Production and study of baryons with beauty at the Italian heavy-flavor factory (Super*B*)

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Super*B* is an INFN flagship project for a new high-luminosity heavy-flavor factory. Along with its companion detector, it is dedicated to the search for CP violation effects in the *B* meson sector with the aim of looking for direct and indirect signals of new physics, beyond the Standard Model. However it could offer as well the opportunity for a systematic, high-statistics study of *b* baryon properties and for a search for super-nuclei, that is bound nuclear systems with an explicit content of beauty.

1 Introduction

Following a long and successful tradition in building and operating lepton colliders, INFN launched a plan to construct the new Super*B* e^+e^- complex accelerator [1]. The selected site is the Tor Vergata University Campus, near Rome and close to the INFN-LNF historical research center. Super*B* will be an asymmetric, double-ring accelerator designed to run at the $\Upsilon(4S)$ resonance center-mass (c.m.) energy with a baseline luminosity in excess of 10^{36} cm^{-2} s^{-1}, that is about two orders of magnitude larger than the peak luminosity of the existing *B*-factories. The nominal beam energies will be $E_{e^+} \approx 6700$ MeV and $E_{e^-} \approx 4200$ MeV but Super*B* will have the capability of running in the c.m. energy range between $\psi(3770)$ (the charm threshold) and $\Upsilon(5S)$ resonance as well. Finally, it will be possible to have a $\sim$70% polarized electron beam [2], that also has significant impact on the physics potential of this project.
This next generation flavor-factory, along with its companion detector [3], will be mainly dedicated to the measurements of CP violating processes in the *B* meson sector, looking for deviation from the Standard Model predictions that can be interpreted as signals for new physics. At the same time the experiment will perform high-precision tests of the Standard Model. In addition Super*B* should be considered within a synergic strategy with LHCb, the flavor physics experiment recently started at the CERN LHC hadron collider. On one hand, if new physics phenomena will be observed at LHC, data from very sensitive heavy-flavor experiments will be necessary to constrain such results and to better understand their

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nature. In this respect a high-luminosity, asymmetric flavor factory can then provide a set of complementary information. Moreover this alternative approach offers the additional advantage of cleanly extracting the signal, typical situation experienced at electromagnetic machines where the environment is much cleaner. On the other hand, if no evidence for physics beyond Standard Model will be found at the energy frontier experiments, then measurements that will be performed at Super$B$ would allow for an alternative way to explore an energy range up to 10 TeV. The complete, wide spectrum of Super$B$ physics reach is described in [4].

However Super$B$ might offer a playground for a systematic study of the properties of b baryons and for an investigation of their interactions with nucleons in nuclei.

2 Bottom baryon production

Information on b baryons is scarce. It is sufficient to browse the last edition of The Review of Particle Physics [5] to realize how different is the level of knowledge about, for instance, B mesons and b baryons. In some cases the existence itself of such particles still ranges from very likely to certain and then a confirmation is highly desirable as long as the assessment of their quantum numbers and their branching fractions. One of the reasons of this lack of data is purely experimental: it is not so easy to abundantly produce heavy-flavor baryons and it is very challenging to extract signals from a huge background. A significant contribution to this field is being provided by the Tevatron Collider experiments [6] and very likely many data will soon flow from LHC. However flavor factories can play an important role as well.

The idea of creating heavy-flavor baryons at an e^+e^- collider is not brand new. About 20 years ago it was suggested [7] to exploit the charm and the beauty exchange reaction on nuclei in order to produce charmed and bottom baryons at the ARES facility, a proposed high-luminosity, single-pass, e^+e^- machine. The same method was recently used at DAΦNE, by the FINUDA experiment [8], in order to produce Λ and Σ hyperons via the strangeness exchange reaction induced by K^- following the ϕ resonance decay. Now Super$B$ offers again the opportunity to have a unique source of b baryons.

At first glance it may be objected that the available c.m. energy ($\sim$10600 MeV) is not enough to produce even the lightest b baryon-antibaryon pair (m($\Lambda_b^0\overline{\Lambda_b^0}$) $\approx$ 11240 MeV). However the leading idea of the proposed experimental method is to put a thin target on the flight path of B^- mesons, emitted in the $\Upsilon(4S)$ resonance decay, in order to produce b baryons via the beauty exchange reactions

$$B^-_{stop} + \mathcal{N}_{bound} \rightarrow \Lambda_b^0 + \pi^{-0}, \tag{1}$$

$$B^-_{stop} + \mathcal{N}_{bound} \rightarrow \Sigma_b^{\pm} + \pi^{-0+}, \tag{2}$$

$$B^-_{stop} + \mathcal{N}_{bound} \rightarrow \Sigma_b^{*\pm} + \pi^{-0+}, \tag{3}$$

$$B^-_{flight} + \mathcal{N}_{bound} \rightarrow \Xi_b^{-0} + K^{+0}, \tag{4}$$

where $\mathcal{N}_{bound}$ indicates either a proton or a neutron bound in a nucleus. While processes (1–3) occur even with stopped particles, it has to be checked whether reaction (4) can be induced by B^- mesons in flight. Unfortunately the possibility of generating Ω_b^- by this method is completely out of discussion. The properties of the produced Λ_b^0, $\Sigma_b^{\pm}$, $\Sigma_b^{*\pm}$ and, possibly, Ξ_b^{-0} hadrons will be then studied, with unprecedented accuracy, through the measurement of their decay products in the Super*B* companion apparatus. Such a systematic observation of *b* baryons will offer the opportunity to get information on non-perturbative QCD and the potential models. The large mass difference between *b* quark and the other constituent quarks could in fact allow a significant simplification in the theoretical description of a system where a light quark pair (diquark) orbits around the "nucleus" *b* quark.

