A possible naming scheme for exotic hadrons

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Based on many discussions with LHCb colleagues

Hadron Spectroscropy: The Next Big Steps
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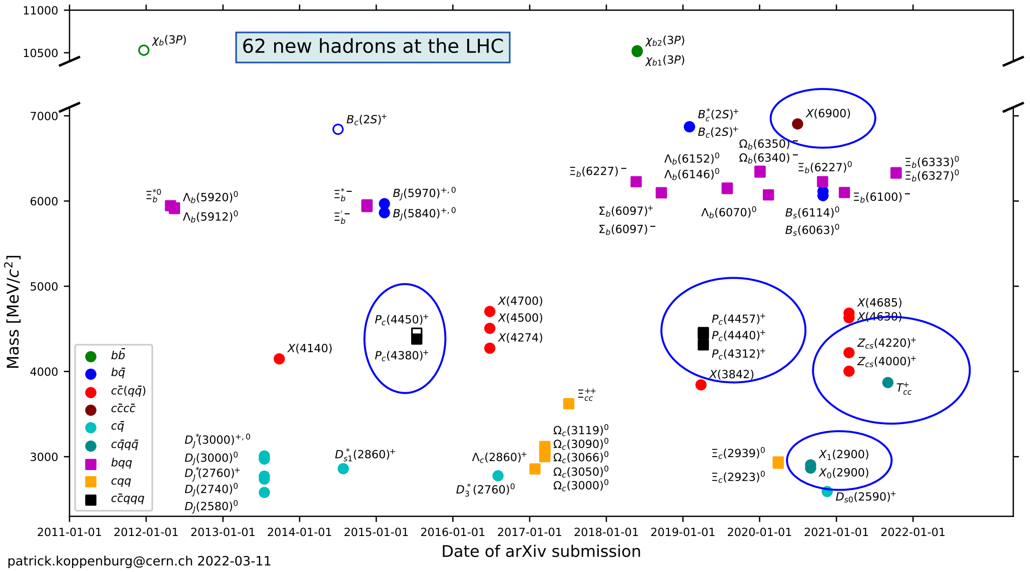
What is the problem?

- Several discoveries that do not fit into PDG naming convention.
- Mostly (not always) following PDG rule to use “X” for states where not all QNs measured
- Names assigned ad-hoc
  - Problems/conflicts likely if current rate of discoveries continues
- Names may become popularised even if not used in LHCb papers
  - e.g. T_{cccc} for X(6900)



https://www.nikhef.nl/~pkoppenb/particles.html or https://gitlab.cern.ch/lhcb-docs/FIGURE/LHCb-FIGURE-2021-001

PDG naming convention -- based only on quantum numbers

https://pdg.lbl.gov/2021/reviews/rpp2020-rev-naming-scheme-hadrons.pdf

Table 8.1: Symbols for mesons with strangeness and heavy-flavor quantum numbers equal to zero. States that do not yet appear in the RPP are listed in parentheses.

$J^{PC} =$	0^{-+}, 2^{-+}, ⋮	1^{+-}, 3^{+-}, ⋮	1^{--}, 2^{--}, ⋮	0^{++}, 1^{++}, ⋮
Minimal quark content				
$u\bar{d}, u\bar{u}-d\bar{d}, d\bar{u}$ $(I=1)$	π	b	ρ	a
$d\bar{d}+u\bar{u}$ and/or $s\bar{s}$ $(I=0)$	η,η'	h,h'	ω,ϕ	f,f'
$c\bar{c}$	η_c	h_c	ψ^*	χ_c
$b\bar{b}$	η_b	h_b	Υ	χ_b
$I=1$ with $c\bar{c}$	(Π_c)	Z_c	R_c	(W_c)
$I=1$ with $b\bar{b}$	(Π_b)	Z_b	(R_b)	(W_b)

