Identification of New 5-pion Meson States in the GlueX Experiment using Amplitude Analysis

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Abstract

There is a long history of studies of atomic bound states, which confirmed the predictions of quantum mechanics and quantum electrodynamics. A similar program of spectroscopy has been in progress for nucleons and the simpler mesons to understand the Strong Interaction and test the predictions of its theory - quantum chromodynamics (QCD). The GlueX experiment focuses on light-meson spectroscopy with mesons produced by a photon beam in recoil from a proton. The experiment seeks to identify the predicted "exotic" states: meson states with quantum numbers that cannot be attained with quark degrees of freedom alone and may indicate excitations of the "glue" between the valence quarks. The techniques of this search with GlueX and of identification of new 5π states through Amplitude Analysis is presented.

Introduction

Problem in hadron spectroscopy: wide, overlapping resonances
How to separate hadronic states and identify their quantum numbers?

Solution: "Amplitude Analysis" a.k.a "Partial Wave Analysis"

1. Write down a probability fit function from an orthogonal set of amplitudes: relative strengths can be free parameters
2. Evaluate the probability for each event based on this model
3. Perform optimization of global probability through e.g. Maximum Likelihood

Consider the Likelihood function extended with the Poisson probability of observing the N events:

$$\mathcal{L} = \frac{e^{-\mu}\mu^N}{N!}\prod_i^N P(\vec{x}_i,\vec{\theta}) \qquad \text{but, } P(\vec{x}_i,\vec{\theta}) = \frac{I(\vec{x}_i,\vec{\theta})}{\mu}$$

where $\vec{x}_i$ captures the kinematics of the event and $\vec{\theta}$ is a set of fit function model parameters and μ is the expected number of events in the detector

Modelling the Event Probability:
A single stage decay amplitude factor must take into account:

1. invariant mass distribution of the mother particle (resonance lineshape)
2. spin of mother particle
3. orbital angular momentum state
4. spin of daughter particles

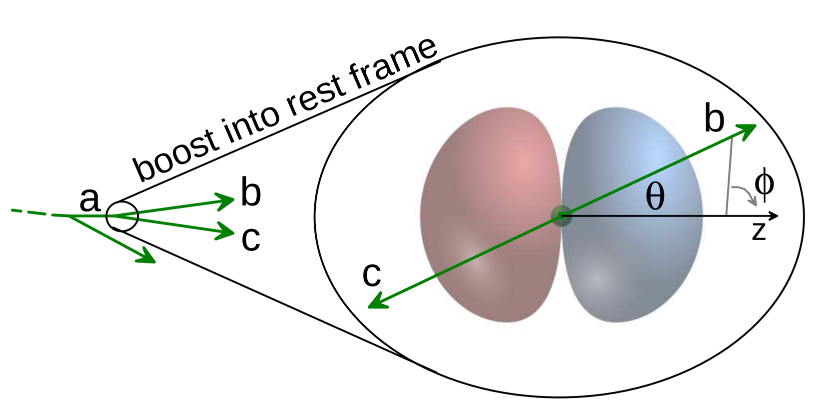


Figure: Illustration of a 2-body decay analysis

If (4) is trivial, e.g. daughters are pions
then spherical harmonic angular dependence: $Y^l_m(\theta,\phi)$
otherwise: Wigner D-matrix: $D^l_{m,\lambda}(\phi,\theta,0)$

The Gluonic Excitations Experiment: "GlueX"

