Excited states in hadronization

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In the previous report we have discussed the computation of probabilities for coalescence of two distinguishable, non-relativistic particles into bound state with well-defined angular momentum, described by a isotropic 3-D harmonic oscillator potential [1]. The initial particles are represented by generic Gaussian wave packets of given average positions and momenta. Using a phase-space formulation we had arrived at final probabilities $P_{kl}(\boldsymbol{r},\boldsymbol{p})$ for forming bound state with quantum numbers k, l and summed over all possible m (k = radial, l = angular momentum, m = magnetic quantum numbers). They are expressed in terms of the relative center coordinates of the wave packets in phase space, $\boldsymbol{r}$ and $\boldsymbol{p}$. For example, in the simplest case[1]

$$P_{10} = \frac{1}{2} e^{-v} \left(\frac{1}{3} v^2 - \frac{1}{3} t \right)$$

for $k = 1$, $l = 0$. Here $v = (\nu^2 r^2 + p^2/\nu^2\hbar^2)/2$ and $t = (r^2 p^2 - (\boldsymbol{r}\cdot\boldsymbol{p})^2)/\hbar^2$. Since $t = L^2/\hbar^2$, where L is the classical angular momentum of the wave packet centroids, one can clearly correlate the initial angular momentum of the 2-quark system with the probabilities to form states with a particular orbital angular momentum l.

In the current reporting period we have used these probabilities to implement the recombination of quarks and antiquarks into mesons up $N = 2k + l = 4$ into Hybrid Hadronization. Taking into account the correct spectrum of hadrons is important in many applications, and we expect this to hold for hadronization as well. Hybrid Hadronization is a hadronization model which combines quark recombination and Lund string fragmentation [2]. By sampling recombination probabilities, quarks close enough in phase space will directly recombine into hadrons while partons further apart in phase space are forming color singlet string systems which then fragment into hadrons. The total probability for recombination of a given quark-antiquark pair contains the probability for overlap in phase space as well as factors from the overlap of spin and color states, $P_{tot} = P_{kl} \times P_{spin} \times P_{color}$.

We use PYTHIA 8 to prepare final parton systems in 91 GeV e^++e^- collisions and feed these, including their color tag information, into a standalone version of Hybrid Hadronization.

Fig. 1 shows the yields per event (recombination only) for mesons with different quantum numbers, radial $n_r = k$, orbital angular momentum l, and total angular momentum j. The most important outcome of this study is that p- and d-wave mesons are important channels for recombination even in the most dilute collision system represented by e^++e^-. Note that many mesons up to $N = 4$ are not available in the Particle Data Book and have been assumed in this study, with their masses extrapolated from empirical scaling laws. More detailed studies of the impact of excited mesons are under way.

[1] This refers to the fact that results are simplest if the widths of the particle wave packets and the harmonic oscillator potential are in a certain relation [1].

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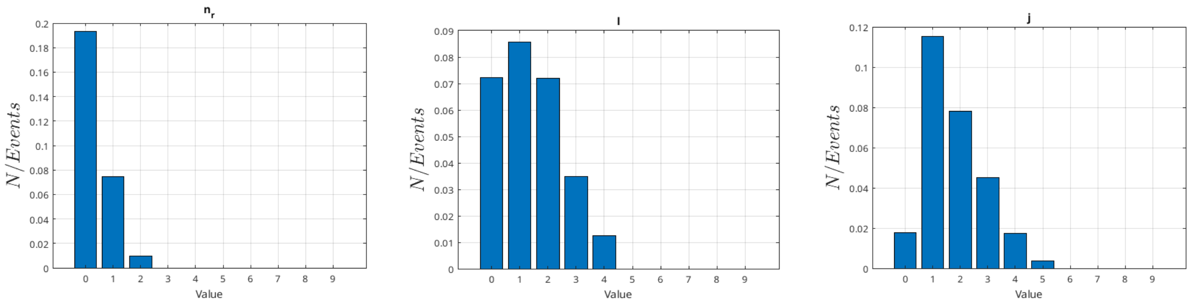

Fig. 1. Yields per events for recombined mesons states with particular quantum numbers n_r, l and j. $n_r = k$ here is the radial quantum number and j denotes total angular momentum from the operator $\boldsymbol{J} = \boldsymbol{L} + \boldsymbol{S}$. One can see that p-wave and d-wave mesons ($l = 1, 2$, resp.) play an important role in recombination, even in a dilute systems.

[1] M. Kordell II, R.J. Fries and C.M. Ko, Annals Phys. **443**, 168960 (2022).

[2] K. Han, R.J. Fries and C.M. Ko, Phys. Rev. C **93**, 045207 (2016).