1. Physics Group: ***“Open-Charm” (heavy-light systems and electroweak)***
2. Physics Group Convener(s): *J.G. Messchendorp, L. Schmitt*
3. List of groups involved: *FZJ, GSI/FAIR, U of Giessen, KVI-CART, Mainz, U of Muenster*

List of relevant TAG members: *N. Brambilla, M. Lutz, T. Mannel, S. Ryan, W. Schweiger, J. Heitger\* (\* not a member of TAG)*

1. List of physics subtopics:
	* *Open-charm production in p-pbar*
	* *D(s) spectroscopy: exotics, transitions, and decays;*
	* $Λ\_{c}, Σ\_{c}, Ξ\_{c}$ *spectroscopy: exotics, transitions, and decays;*
	* *(semi-)leptonic decays: form factors and decay constants;*
	* *Electroweak: (in)direct CPV, rare decays, …*
2. Importance/Impact:
*should involve the PANDA TAG members*
3. Please give a short summary (< ½ page) for the motivation of this topic.

Open-charm systems refer to hadrons that contain one charm or an anti-charm quark embedded in an environment composed of light quarks and gluons. The physics interests to study these systems are manifold. From a birds-eye view, open-charm systems form an ideal tool to link various other fields in hadron and particle physics. A few key examples are given below.

Decay studies of the open-charm systems link the dynamics of QCD with the electroweak sector. The lowest-lying open-charm hadrons ($D\_{(s)}, Λ\_{c}, Ξ\_{c}$) decay weakly, and thereby, are ideal systems to measure standard model (SM) parameters and to search for “new physics” via CKM parameter studies, rare decays, and (in)direct CPV studies. More specifically, at HESR it will be possible to produce large numbers of D-mesons and $Λ\_{c}$ baryons which will eventually allow us (depending on the luminosity and on the production cross section) to study rare decays and even CP violation in mesons with charm. This bears the potential to uncover new physics as a deviation from the small SM value for CP violation and decays like $D^{0}\rightarrow μ^{+}μ^{-}$and $D^{0}\rightarrow γγ$. For the decays of open-charm hadrons, a good understanding of the “hadron structure” is of importance, which is accessible experimentally via measurements of form factors and decay constants in (semi-)leptonic decays. These measurements can be used to benchmark predictions from Lattice QCD or alternatively give an improved determination of the CKM matrix elements. In this context, PANDA offers good perspectives to study long-distance effects in weak decays via radiative transitions of the type $c\rightarrow uγ$.

From a spectroscopy point-of-view, a study of open-charm hadrons connects well to the physics aspects of hadron systems composed of light quarks (u,d,s). The presence of a relatively heavy charm quark leads to a approximated flavor (mass) independent and spin-independent strong interaction described by heavy-quark symmetry (HQS). This symmetry (and its breaking) helps to formulate a controllable theory and, thereby, it helps considerably in the interpretation of open-charm systems. The light quarks can be considered as “tethered” to a relatively heavy quark, which thereby helps in the interpretation of more complex systems that are composed of light hadrons only. For the charm-baryon systems, HQS can be exploited to study the di-quark correlations in baryons. A systematic comparison with the properties of the analogue open-bottom hadrons, in which HQS is a more precise symmetry, provides access to the HQS breaking. In this context, the (open) charm and bottom systems complement each other. Our physics goals for baryonic systems composed of a charm quark, strongly overlaps with the ambitions of the baryon spectroscopy physics group of PANDA. Synergy between the two physics groups and common discussions on this topic are being pursued.

A study of open-charm systems is complementary to the searches for glueballs, hybrids, and unconventional multi-quark and molecular states. Key examples of such a kind of hadrons (as commonly believed) are the DsJ(2317) and the $Λ\_{c}(2940)$. Open-charm spectroscopy with PANDA will potentially determine the resonance parameters of these unconventional hadrons more precisely and might reveal a complete new class of hadronic matter.

