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Production of Heavy Baryons at the Super$B$

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The Super$B$ machine will be a heavy flavour factory where e^+-e^- beams will collide with a peak luminosity in excess of 10^{36} cm$^{-2}s^{-1}$ at the center of mass energy (c.m.) of the Υ(4S) resonance. The $B\bar{B}$ meson pairs, produced with a B.R. 96% from the decay of the Υ(4S), will allow to measure the B-meson decay channels with unprecedented precision. The Super$B$ beams will be characterized, at the interaction region (I.P.), by transversal dimensions of only few microns. This fact could open the possibility to put very close to the I.P. a suitable shaped target to intercept the B^- mesons before their decay. As a result of the interaction of the slow B^- mesons with the nucleons of the target nuclei, baryons with beauty, as the Λ_b and the Σ_b, Σ_b^*, can be produced with high cross section. A production rate of $\approx$2000 heavy baryons per day per nucleon seems achievable. The same detector that is foreseen to equip the Super$B$ I.P. can be used for their detection. This would allow a systematic study of the properties of the heavy baryons with beauty (for which not so many data exist) and, furthermore, to investigate their interactions with nucleons in nuclei, a topic totally unexplored until now. With a similar technique, working at the c.m. energy of the $\psi(3770)$, charmed baryons could be also produced and studied as well as their interaction on nuclei. A possible set up to implement such a configuration on the Super$B$ will be discussed and the results of preliminary calculations presented.

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1. Introduction

The Super*B* is a new Europen Accelerator Facility, an INFN project aiming to build in Italy an e^+-e^- collider of high luminosity able to operate up to the energy of the Υ(4S) resonance, i.e. 10.58 Gev in the c. m.. It will be asymmetric, with (maximum) energies of 6.7 GeV and 4.2 GeV for e^+ and e^-, respectively. The beams will not collide exactly $head-on$ but at a crossing angle of ≈66 mrad: thanks to the method of the $crab-waist$, developed and realized at the DAΦNE collider of INFN-Laboratori Nazionali di Frascati (LNF), a peak Luminosity in excess of 10^{36} cm$^{-2}s^{-1}$ is expected at the Υ(4S) resonance energy. Moreover it will be possible to achieve a 60%−85% polarization of the electron beam, significantly enlarging the physics reach of this project. The Super*B* can also be employed as a high brilliant source of synchrotron radiation for condensed matter studies, 30 times brighter than ESFR. The site of the collider as been selected in the area of the Tor Vergata University in Rome, close to the LNF. Detailed information on Super*B* and its detector can be found in [1], [2] and [3]. The main physics goals of Super*B* will be to identify the flavour structure of New Physics, being sensitive to it through flavour properties, CP violation, asymmetries in B and D decays, and rare decays. In this respect Super*B* is expected to probe New Physics scales up to 10-100 TeV through indirect, high precision measurements. Exhaustive details on the physics capabilities of Super*B* can be found in [4], [5] and in the paper of F. Wilson in this Volume.

A peculiarity of the Super*B* with respect to all other e^+-e^- colliders is, a part its high Luminosity, the extremely reduced transversal dimensions of the beams at the I.P., as can be seen in Table1.
The small transversal beam dimensions at I.P. of the Super*B* is the key parameter that could open

Table 1: Some relevant parameters of previous or existing e^+e^- colliders and of the Super*B*

e^+e^- Collider	Max. Beam Radius at I.P. (μm)	Peak Luminosity (10^{30} cm$^{-2}s^{-1}$)
DAΦNE	800	450
BEPC-II	380	330
PEP-II	157	12069
KEKB	124	21093
Super*B*	7.4	$> 10^6$

the possibility to explore, employing the same detector, a new topic: the production and study of the heavy baryons, as, for instance, those containing the $b-quark$: Λ_b, Σ_b and Σ_b^*. Differently to the case of the B mesons, such b-baryons have been studied with much less accuracy until now [6]. Super*B* could allow such a study that, after the shutting down of the Tevatron, only at LCH can be efficiently performed. The Υ(4S) decays into $B^\pm$ mesons with a B.R. of 51%. The $B^\pm$ mesons have a cτ of ≈500 μm: at Super*B* they have an average *decay length* $\beta c\tau \approx$ 115 μm, calculated considering their momentum distribution shown in Fig.1. This distance is significantly greater than the Super*B* beam radii at I.P., a feature never reached in past or existing colliders. This means that, if a suitable material can be put at a distance from the I.P. of the order of the average *decay length*

$\beta c\tau \approx 115\ \mu$m, it can act as a *target* on which a significant number of the $B^{\pm}$ mesons will interact before decay, while leaving the beam circulation unperturbed.

