

BABAR at JLab?

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Abstract

Recent discussions at JLab have examined the feasibility and motivation for a “low energy” electron-ion collider at JLab, operating in the range $s_e = 100$ to 400 GeV^2 . In this note, I discuss some issues regarding the utility of bringing the BABAR detector to JLab for such a machine.

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I. SUMMARY

The BABAR detector operated at PEP-II with a design luminosity of 10^{33} Hz/cm² and a final sustained luminosity of 10^{34} Hz/cm². The BABAR detector operated at the Upsilon 4S (10.579 GeV) resonance, with colliding beams of 9 GeV electrons and 3.1 GeV positrons. Thus the kinematic configuration of PEP-II is very similar to the proposed configurations for a “Valence Physics” collider at JLab. The BABAR detector, and its integration into PEP-II is described in arxiv:hep-ex/0105044. The final year of operation is described by J. Seeman in the proceedings of EPAC08, paper.kek.jp/e08/papers/tuxg01.pdf.

1. PEP-II

The fundamental beam crossing period of PEP-II is 4.2 ns, although depending upon the luminosity (*i.e.* number of filled bunches in the ring), the actual period could be as long as 10.5 ns. The beams are brought into collision with permanent magnet dipoles located at ± 21 cm from the Interaction Point (IP).

A. The BABAR Detector

The following features of BABAR make it an excellent candidate for a high performance detector at an ep collider at JLab:

- Compact design, with the beam line 3.5 meters above the floor. This is shorter than the beam height in Hall B and only slightly taller than the 10' beam heights in Halls A and C.
- Excellent π/K separation up to 4 GeV/c with the DIRC detector
- Superconducting solenoid magnet, with maximum design field of 1.5 Tesla
- High resolution CsI calorimeter, covering 80% of the $\Upsilon(4S)$ CM decay phase space.
- A high performance Si Vertex Tracker.

Some aspects of the BABAR detector are less attractive for ep or eA physics at JLab. These include

- Slow readout of the CsI calorimeter. The CsI(Th) photodiodes are read-out with a shaping time of $\approx 2\mu\text{s}$. This matches the decay curve of CsI, which has two main components: 64% of the light is emitted with a decay time of 680 ns, and 36% of the light is emitted with a decay time of 3340 ns. Thus it is crucial to consider the relative background rates in PEP-II, and an ep collider, since it is the background occupancy that will determine the feasibility of using the BABAR calorimeter at JLab.
- Large minimum scattering angles. For electrons, the minimum angle is 16 degrees, for positrons the minimum angle is 38 degrees. Note that this corresponds to a symmetric acceptance $|\cos\theta^*| \leq 0.9$ in the Upsilon rest frame.

For ep physics, the electron acceptance removes all low Q^2 physics, but retains full acceptance for Deeply Virtual processes, with a threshold of around $Q^2 > 2\text{GeV}^2$. Replacing the positron beam with a proton or ion beam, the acceptance is severely limited for forward tagging. It may be possible to remedy the forward and backward acceptance with supplementary detectors downstream (with respect to each beam) of BABAR. However, these detectors would be largely in the shadow of the final focus dipoles and quadrupoles. Thus the entire IP optics would have to be re-evaluated, with probably the addition of crab-crossing cavities.

B. Background Comparison

In order to assess whether the slow readout of the CsI(Th) is compatible with a high luminosity ep collider, I compare the background rates in an e^-e^+ and an ep collider. The calculations are given in detail in section II

The dominant high energy backgrounds in an e^-e^+ collider are:

1. Resonant excitation of the $\Upsilon(4S)$ resonance. This cross section is 3.4 nb.
2. Continuum annihilation to two muons.
3. Continuum annihilation to hadrons. This is described by the perturbative process $e^+e^- \rightarrow q\bar{q}$
4. Bhabha Scattering, $e^+e^- \rightarrow e^+e^-$.