- $X(3872)$ will appear as '$\chi_{c1}(3872)$ also known as $X(3872)$';
- $X(3900)^{\pm}$ will appear as '$Z_c(3900)^{\pm}$';
- $X(4260)$ will appear as '$\psi(4260)$ also known as $Y(4260)$';

No rule for exotic mesons with s, c, b QNs

1. Baryons with miminal content of *three* u and/or d quarks are N's (isospin 1/2) or Δ's (isospin 3/2).
2. Baryons with *two* u and/or d quarks are Λ's (isospin 0) or Σ's (isospin 1). If the third quark is a c or b quark, its identity is given by a subscript.
3. Baryons with *one* u or d quark are Ξ's (isospin 1/2). One or two subscripts are used if one or both of the remaining quarks are heavy: thus Ξ_c, Ξ_{cc}, Ξ_b, etc.*
4. Baryons with *no* u or d quarks are Ω's (isospin 0), and subscripts indicate any heavy-quark content.
5. A baryon that decays strongly has its mass in parentheses. Examples are the $\Delta(1232)$ $3/2^+$, $\Sigma(1385)$ $3/2^+$, $N(1440)$ $1/2^+$, $\Xi_c(2645)$ $3/2^+$.

In short, the minimal number of u plus d quarks together with the isospin determine the main symbol, and subscripts indicate any content of heavy quarks. A Σ always has isospin 1, an Ω always has isospin 0, etc.

More recently, the LHCb collaboration found a series of candidates for pentaquark states in the $J/\psi p$ system extracted from data on $\Lambda_b^0 \to J/\psi K^- p$ [4,5].** These have the quantum numbers of excited nucleons, but have a minimal quark content of $c\bar{c}uud$. Following the name established by the LHCb collaboration, we label these $P_c^+(\text{mass})J^P$, with the mass given in parentheses.

No obvious way to extend to other PQ states

Examples

- $X_0(2900)$ and $X_1(2900)$ discovered as D^-K^+ resonances [LHCb-PAPER-2020-025]
  - All QNs except isospin determined (could be I=0,1)
  - If/when isospin measured (discovery/absence of partners), what should these states be called?
- $Z_{cs}(4000)$ and $Z_{cs}(4220)$ discovered as $J/\psi K^+$ resonances [LHCb-PAPER-2020-044]
  - All QNs determined (assuming I=½; J^P still ambiguous for $Z_{cs}(4220)$)
  - Chosen name breaks PDG convention: Z should be I=1, spin not indicated

- P_c states discovered as J/ψ p resonances [LHCb-PAPER-2015-029, LHCb-PAPER-2019-014]
  - spin-parity not yet known
    - [according to PDG, J^P should be stated explicitly in name. presumably this won't be done in practice, as it is not usually done for other baryons]
  - J/ψ p resonances are presumably I = ½, but what should we call I = 3/2 states?
  - Possible J/ψ Λ resonances denoted P_{cs} [LHCb-PAPER-2020-039]
    - Presumably I=0, but not measured. Do we need a different name for I=0 and I=1?
  - How would this scheme be extended to PQ states with open charm?

Need for a new naming scheme

- Many states discovered at LHC experiments (mainly LHCb) in recent years
  - 10 manifestly exotic (not fitting into existing naming scheme); 9 in last ~3 years
  - Complementing discoveries at other experiments, notably BESIII, Belle & BaBar
  - Assumption that many more will following in coming years
- Naming *could* continue without any explicit scheme
  - … but likely to end in a confusing mess
  - groups will invent their own, conflicting, schemes
- Scientific tradition that those making discoveries get naming rights
  - LHCb discussing a possible scheme, but would appreciate input from other experiments and the rest of the community