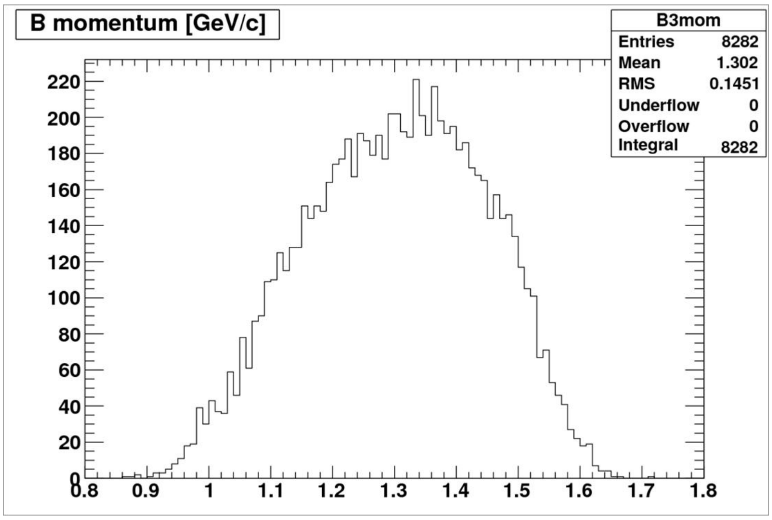

Figure 1: Momentum distribution of the charged B mesons from Υ(4S) decay at the Super$B$ (as reconstructed by the *fast* Monte Carlo version of the simulation code).

2. Heavy Baryons production at Super$B$

The momentum distribution of the B^- mesons from Υ(4S) decay at Super$B$ is bell shaped, with an average momentum of $\approx$1.3 GeV/c and a range from $\approx$0.90 GeV/c to $\approx$1.65 GeV/c (Fig.1). Considering their mass ($m_{B^-} = 5.28\ GeV/c^2$), such B^- mesons result largely not relativistic ($\beta_{B^-} \ll 1$), i.e. *slow*. A slowing B^-, as those produced at the Super$B$, interacting with a nucleon N (p or n) has access to only two inelastic channels:

$$B^-_{slow} + p \rightarrow B^0 + n \tag{2.1}$$

$$B^-_{slow} + p(n) \rightarrow \Lambda_b + \pi^0(\pi^-) \tag{2.2}$$

The interaction 2.1 is a *charge exchange reaction* (CEX): this reaction has a threshold of $\approx$0.35 GeV/c, that, even if accessible to the Super$B$ B^-s, it is expected to have a cross section rather low in their momentum range. The interaction 2.2 can be called a *beauty exchange reaction* (BEX): the B^- meson transfers its b-quark to the nucleon, transforming it in (for instance) a Λ_b while picking up from it a light quark to become a π. This is a reaction analog, in the strange sector, to the *strangeness exchange reaction*: $K^-_{slow} + p(n) \rightarrow \Lambda^0 + \pi^0(\pi^-)$.

It is worth to note that, contrarily to reaction 2.1, the reaction 2.2 has no threshold: also B^-s at rest have access to it (with a probability close to 100% in this case). It is then expected that, in the momentum range of the Super$B$ B^-s, reaction 2.2 is largely prevailing, and with an increasing cross section as the B^-s slow down in crossing the target. The main *competitor* for it is the decay of the B^-s: in this respect, the other key parameter is the high Luminosity of the Super$B$ that should allow the survival of a significant flux of B^-s capable to interact in a (nearby) target.

Besides the Λ_b, several other *beauty* baryons can be produced with a reaction similar to 2.2:

$$B^-_{slow} + N \rightarrow \Sigma^{\pm}_b + \pi^{-0+} \tag{2.3}$$

$$B^-_{slow} + N \rightarrow \Sigma^{*\pm}_b + \pi^{-0+} \tag{2.4}$$

In case of the reaction:

$$B^-_{slow} + N \rightarrow \Xi^{-0}_b + K^{+0} \tag{2.5}$$

the situation can be very tricky: the reaction 2.5 is below threshold of $\approx$70 MeV for $B^-_{at\ rest}$ on a free nucleon: what, however, in case of the Super$B$ B^-s on N bound in nuclei?