All of the continuum processes fall as powers of s . Therefore, with the exception of the first process, all of these processes are actually dominated by the radiative return mechanism, in which one or other of the incident beams pre-radiates before scattering or annihilation. The Radiative Return (RR) cross sections (for $s = 100 \text{ GeV}^2$) are:

1. Continuum annihilation to two muons: $\sigma^{RR} = 1 \mu\text{b}$.
2. Continuum annihilation to light (non-strange) hadrons: $\sigma^{RR} = 10 \text{ nb}$.
3. Continuum annihilation to strange hadrons: $\sigma^{RR} = 0.6 \text{ nb}$. Continuum annihilation to open charm: $\sigma^{RR} = 0.02 \text{ nb}$.
4. Bhabha Scattering: I have not completed this calculation. At the low energy end of the radiative return spectrum, di-muon production will dominate, but near the full CM energy, the Bhabha yield is much larger than the di-muon yield.

In summary, treating muons as hadrons, the total inclusive hadron production cross section in BABAR is approximately $1 \mu\text{b}$, and dominated by muons. The true hadronic production cross section is only 15 nb . The purely electromagnetic yield will depend on the lower threshold, and maybe larger than the muon yield.

The dominant hadronic background in an electron-ion collider is from quasi-real photoproduction. For ep collisions, the γp total cross section can be effectively modeled as the Delta resonance, plus a constant 100μ barn cross section. The quasi-real photon flux described as (per incident electron)

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{t^V(E_e, E_\gamma)}{E_\gamma}, \quad (1)$$

with $t^V \approx 0.02$, approximately constant. This same approximation was used for the radiative return calculations above for BABAR. The total hadronic ep cross section is then approximately $10 \mu\text{b}$.

Thus the hadronic rate in an ep collider is roughly 10 times the hadronic rate in an e^+e^- collider at the same CM energy. This can be understood, on the basis of the partonic structure of the proton. The elementary processes scale as an inverse power of s , and the electron or photon sees the incident proton as a beam of momentum partons, of mean square charge 1.

If the background rate is 10 times higher in ep collisions than e^+e^- collisions, does this mean that BABAR is unsuited for JLab? Not necessarily, but the rates should be evaluated in more detail. First, BABAR operated at luminosities up to 10^{34} , whereas the upper bound on the luminosity of an ep collider at the same s is probably 10^{33} . This immediately compensates the background. Secondly, even at 10^{34} , a $10\ \mu\text{b}$ cross section implies only 500 Hz rate per 25 crystal cluster in the calorimeter. This is well below the sampling rate of $1/(2\ \mu\text{s}) = 500\ \text{KHz}$.

II. DETAILED BACKGROUND CALCULATIONS

The following detailed notes are under development and are incomplete.

A. Electron Positron Collider

The BABAR detector operated at the Upsilon 4S (10.579 GeV) resonance. The total hadronic cross section includes both the continuum and resonance annihilation.

1. Upsilon 4S production

The annihilation cross section on a broad resonance is (PDG):

$$\sigma(\sqrt{s}) = \frac{2J+1}{(2s_1+1)(2s_2+1)} \frac{4\pi}{k_{CM}^2} \left[\frac{\Gamma^2/4}{(\sqrt{s} - M_R + \Gamma^2/4)} \right] B_{in} B_{out}$$

where $B_{in,out}$ are the branching fractions for the initial and final channels. For the $\Upsilon 4S$, $J = 1$, and the beam spread is much narrower than the decay width Γ . With $B_{e^+e^-} = 1.57 \cdot 10^{-5}$:

$$\begin{aligned} \sigma(M_R) &= \frac{5}{4} \left[\frac{4\pi}{M_R^2/4} \right] 1.57 \cdot 10^{-5} \\ &= 3.4\text{nb} \end{aligned}$$

2. Continuum Annihilation

The total rate in an e^+e^- collider includes hadronic and electromagnetic processes. The hadronic rate includes both direct annihilation and radiative return. The annihilation cross

section to muons plus hadrons is

$$\begin{aligned}\sigma_{Tot} &= \frac{86.8 \text{ nb GeV}^4}{s^2} \left[1 + \sum_f Q_f^2 N_C \right] \\ &= \frac{86.8 \text{ nb GeV}^4}{s^2} [1 + R(s)]\end{aligned}$$