3 The experimental setup

In the innovative collision scheme designed in order to reach the highest possible luminosity [9], e^+ and e^- beams will have extremely reduced dimensions at the interaction point: 7.211 μm in the horizontal plane and 0.036 μm in the vertical one. These numbers make Super*B* particularly suitable for the installation of a thin target as close as possible to the $\Upsilon(4S)$ formation point, capable of intercepting the maximum fraction of the B^- mesons following the resonance decay. Actually this is the crucial point of the project, since the choice of the distance from the interaction point and the target entrance surface is constrained by the very small B^- meson $c\tau$ value (492.0 μm) and by the requirement of avoiding any interference with the circulating beams.

Another favorable condition is represented by the fact that e^+ and e^- beams will not collide head-on. This means that, besides the 2.519 GeV/c longitudinal (i.e. along the beam pipe axis) boost, $\Upsilon(4S)$ has a sizeable transverse momentum component (0.359 GeV/c) as well. Moreover preliminary Monte Carlo calculation shows that the angular distribution of the generated B^- mesons is such that they are preferentially emitted in the horizontal plane. An interesting solution could be then that of putting the target only in the hemisphere where the B^- mesons are produced with higher energy. The advantage is twofold: the target could be placed a little bit far away from the interaction point and the B^+ mesons traveling in the opposite, free hemisphere can be exploited in order to tag the event. The option currently under evaluation is that of using a half hollow cylinder, 1 mm long and with an internal radius of 0.2 mm and an external one of 0.5 mm. It will be placed with its axis coincident with the beam pipe one and, keeping in mind that Super*B* is an asymmetric machine, completely shifted in the $z > 0$ halfspace, i.e. beyond the interaction point, along the e^+ flight direction. The arguments to be taken into account in order to choose the proper target material are its mechanical stability, its electrical conductibility, the heating during accelerator normal operation and the power deposition in case of beam loss. Gold or Platinum seem to be the best candidates to fulfill these technical requirements. Very likely the target will be efficiently cooled and should be (re)movable during the beam injection and machine tuning phase. However this does not represent an issue since it is possible to conceive a mechanism very similar to that routinely used to operate the beam scraper system.

The $e^+ + e^- \rightarrow \Upsilon(4S)$ production cross section is ∼1.1 nb. This means that at the design luminosity value of 10^{36} cm^{-2} s^{-1} $\Upsilon(4S)$ resonance will be generated at a rate of 1.1 kHz. By keeping in mind that it decays in a B^+B^- meson pair with a branching fraction of 51.6% we may expect to have a B^- meson flow of ∼550 Hz. By taking into account the fraction of surviving B^- with $\beta\gamma \approx 0.2$ (0.7%) and by making an educated guess about target acceptance and stopping efficiency (10%), reconstruction efficiency of the apparatus (10%) and accelerator daily duty cycle (70%) we estimate a b baryon production rate in excess of 2000 events per day.

4 From hyper- to super-nuclear physics

Another topic of fundamental interest that could be addressed is the investigation of b baryons interaction with nucleons in nuclei. It is indeed worth to remind that this experimental approach is the unique method to infer information about b baryon-nucleon interaction at low energies. This is a completely unexplored field and the challenge is to see whether a b baryon can become part of the target nucleus and can then form a nuclear bound system, called super-nucleus. The possible existence of such objects was suggested several years ago by Tyapkin [10], in complete analogy to what happens with s baryon Λ which can replace one nucleon in a nucleus to form nuclear bound systems, known as hyper-nuclei [11]. This is a very natural extension based on the expectation that the entire family of baryons experiences exchange forces which are similar to the corresponding interaction potentials. This statement is endorsed by the close similarity of the quark structure of the lightest flavored baryons Λ(uds), Λ_c^+(udc) and Λ_b^0(udb).

From the experimental point of view the main issue is the energy distribution of the b baryons generated in the processes (1–4). Preliminary calculations indicate that, when produced on free nucleons, their momentum spectrum typically ranges from ∼0.2 to ∼1.3 GeV/c. This fact could then reduce the fraction of b baryons with a sizeable probability of sticking to the target nucleus. To this purpose a careful study of how the nuclear medium affects the energy distribution of the produced b baryons must be performed in order to get a realistic estimation of the super-nuclei formation rate. As far as the identification of the produced super-fragment is concerned, a possible strategy could be based on the measurement of the generally high-energy decay products.

5 Conclusions

The construction of the Super*B* collider will allow to shed light on many fundamental aspects of the flavor physics thanks to the capability of collecting in a reasonable amount of time large data samples corresponding to an integrated luminosity ranging from 50 to 100 ab^{-1}.

However this new facility may offer the opportunity for carrying on a nuclear physics experiment, dedicated to a high-statistics study of b baryons properties and of their interactions with nucleons in nuclei, a subject absolutely unknown at present. This way it will be possible to look for super-nuclei as well, a definitively hard experimental task but of fundamental interest. Such an experiment may be integrated in the Super*B* companion apparatus.

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