It is possible to have a first, rough estimate of the heavy baryon production rate from BEX reactions at the Super$B$. With a Luminosity of 10^{36} cm$^{-2}s^{-1}$ at the c.m energy of 10.58 GeV, the Υ(4S) resonance is produced with a cross section of 1.1 nb, decaying into B^+B^- pairs with a rate of $\approx$550 Hz. Considering that only 0.7% B^-s survive up to some *useful* distance (here considered to be $\approx$5 times bigger than the B^- Super$B$ decay length), and that this number is further reduced, due to the target acceptance and *slowing down* efficiency, to $\approx$7%, a rate of BEX reactions of 0.28 Hz is estimated. If the detection and reconstruction efficiency in any of the heavy baryon decay channels is of the order of 10%, the rate of the detected number of heavy baryons would be $\approx$0.028 Hz. Finally, for a detector-Super$B$ daily duty cycle of 80%, there would be collected $\approx 1.9x10^3$ events/day per nucleon. This last point is very relevant: the BEX reaction, being a strong one, is expected to happen on the surface nucleons of the target nuclei, whose number, as it is well know, scales as $A^{2/3}$, being A the nucleus atomic number. This evaluation must, of course, be confirmed by more complete and refined calculations: the conservative *safety* margins considered in the above calculation should, however, ensure the correct order of magnitude of the estimated rate.

As a matter of comparison, recent results from LHCb, shows a *measured* yield of $\approx$270 Λ_b/34.5 pb^{-1} [7]: at the current (Oct. 2011) LHC Luminosities, this can be extrapolated to $\approx$ 650 measured Λ_b/day.

At the Super$B$, the peculiar configuration of the beam crossing and the different e^+ and e^-– momenta at the c.m. energy corresponding to the Υ(4S) resonance suggest using a very attractive configuration for a target. In Fig. 2 the I.P. beam geometry, beam energies and Υ(4S) flight path are schematically depicted. As a consequence of the Υ(4S) flight path, the resulting $B^{\pm}$ angular distributions have the behaviour shown in Fig. 3. It is immediately seen the existence of a preferred angular cone of emission for the $B^{\pm}$ mesons: this means that a suitable target can intercept a big fraction of the outgoing mesons without the need to *encircle* the I.P region, so minimizing any background generation.

3. Heavy Baryons (and Mesons) interactions on nuclei

The Super$B$ and its detector used together a suitable target close to the I.P. can not only study the sector of the heavy baryons, but would be the unique place in which the study of the interaction

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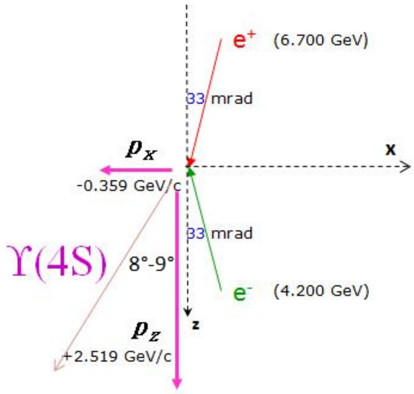

Figure 2: Schematic drawing of the geometry and relevant momenta in the Super*B* I.P.

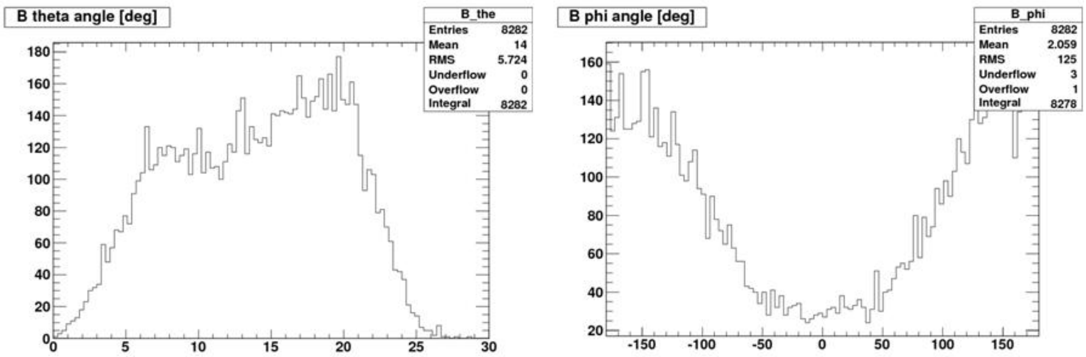

Figure 3: Polar (theta) and azimuthal(phi) angular distributions of the $B^{\pm}$ mesons from ϒ(4S) decay at the Super*B* (as reconstructed by the *fast* Monte Carlo version of the simulation code).