Desirable features of a naming scheme

- Should be backwards-compatible, to the extent possible
  - Both with existing PDG scheme and previous publications
- Should be as simple as possible
  - Understandable by non-experts (will inevitably require effort, as the current scheme does!)
  - Avoid tortuous naming, e.g. with multiple sub/superscripts
  - No conflicts with existing particles names
    - avoid B, D, H, J, K, N, W, a, b, f, g, h, n & basically all greek letters) + X for unknown QNs
    - conflict in use of Z already exists, but don’t make worse
    - Y not ideal as barely distinguishable from Υ (Upsilon) in many fonts
- Should be based on measurable properties, not interpretation
  - i.e. follow PDG convention that name depends on quantum numbers (and mass) only
- Should be future-proof, to the extent possible
  - Avoid having to repeat this discussion in future, if we can
  - Cannot foresee every possible discovery
    - could aim to cover all possible 4- and 5-quark combinations, but (e.g.) what about 6?

Attempts at proposals

Any possible proposal will get criticised (this is fine, and welcome)

Have aimed to make “straw” proposal as a basis for discussion

Has been discussed within LHCb

- A lot of feedback received, including conflicting opinions!
- No “perfect” solution, but aim to avoid significant pitfalls

Further comments and suggestions for improvements are very welcome

Proposal:

$T^{\eta,\theta,\pi}$; $P^{\Lambda,N,\Sigma,\Delta}$

“iso-superscript”

Proposal outline

- Basic idea: T for tetra, P for penta, plus existing symbols to indicate isospin
  - Isospin symbol as superscript to avoid multiple subscripts
  - T states: I = 0, ½, 1 ↔ η, θ, π; P states I = 0, ½, 1, 3/2 ↔ Λ, N, Σ, Δ
- Subscript Υ, ψ, φ to denote hidden beauty, charm, strangeness
  - in order of mass, and repeated if necessary
- Subscript b, c, s to denote open flavour content
  - in order of mass, where more than 1 needed, e.g. T_{cs}
  - repeated if necessary, e.g. T_{bb} for an I=0 $bb\overline{ud}$ state
  - overlines on subscripts only where necessary
    - e.g. $\overline{T}_{bb}$ is the antiparticle I=0 $\overline{bb}ud$ state, but T_{bc} and $T_{b\bar{c}}$ denote different states
    - first subscript (heaviest quark) defines whether symbol has overline: $T_{b\bar{c}}$ contains $b\bar{c}$, $\overline{T}_{b\bar{c}}$ contains $\bar{b}c$
- Should be extendable for 6 or 7 quark states (not considered in detail yet)

Proposal outline

- Mesons:
  - Additional subscript for spin and superscript * to denote natural spin-parity
- Baryons:
  - Spin parity specified after symbols
- Mass in parentheses, followed by superscript for charge
  - Charge superscript can be dropped when not necessary (I=0 states)
- All as for conventional hadrons

Exotic mesons: impact on existing states

- Z_c and Z_b states (PDG convention) become $T^{\pi}{}_{\psi}$ and $T^{\pi}{}_{\Upsilon}$
- $Z_{cs}(4200)^+$ ($I = ½$, $J^P = 1^+$) becomes $T^{\theta}{}_{\psi s1}(4200)^+$
  - n.b. charge conjugate is $T^{\theta}{}_{\psi s1}(4200)^-$, i.e. no bars (c.f. D_s^+ & D_s^-)
  - isospin partner $T^{\theta}{}_{\psi s1}(4200)^0$ (quark content $c\bar{c}s\bar{d}$) has antiparticle $\bar{T}^{\theta}{}_{\psi s1}(4200)^0$
- X(6900) becomes $T^{\eta}{}_{\psi\psi}(6900)$
  - with additional labels once J^P measured; η superscript can be dropped since obvious
- $X_0(2900)$ and $X_1(2900)$
  - become $T^{\eta}{}_{cs0}{}^*(2900)^0$ and $T^{\eta}{}_{cs1}{}^*(2900)^0$ if I=0 or $T^{\pi}{}_{cs0}{}^*(2900)$ and $T^{\pi}{}_{cs1}{}^*(2900)$ if I=1
  - bar required to distinguish neutral particle and antiparticle
    - $T_{cs}{}^0$ contains c and s, $\bar{T}_{cs}{}^0$ contains $\bar{c}$ and $\bar{s}$
- $T_{cc}{}^+$ becomes $T^{\eta}{}_{cc}{}^+$, assuming I=0
- n.b. no change to, e.g., $\chi_{c1}(3872)$
  - this scheme only for states with manifestly exotic quantum numbers