1. Please summarize the originality of the measurements.

*can only PANDA do that, is PANDA the first to do that, why is PANDA in a better position*

Open-charm spectroscopy, decay, and its connection to the electroweak sector are as a whole not unique for PANDA. There are, however, a few features that could place PANDA in a better position. One of the features is the associative production of open-charm hadrons, i.e. $D\overbar{D}, Λ\_{c}\overbar{Λ}\_{c}$, etc., in particular near the production threshold. Such methods are not accessible by the main competitors, namely LHCb and BELLE II. In the case of the electroweak physics program, the associated production has the advantage that it conserves a strong correlation of the $D\overbar{D} $pairs in the hadronisation process. For the spectroscopy studies, the basic resonance parameters, like mass, width, and lineshape, can be determined with excellent accuracy, which is in particular interesting for narrow states such as the DsJ(2317). Another, in this case unique, feature of PANDA is the usage of antiproton-proton annihilations in comparison with electron-positron annihilations. For example, in the case of Ds spectroscopy, one expects to become sensitive to D-waves. However, the uniqueness of open-charm production via antiproton-proton annihilations brings in a large uncertainty in the expected cross sections. Theoretical calculations predict cross sections that vary largely from nanobarns to microbarns due to a lack of empirical information. This large uncertainty brings in another unique aspect for open-charm production with PANDA, namely that cross section measurements will provide information about the dynamics that play a role in the process.

The main competitor, concerning the amount of open-charm mesons and baryons produced, is LHCb. This experiment is strongly limited in the detection of photons and electron-positron pairs. The photon detection of PANDA might, therefore, play an important role that would allow competing with LHCb on channels that involve photons. For this aspect, the radiative and rare decays of open-charm hadrons channels, like $D^{0}\rightarrow γγ$ and $Λ\_{c}\rightarrow pγ$, could be a unique opportunity to pursue with PANDA, since it is new and out of reach for LHCb. Moreover, the physics case (long-distance effects) is very well motivated since it has a large potential to constrain “new physics” in the charm sector. In particular, the radiative decay of $Λ\_{c}$ baryons is new and a relatively large $Λ\_{c}\overbar{Λ}\_{c}$ production cross section (with respect to $D\overbar{D}$ production) can be expected (couple of hundreds of nanobarns), albeit with a large theoretical uncertainty. Similarly, studying radiative and soft-$π^{0}$ transitions between open-charm states could be a unique opportunity for the hadron structure program of PANDA. The competitiveness in this aspect with BES III or BELLE II depends strongly on the cross section for open-charm production in antiproton-proton annihilation. Note that the maximum center-of-mass energy covered by BES III is about 4.5-4.6 GeV, which strongly limits their studies of highly excited D(s) mesons and charmed baryons (in contrast to PANDA).

1. Please indicate competition in the goals, the methods and the reactions channels involved.

*competition on the narrow and wider physics case*

In general, the main competitors in the field of open-charm are BES III, BELLE II and mostly (due to its very high statistics) LHCb, as outlined above. BELLE II and LHCb study extensively electroweak aspects, such as CP violation and rare decays, in both the B and D-sector. BES III has an open-charm program that includes the production of quantum entangled $D\overbar{D}$ pairs and, since recently, $Λ\_{c}\overbar{Λ\_{c}}$ pairs close to its production threshold. For the spectroscopy aspects, we foresee competition from J-PARC as well.

1. Is there a unique selling point? Please explain this (< ¼ page)

*what can we do, what others can’t and how important is it?*

Most of these aspects are outlined in b). In addition, PANDA features a very large acceptance and a complete set of observables (charged, neutral, PID). For both the electroweak studies as well as structure studies, a rich spectrum of channels is available and can, thereby, be exploited to improve the sensitivity by selecting “golden channels” with a large impact. This should be followed up in the near-future discussions with the TAG.

1. Details for each subtopic listed above
*Example: ccbar Molecule (XYZ)*
2. What are the required momentum(-range) settings?

*Open-charm production in p-pbar*

Antiproton beam momentum in range from 6.4 GeV/c up to 15 GeV/c (or higher if the maximum design momentum can be exceeded).