of heavy mesons and heavy baryons on nucleons in nuclei, for which no data exist at all, could be also performed. Already in 1989 it was analyzed the possibility that a collider foreseen to work at the c.m. energy similar to that of the Super*B* could offer to study the interaction of baryons containing the charm and bottom quark with nuclei [8]. The kinematical properties of the heavy baryons (Y_b) generated by means of the reactions 2.2-2.4 make the Super*B* very appealing for this type of study. In fact, the produced Y_bs have momentum distributions with an average value of ≈1.25 GeV/c, as can be seen in Fig.4 for the case of the Λ_b: this average momentum value translates, considering their masses, into an average velocity

$$\beta_{Y_b} \approx \beta_{N_{bound}}, \tag{3.1}$$

where $\beta_{N_{bound}}$ is the average velocity of nucleons in nuclei. This velocity overlap favors the formation of possible bound states, that, experimentally, would be signaled by the presence of sharp peaks in the momentum distributions of the π at values of $\approx (0.55-0.60)$ GeV/c.

The B^- mesons produced at the Super*B* are a bit faster to fulfill 3.1: they however, slowing down in the target, quickly cross the right velocity window. This fact, again, can favor the formation

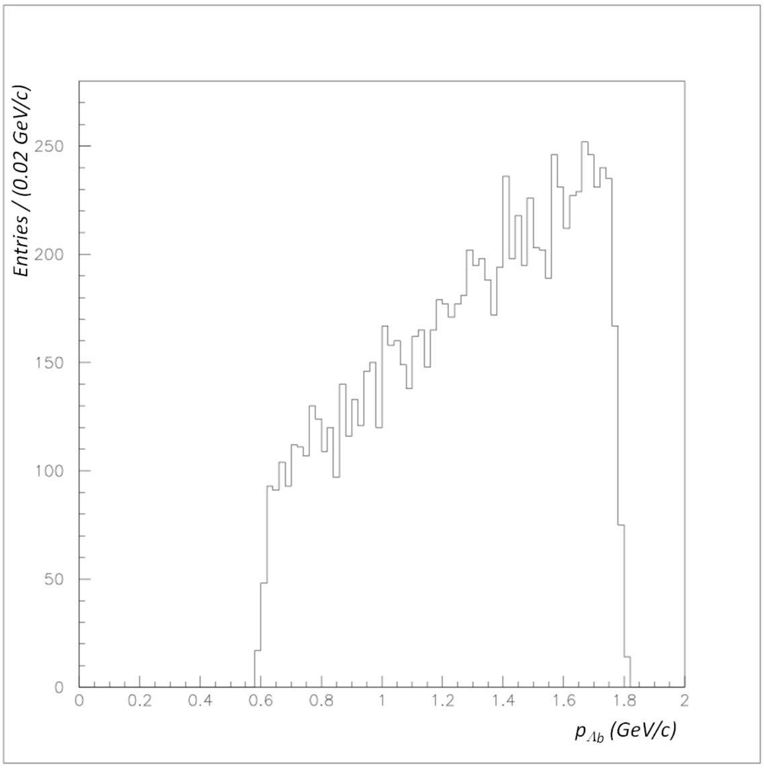

Figure 4: Momentum distribution of the Λ_b baryons from the reaction 2.2, considering the average momentum of the B^- from Super*B*. Similar distributions are obtained for the Y_b baryons from reactions 2.3 and 2.4.

of even more exotic bound systems in which a B^- meson is deeply bound with nucleons in nuclei, as predicted in [9].

In case of the Super*B* working at the c.m. energy of the $\psi(3770)$, its decays into D^+D^- pairs, with B.R. $\approx$ 41% can be used, similarly as for the bottom mesons, to produce and study charmed baryons (from Λ_c^+ up to the $\Sigma_c(2520)$) by means of the interaction of slow D^- mesons on target nuclei, as well as to study the interactions of the produced charmed mesons on nucleons in nuclei. The lower luminosity of the Super*B* at $\approx$ 3.77 GeV c.m. energy is compensated by the higher cross section for the production of the $\psi(3770)$ respect to the Υ(4S) resonance.