Exotic baryons: impact on existing states

- All P_c states become P^N_ψ (assuming I=½)
  - Antiparticle of $P^N_\psi(4312)^+$ is $\bar{P}^N_\psi(4312)^-$
  - Could imagine dropping "N" superscript (treating I=½ as default if not specified otherwise)
- $P_{cs}(4459)^0$ becomes $P^\Lambda_{\psi s}(4459)^0$ (assuming confirmed & I=0)
  - Antiparticle is $\bar{P}^\Lambda_{\psi s}(4459)^0$

‡ indicates assumed QNs

Translations

Minimal quark content	Current name	$I,\ J^{P(C)}$	Proposed name	Reference
$c\bar{c}$	$\chi_{c1}(3872)$	$I=0,\ J^{PC}=1^{++}$	$\chi_{c1}(3872)$	[22, 23]
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I=1,\ J^P=1^+$	$T_{\psi 1}^{\pi}(4430)^+$	[24, 25]
$c\bar{c}u\bar{d}$	$Z_c(4100)^+$	$I=1,\ J^P=1^{-\,\ddagger}$	$T_{\psi 1}^{\pi *}(4100)^+$	[26]
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I=\frac{1}{2},\ J^P=1^+$	$T_{\psi s1}^{\theta}(4000)^+$	[7]
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I=\frac{1}{2}$	$T_{\psi sJ}^{\theta}(4220)^+$	[7]
$c\bar{c}c\bar{c}$	$X(6900)$	$I=0$	$T_{\psi\psi J}(6900)$	[4]
$cs\bar{u}\bar{d}$	$X_0(2900)$	$I=0^{\ddagger},\ J^P=0^+$	$T_{cs0}^{\eta *}(2900)^0$	[5, 6]
$cs\bar{u}\bar{d}$	$X_1(2900)$	$I=1^{\ddagger},\ J^P=1^-$	$T_{cs1}^{\pi *}(2900)^0$	[5, 6]
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$	$I=0^{\ddagger},\ J^P=1^{+\,\ddagger}$	$T_{cc1}^{\eta}(3875)^+$	[8, 9]
$c\bar{c}uud$	$P_c(4312)^+$	$I=\frac{1}{2}^{\ddagger}$	$P_{\psi}^{N}(4312)^+$	[3]
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I=0$	$P_{\psi}^{\Lambda}(4459)^0$	[19]

In practice “obvious” super- & sub-scripts likely to be dropped

Last thoughts

- Possible to come up with a scheme that satisfies most desirada
  - relatively simple, largely following existing (PDG) principles
  - perfect backwards-compatibility not possible
- Existing “straw” proposals seem to provide reasonable starting point
  - Some annoying features (changes of well-established names, multiplicity of super/subscripts)
  - No scheme will be perfect, and need flexibility to accommodate future discoveries
    - e.g. Open-charm exotic mesons exist, so open-charm exotic baryons probably do too
- Hope to get further feedback so that whatever scheme emerges will be accepted in the community

History repeats itself

CERN Courier, November 1985

Thanks @NikoSarcevic

https://twitter.com/NikoSarcevic/status/1455440739219951617?t=x5n5xCEBD8hT2y-n5nWOoQ&s=19

New names for old mesons

The Particle Data Group collates information on particle properties from experiments carried out at Laboratories all over the world and brings out regular editions of its 'Review of Particle Properties' – the particle physicists' handbook.

