link.aps.org/abstract/PRL/V66/P02720/`

[DGH92] J. F. Donoghue, E. Golowich, B. R. Holstein, Dynamics of the Standard Model, Cambridge University press (1992)

[E+04] S. Eidelman, et al. (Particle Data Group), Review of particle physics, Phys. Lett. **B592** (2004) 1, URL `http://pdg.lbl.gov/pdg.html`

[GMOR68] M. Gell-Mann, R. J. Oakes, B. Renner, Behavior of Current Divergences under SU(3)×SU(3), Phys. Rev. **175** (1968) 2195, URL `http://link.aps.org/abstract/PR/v175/i5/p2195`

[Gol61] J. Goldstone, Filed theories with 'superconductor' solutions, Nuovo Cim. **19** (1961) 154

[HY03] M. Harada, K. Yamawaki, Hidden local symmetry at loop: A new perspective of composite gauge boson and chiral phase transition, Phys. Rept. **381** (2003) 1, URL `http://arxiv.org/abs/hep-ph/0302103`

[Kar95] F. Karsch, The Phase transition to the quark gluon plasma: Recent results from lattice calculations, Nucl. Phys. **A590** (1995) 367c, URL `http://arxiv.org/abs/hep-lat/9503010`

[Kar02] F. Karsch, Lattice QCD at high temperature and density, Lect. Notes Phys. **583** (2002) 209, URL `http://arxiv.org/abs/hep-lat/0106019`

[LKB96] G.-Q. Li, C. M. Ko, G. E. Brown, Effects of in-medium vector meson masses on low-mass dileptons from SPS heavy-ion collisions, Nucl. Phys. **A606** (1996) 568, URL `http://arxiv.org/abs/nucl-th/9608040`

[Mut87] T. Muta, Foundations of Quantum Chromodynamics, World Scientific (1987)

[NJL61] Y. Nambu, G. Jona-Lasinio, Dynamical model of elementary particles based on an analogy with superconductivity. I, Phys. Rev. **122** (1961) 345, URL `http://link.aps.org/abstract/PR/v122/p345`

[Rap03] R. Rapp, Dileptons in high-energy heavy-ion collisions, Pramana **60** (2003) 675

[RW00] R. Rapp, J. Wambach, Chiral symmetry restoration and dileptons in relativistic heavy-ion collisions, Adv. Nucl. Phys. **25** (2000) 1, URL `http://arXiv.org/abs/hep-ph/9909229`

[Sas05] C. Sasaki, Chiral phase transition in QCD and vector manifestation (2005), URL `http://arxiv.org/abs/hep-ph/0504073`

[Trn05] D. Trnka (CBELSA/TAPS), First observation of in-medium modifications of the omega meson (2005), URL `http://arxiv.org/abs/nucl-ex/0504010`

[VKB+98] M. K. Volkov, E. A. Kuraev, D. Blaschke, G. Ropke, S. M. Schmidt, Excess low energy photon pairs from pion annihilation at the chiral phase transition, Phys. Lett. **B424** (1998) 235, URL `http://arxiv.org/abs/hep-ph/9706350`

[W+95] P. Wurm, et al., New Results from NA45/CERES, Nucl. Phys. **A590** (1995) 103c

[Wei67] S. Weinberg, Precise relations between the spectra of vector and axial vector mesons, Phys. Rev. Lett. **18** (1967) 507, URL `http://link.aps.org/abstract/PRL/v18/p507`

[Wei96] S. Weinberg, The Quantum Theory of Fields, vol. 2, Cambridge University Press (1996)