*D(s) spectroscopy*

Antiproton beam momentum in range from 6.4 GeV/c (D), 8 GeV/c (Ds) up to 15 GeV/c (or higher if the maximum design momentum can be exceeded). For mass and width studies of DsJ(2317,2460,2536), scanning is foreseen in steps of about 100 keV/c2 in the vicinity of the corresponding mass. For searches of new states, the usage of highest beam momentum is advantageous.

$Λ\_{c}, Σ\_{c}, Ξ\_{c}$ *spectroscopy*

Antiproton beam momentum in range from 10.1 GeV/c up to 15 GeV/c (or higher if the maximum design momentum can be exceeded). Mass scanning around various resonance states or around meson-baryon thresholds, e.g. D\*N for $Λ\_{c}(2940)$ corresponding to antiproton energy of 13.6 GeV/c, could be advantageous. For searches of new states, the highest beam momentum is advantageous.

*(semi-)leptonic decays*

Antiproton beam momentum at least 6.4 GeV/c. Preferably such that the highest production cross section is achieved: either at resonance or at a higher momentum (8 GeV/c).

*Electroweak*

Antiproton beam momentum at least 6.4 GeV/c: either resonance production (e.g. Psi(3770)) or momentum for highest continuum cross section (8 GeV/c).

1. What is the required integrated luminosity?

*sometimes this can only be guessed, since production cross sections are unknown.*

*Please then give a guestimate and explicitly list all input variables,*

*like signal and background assumptions (e.g. 1 nb cross section, 10.000 rec. events, S/B=1:1)*

The estimates presented here refer to the associate production of pairs of open-charm hadrons. The cross section for this process is not known and predictions vary between nb to $μ$b. The feasibility of many aspects of the open-charm physics program depends crucially on the actual value of the cross section.

*Open-charm production in p-pbar*

For the open-charm production in p pbar collisions, the cross sections, angular distributions, and excitation spectra are the main objectives. Typically, 107 reconstructed pairs of open-charm mesons and baryons (assuming S/B=1:1 or better) each would be needed to reach a %-level statistical precision with sufficient binning in energy and angle.

*D(s) spectroscopy*

For the width measurement (mass scan) of the DsJ(2317) as an example and assuming 5 nb at 5 MeV above threshold at least 50 pb-1 (integrated over 15 scan points) is required with a S/B=1:1 (assumption) and in the inclusive mode (Ds + missing mass, about 25% efficiency). Note that for exclusive measurements, the rates will reduce by two-orders of magnitude. For first cross section measurements of the open-charm meson production, an order of magnitude less luminosity would be required.

$Λ\_{c}, Σ\_{c}, Ξ\_{c}$ *spectroscopy*

For spectroscopy aspect of charmed baryons, we would guess similar luminosity requirements as for the D(s) spectroscopy.

*(semi-)leptonic decays*

In general, 5x108 exclusive D(s)D(s)bar pairs are required to be produced to be competitive with other experiments as outlined earlier. Assumption: ~10% detection efficiency and known branching fractions. Integrated luminosities expected to be required are of order fb-1.

*Electroweak*

Similar luminosity requirements as for the (semi)leptonic decay studies.

1. List “all” channels of interest
*List either in a generic or in an explicit list (if possible) all or the kind of reactions which need to be investigated.*

*Open-charm production in p-pbar*

associated production of pairs of charmed mesons and baryons

*D(s) spectroscopy*

DsDs0(2317)

DsDs1(2460)

DsDs1(2536)

radiative, pi, 2pi, K transitions among D(s) states.

D -> Kpipi / KKpi (Dalitz)

$Λ\_{c}, Σ\_{c}, Ξ\_{c}$ *spectroscopy*

radiative and hadronic transitions among states

hadronic decays of $Λ\_{c}, Ξ\_{c} $for light-quark hadron studies (Dalitz)