Target: $30\,\mathrm{cm}$ LH_2 Solenoid: $2.2\,\mathrm{T}$ field

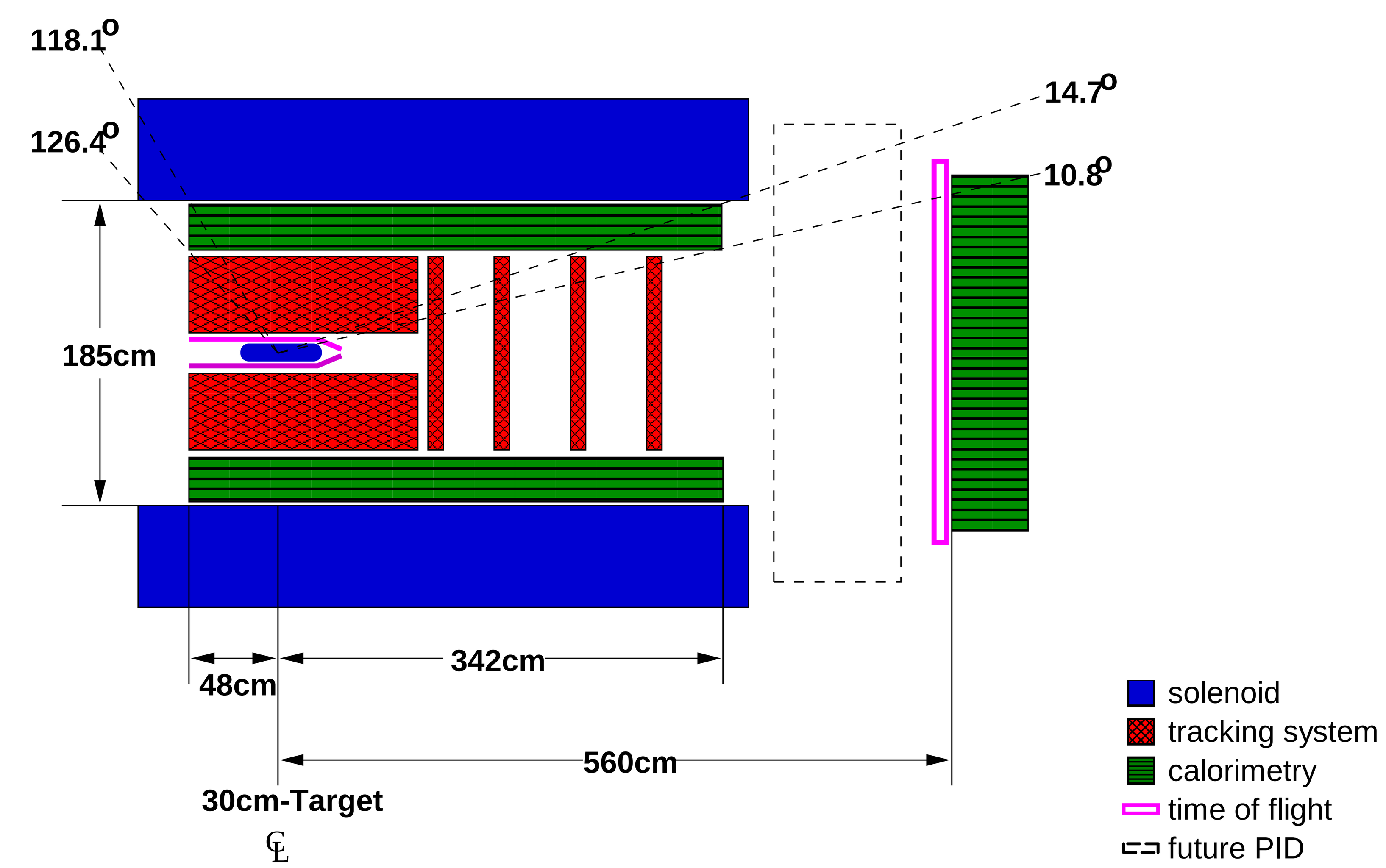


Figure: The GlueX detector colored by system category

Amplitude for $\gamma p \to Xp \to b_1\pi p \to 5\pi p$

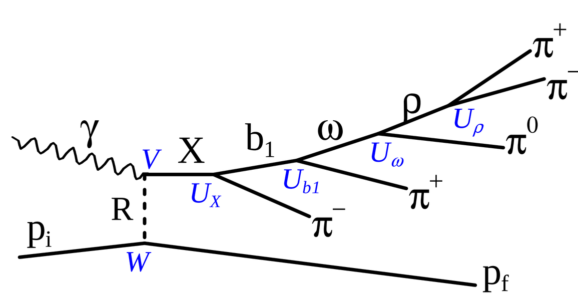
Scattering Amplitude:

$\langle \mathbf{p_f},\epsilon_f;\mathbf{q}_\pi;\mathbf{q}_\rho\lambda_\rho;\mathbf{q}_\omega\lambda_\omega;\mathbf{q}_{b_1}\lambda_{b_1}|S|\epsilon_\gamma;\mathbf{p_i},\epsilon_i\rangle =$

production: $\langle J_X M_X \epsilon_X|V|\epsilon_\gamma;\lambda_R\epsilon_R;\Omega_0\rangle\times$

decay amp.: $\langle \mathbf{q}_\pi;\mathbf{q}_\rho\lambda_\rho;\mathbf{q}_\omega\lambda_\omega;\mathbf{q}_{b1}\lambda_{b1}|U|J_X M_X \epsilon_X\rangle$

recoil vertex: $\langle \lambda_R\epsilon_R;\Omega_0;\mathbf{p_f},\epsilon_f|W|\mathbf{p_i},\epsilon_i\rangle\times$



The decay amplitude may be further broken down by decay stages:

$$\langle\Omega_{b_1}\lambda_{b_1}0|U_X|J_X M_X\rangle\langle\Omega_\omega\lambda_\omega 0|U_{b_1}|1,M_{b_1}\rangle\langle\Omega_\rho\lambda_\rho 0|U_\omega|1,M_\omega\rangle\langle\Omega_\pi 00|U_\rho|J_\rho,M_\rho\rangle$$

With several insertions of complete sets of states, each can be expressed:

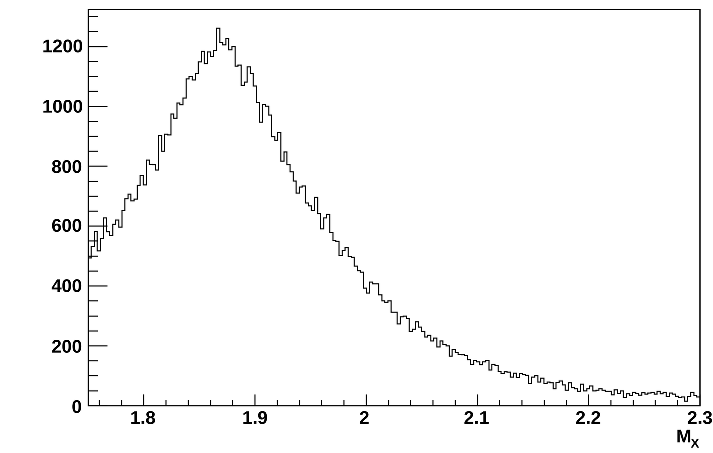
$$\langle\Omega\lambda_1\lambda_2|U|JM\rangle = \sum_{L,S}\langle\Omega\lambda_1\lambda_2|JM\lambda_1\lambda_2\rangle\langle JM\lambda_1\lambda_2|JMLS\rangle\langle JMLS|U|JM\rangle =$$

$$\sum_{L,S}\left[\sqrt{\frac{2J+1}{4\pi}}D^{J*}_{M\lambda}(\Omega)\right]\left[\sqrt{\frac{2L+1}{2J+1}}\left(\begin{array}{cc|c} L & S & J \\ 0 & \lambda & \lambda\end{array}\right)\left(\begin{array}{cc|c} S_1 & S_2 & S \\ \lambda_1 & -\lambda_2 & \lambda\end{array}\right)\right]a^J_{LS}$$

Simulation

5-pion events were generated based on probabilities derived from

1. $J^{PC} = 1^{--}$
   $M = 1.89\,\mathrm{GeV}, \Gamma = 0.16\,\mathrm{GeV}$
2. $J^{PC} = 2^{+-}$
   $M = 2.00\,\mathrm{GeV}, \Gamma = 0.25\,\mathrm{GeV}$



Results

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