Twenty years ago, the Group introduced a new convention for naming baryons (half-integer spin particles), which has gone on to become standard. This contrasts with the mesons (integer spin particles), which use an alphabet soup of largely uninformative names, some particles with related quantum numbers having very different names, while other disparate particles have inherited confusingly similar labels.

CERN Courier, November 1985

It is easy to invent logical and consistent naming schemes, however it is unpleasant and confusing to have to learn lots of new names. Thus having considered schemes of various degrees of radicalism (and having exposed part of the physics community to them) the Particle Data Group now ends up with a set of new names. The exception is the celebrated J/psi, which has such a monstrous name that nearly everybody wants to keep it!

Under the new meson scheme, the quantum numbers (spin, parity, isospin, etc.) and the quark content define the names. The spin is indicated by subscript, except for the spin zero, negative parity (pseudoscalar) and spin one, negative parity (vector) particles, where the subscript is omitted.

For mesons which are not bound states of quarks and antiquarks (such as 'glueballs'), the quantum numbers (when non-exotic) determine their names, just as for quark-antiquark bound states. This seems appropriate since such states will be difficult to distinguish from quark-antiquark ones and will likely mix with them.

A difficulty arises with related isospin singlet particles (eta and eta prime, omega and phi, f and f prime). For the lightest such states, the existing conventions will be followed. Primes are being reserved for use in these cases, so the old habit of using primes to denote radial excitations has been dropped.

Many familiar names stay – pi, eta, rho, omega, eta prime, phi, J/psi, chi, upsilon, etc. Some names undergo minor changes: $A_2(1320)$ for example, becoming $a_2(1320)$, while others get a complete face-lift, $S^*(975)$ becoming $f'_0(975)$.

For mesons containing strange and other heavy quarks, the heavier of the two quarks provides the label – K for a strange quark, D for a charmed quark, B for beauty and T for top. A letter subscript is added for the lighter quark, unless it is 'up' or 'down'. Thus the F (charm/strange) meson becomes D_s. Another subscript gives the spin (again omitted for pseudoscalar and vector mesons). Finally a superscript asterisk is added for states with 'normal' spin-parity assignments from a quark model picture (zero plus, one minus, two plus, etc.). Thus the names K, K^*, D, D^* and B do not change, but K^* (1430) becomes K_2^* (1430), L (1770) becomes K_2 (1770), etc.

The new scheme admittedly can lead to cumbersome notations, but not for states that are likely to be common. To facilitate the transition, the Particle Data Group will use both the old and the new meson labelling schemes for a few editions of the Review of Particle Properties.

From Matts Roos

CERN Courier, November 1985

Back up

(including comments received so far)

Aside: numbering scheme

MC generators need a unique numbering scheme for hadrons (and all particles)

Existing scheme does not cover all known states

https://pdg.lbl.gov/2021/reviews/rpp2020-rev-monte-carlo-numbering.pdf

Developers expressing desire for a future proof scheme

Should ideally have a one-to-one matching between naming and numbering

Suggest to leave this aside for now. Figure out a naming scheme first, then figure out how to best match it to a numbering scheme

Alternative proposal:
T,U,Z; O,P,Q,R
“the roman alphabet”

Exotic mesons (minimal 4q content with ≥ 1 heavy flavour)