*(semi-)leptonic decays*

 D\_(s)Dbar\_(s) -> K+K-pi + \mu\nu

DDbar -> K-pi+pi+ + \mu\nu

Ds -> eta/eta’ e^+\nu

*Electroweak*

D0D0bar, D+D-, DsDsbar, $Λ\_{c}\overbar{Λ}\_{c}$

Decays: SCS, CF, DCS, radiative

1. Which (non-)exclusive channels pose as role models (e.g. for simulations)

*Example: J/psi pipi eta, J/psi pipi scan*

*Open-charm production in p-pbar*

p+pbar -> D0 D0bar -> (K pi) + (K pi)\* / (K pi) + X

p+pbar -> D+D- -> (K 2pi) + (K 2pi)\* / (K 2pi) + X

p+pbar -> Ds+Ds- -> (2K pi) + (2K pi)\* / (2K pi) + X

p+pbar -> Lambdac+Lambdac- -> (p K pi) + (p K pi)\* / (p K pi) + X

p+pbar -> Lambdac+Lambdac- -> (Lambda pi) + (Lambda pi)\* / (Lambda pi) + X

p+pbar -> Lambdac+Lambdac- -> (Lambda pi) + (p K pi)\*

*D(s) spectroscopy*

All given in c)

$Λ\_{c}, Σ\_{c}, Ξ\_{c}$ *spectroscopy*

$$Λ\_{c}\left(2940\right)^{+}Λ\_{c}^{-}\rightarrow pD^{0}+\overbar{p}K^{+}π^{-}$$

*(semi-)leptonic decays*

D\_(s)Dbar\_(s) -> K+K-pi + \mu\nu

Ds -> eta/eta’ e^+\nu

*Electroweak*

$$D^{0}\overbar{D}^{0}\rightarrow γγ+Kπ$$

$$Λ\_{c}^{+}Λ\_{c}^{-}\rightarrow p γ+\overbar{p}Kπ$$

1. What are typical potential trigger scenarios (guestimates!) ?

In general, the trigger should focus on the detection and reconstruction of weakly decaying $D\_{(s)}, Λ\_{c}, Ξ\_{c}$ baryons that are involved in nearly all the reactions given earlier. For example, the identification of displaced tracks or the invariant mass reconstruction of one of the “tagging” hadrons would be possibilities for an advanced trigger scenario.

1. What are the main background channels and which are the most important filter steps and which detectors are involved to deliver this information?

Also here, we make some general remarks on possible sources of background sources and detectors that would be crucial to filter out these channels. The challenges lie (as for many other physics programs of PANDA) to cope with small cross sections and branching fractions with respect to the many orders larger total ppbar cross section. We foresee that for the key channels of the open-charm program, a complete detector is mandatory. Also from experiences with other experiments (like BESIII), the open-charm activities are very demanding, and hence, likely not a day-1 experiment for PANDA either.

In particular channels of high specific interest for PANDA based on photon detection involving the EMC typically require the detection of the complementary charge conjugate state or particle with opposite charm quantum number with charged tracks for selection and background suppression.

*Typical background sources*

- Misidentification of pions as kaons

- Multiple photons and corresponding combinatorics

- pi0 production in case of radiative decays

- Channels with similar event topologies, f.e. non-resonant contributions with the same final state

*Filters*

- Central and forward tracking (latter in particular for charmed baryon program)

- MVD and STT are essential for tracking and vertex reconstruction

- combination with pellet target and pellet tracking system

- EMC: since the dominant and competitive key channels do contain photons

- GEM to detect particles below 20 degrees

- DIRC for pion/kaon separation

- Muon detector, in particular for (semi)leptonic decays

- (Kinematically) over-redundant information

- Multi-variate analysis with combined PID information

1. Minimal setup required for this subtopic
2. What is the figure of merit for the reactions for this subtopic?

*e.g. S/B, efficiency,… t.b.d. by the subgroup*

*Open-charm production in p-pbar*

Statistical significance per unit of luminosity

*D(s) spectroscopy*

Statistical significance per unit of luminosity, mass and width precision per unit of luminosity

$Λ\_{c}, Σ\_{c}, Ξ\_{c}$ *spectroscopy*

Statistical significance per unit of luminosity, mass and width precision per unit of luminosity

*(semi-)leptonic decays*

Statistical significance per unit of luminosity, precision (stat. & sys.) of form factors and decay constants per unit of luminosity

*Electroweak*

Statistical significance per unit of luminosity, precision (stat. & sys.) $ΔA\_{CP}$ per unit of luminosity