4. A tentative configuration for the target

A suitable target to operate close to the Super*B* I.P., inside the vacuum pipe, should have the following technical characteristics: i) its composition must not contaminate the vacuum; ii) its thermal/electrical conductivity must be very high in order to dissipate the heating induced by the circulating beams; iii) for the same reasons, its melting temperature should not be too much low; iv) it would be also very desirable that it could be remotely movable/removable. For what concerns the efficiency as a heavy baryon *generator*, the target should be made by a very dense material, in order to minimize the path of the heavy mesons slowing down inside it, and of high atomic number, to take advantage of any $\approx A^{2/3}$ scaling law. From all the above, a material as Au seems a good candidate. The kinematical conditions at the Super*B* for the production of the $\Upsilon(4S)$ resonance suggest how such a target should be positioned: in the radial plane, on the side of the transversal boost of the $\Upsilon(4S)$; in the longitudinal axis, in the downstream direction of the $\Upsilon(4S)$ longitudinal boost. The target dimensions would be very small: a thickness and a length of just few hundred μm is foreseeable. The shape can be as a half cylindrical nozzle, cut along a plane parallel to its axis. The inside hole can be shaped as a *trumpet*, diverging toward the longitudinal boost side to cope with the high beam β functions, and with the inner diameter on the side facing the I.P. as small as it is compatible with an unperturbed circulation of the beams. In Fig.5 a possible configuration for such a target is sketched. The distance d is a sort of *dummy* distance, that is the distance travelled

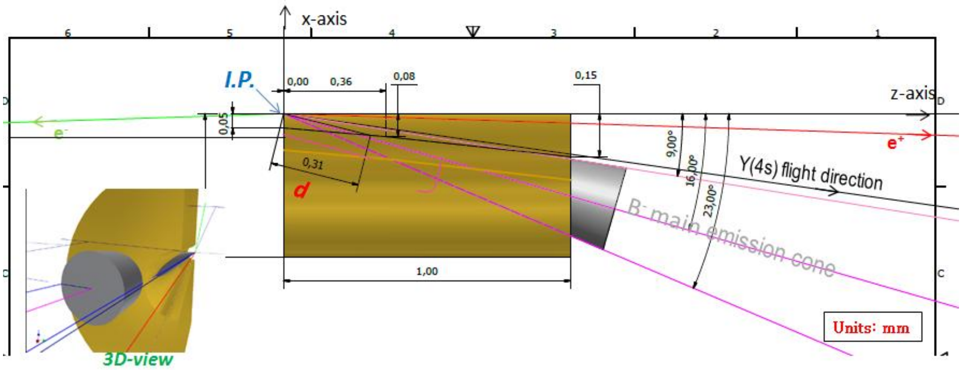

Figure 5: Sketch of a possible implementation of a target nearby to the Super*B* I.P. for the production of heavy baryons: the minimum inner diameter (toward the I.P.) is 50 μm; the *dummy* distance d is 310 μm.

in vacuum by the B^- before entering the target: it is the key parameter to minimize, playing with the nozzle inner radius and its shape. It is worth to note that such a target configuration, leaving fully free the transversal upstream semi plane, could allow to use the decays of the unperturbed B^+ to *tag* the reactions induced on the target nuclei by the B^-, hence providing a powerful method for background suppression.

5. Conclusions

Besides LHC, the Super*B* will be the only other facility where heavy baryons can be produced and studied in abundance. It will be the unique place in which it would be possible to study the interactions of (slow) heavy mesons and heavy baryons with nucleons in nuclei. Moreover, the same detector foreseen to study the heavy meson sector can be employed: the *final* particles resulting from the decays of heavy baryons are, indeed, similar in type and not so dissimilar in momenta from those deriving from the decays of the heavy mesons. A more detailed study and a full simulation of the processes here described are of course needed to finally assess the feasibility of such a research, to provide the effective production rate, taking into account the decay channels of the heavy baryons, the detector acceptance and efficiency, and, especially, the background induced by the presence of the target. In this respect, just now it is the right time to deepen this study, before the first brick of the Super*B* is laid. Later on, it could become too expensive or even impossible to implement it, then losing a unique opportunity.

6. Acknowledgments

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