- T, U, Z to denote isospin 0, ½, 1 states
  - Keep X reserved for states with QNs not yet measured
  - Use Z for I=1 instead of V to keep (some) consistency with current PDG
  - Strictly speaking I=3/2 states also possible (e.g. $cu\bar{d}\bar{d}$) → would be “V” states (may be hard to discover)
- Subscript b, c, s to denote open flavour QNs
  - in order of mass, where more than 1 needed, e.g. T_{cs}
  - repeated if necessary, e.g. T_{bb} for an I=0 $bb\bar{u}\bar{d}$ state
  - overlines on subscripts only where necessary
    - e.g. $\bar{T}_{bb}$ is the antiparticle I=0 $\bar{b}\bar{b}ud$ state, but T_{bc} and $T_{b\bar{c}}$ denote different states
    - first subscript (heaviest constituent quark) defines whether symbol has overline: $T_{b\bar{c}}$ contains $b\bar{c}$, $\bar{T}_{b\bar{c}}$ contains $\bar{b}c$
- Subscript ϒ, ψ, φ to denote hidden beauty, charm, strangeness
  - in order of mass, and repeated if necessary
- Additional subscript for spin and superscript * to denote natural spin-parity
  - As for conventional mesons in PDG scheme
  - Suggest to always include these for clarity
    - for conventional mesons specify neither for $J^P = 0^-$, and only * for $J^P = 1^-$
- Mass in parentheses, followed by superscript for charge, as normal
  - Charge superscript can be dropped when not necessary (I=0 states)

Exotic mesons: impact on existing states

- Z_c and Z_b states (PDG convention) become Z_ψ and Z_Υ
- $Z_{cs}(4200)^+$ ($I = ½$, $J^P = 1^+$) becomes $U_{\psi s1}(4200)^+$
    - n.b. charge conjugate is $U_{\psi s1}(4200)^-$, i.e. no bars (c.f. D_s^+ & D_s^-)
    - isospin partner $U_{\psi s1}(4200)^0$ (quark content $c\bar{c}s\bar{d}$) has antiparticle $\overline{U}_{\psi s1}(4200)^0$
- X(6900) becomes $T_{\psi\psi}(6900)$
    - with additional labels once J^P measured
- $X_0(2900)$ and $X_1(2900)$
    - become $T_{cs0}^*(2900)^0$ and $T_{cs1}^*(2900)^0$ if I=0 or $Z_{cs0}^*(2900)$ and $Z_{cs1}^*(2900)$ if I=1
    - bar required to distinguish neutral particle and antiparticle
        - T_{cs}^0 contains c and s, $\overline{T}_{cs}^0$ contains $\bar{c}$ and $\bar{s}$
- T_{cc}^+ unchanged, assuming I=0
- n.b. also no change to $\chi_{c1}(3872)$
    - this scheme only for states with manifestly exotic quantum numbers

Exotic baryons (minimal 5q content with ≥ 1 heavy flavour)

- O, P, Q, R to denote I=0, ½, 1, 3/2 states
  - Difference between P and R is like difference between N and Δ
  - Difference between O and Q is like difference between Λ and Σ
  - Strictly speaking I=2 states also possible (e.g. $\bar{c}uuuu$) → would be "S" states (maybe hard to discover)
- Subscript b, c, s to denote open flavour QNs
  - bar if necessary to denote antiquark in baryon, e.g. $b\bar{c}uud$ should be $P_{b\bar{c}}$
- Subscript Υ, ψ, φ to denote hidden beauty, charm, strangeness
  - Same as for exotic mesons
- Nothing explicit in name to indicate spin-parity
  - As for conventional baryons in PDG scheme
- Mass in parentheses, followed by superscript for charge, as normal
  - Charge superscript retained even when not necessary (I=0 states)
- All antibaryons with overline, as normal
  - Easier than mesons: baryons are particles (no bar) & antibaryons are antiparticles (with bar)
  - But note that e.g. $P_{b\bar{c}}$ is a different particle to (not antiparticle of) $P_{\bar{b}c}$

Exotic baryons: impact on existing states

- All P_c states become P_ψ (assuming I=½)
  - Antiparticle of $P_\psi(4312)^+$ is $\overline{P}_\psi(4312)^-$
- $P_{cs}(4459)^0$ becomes $O_{\psi s}(4459)^0$ (assuming confirmed & I=0)
  - Antiparticle is $\overline{O}_{\psi s}(4459)^0$