Each lepton in the beam has an accompanying spectrum of quasi-real photons. This spectrum can be approximated by $t^V dk_\gamma/k_\gamma$ with $t^V \approx 0.02$. The cross section for single radiative return from either lepton is therefore

$$\begin{aligned}\sigma_{RR} &\approx \int_0^{Th} \frac{t^V dk_\gamma}{k_\gamma} [\sigma_{Tot}(s' = 4k_1(k_2 - k_\gamma)) + \sigma_{Tot}(s' = 4(k_1 - k_\gamma)k_2)] \\ &= 2t^V (86 \text{ nb GeV}^4) \int_{Th}^s \frac{ds'}{s - s'} \frac{[1 + R(s')]}{(s')^2}\end{aligned}\quad (2)$$

The ratio R of hadron to muon production can be separated into light quark, strange quark, and heavy flavor contributions. For each channel, I approximate the threshold as equal to the lowest mass vector meson of the corresponding flavor:

$$\begin{aligned}R_{ud}(s) &\approx \frac{5}{3} \quad \text{for } s > m_\rho^2 \approx 0.5 \text{ GeV}^2 \\ R_s(s) &\approx \frac{1}{3} \quad \text{for } s > m_\phi^2 \approx 1.0 \text{ GeV}^2 \\ R_c(s) &\approx \frac{4}{3} \quad \text{for } s > m_{J/\Psi}^2 \approx 9.0 \text{ GeV}^2\end{aligned}$$

For di-muon production, the threshold is $4m_\mu^2 \approx 0.04 \text{ GeV}^2$. The integrated Radiative Return cross section is therefore

$$\sigma_{RR} = 2t^V (86 \text{ nb GeV}^4) t^V (86 \text{ nb GeV}^4) \left[\frac{1}{(4m_\mu^2)^2} + \frac{5}{3} \frac{1}{m_\rho^4} + \frac{1}{3} \frac{1}{m_\phi^4} + \frac{4}{3} \frac{1}{m_{J/\Psi}^4} - \left(1 + \frac{5}{3} + \frac{1}{3} + \frac{4}{3} \right) \frac{1}{s^2} \right]\quad (3)$$

Since the low energy dimuon production dominates, separate this yield into the di-muon and hadronic parts:

$$\begin{aligned}\sigma_{RR}(\mu^+ \mu^-) &= t^V (86 \text{ nb GeV}^4) \left[\frac{625.}{\text{GeV}^4} - \frac{1}{100 \text{ GeV}^2} \right] \\ &\approx (54 \mu b) t^V\end{aligned}\quad (4)$$

$$\begin{aligned}\sigma_{RR}(h) &= t^V (86 \text{ nb GeV}^4) \left[\frac{5}{3} \frac{4.}{\text{GeV}^4} + \frac{1}{3} \frac{1.}{\text{GeV}^4} + \frac{4}{3} \frac{0.01}{\text{GeV}^4} - \frac{10}{3} \frac{1}{s^2} \right] \\ &\approx (0.6 \mu b) t^V\end{aligned}\quad (5)$$

These two cross sections are for a full acceptance detector, and are reduced by the actual BaBar acceptance.

B. Bhabha Scattering

The CM frame differential cross section for $e^+e^- \rightarrow e^+e^-$ -scattering (Bhabha scattering), including the coherent sum of annihilation and scattering amplitudes is (ultra relativistic limit):

$$\begin{aligned} \frac{d\sigma}{d\Omega^*} &= \frac{\alpha^2}{2s} \left[u^2 \left(\frac{1}{s} + \frac{1}{t} \right)^2 + \left(\frac{t}{s} \right)^2 + \left(\frac{s}{t} \right)^2 \right] \\ &= \frac{\alpha^2}{2s} \left[\left(\frac{1 + \cos \theta^*}{2} \right)^2 \left(1 - \frac{2}{1 - \cos \theta^*} \right)^2 + \left(\frac{1 - \cos \theta^*}{2} \right)^2 + \left(\frac{2}{1 - \cos \theta^*} \right)^2 \right] \\ &= \frac{\alpha^2}{2s} \left[\left(\frac{1 + \cos \theta^*}{2} \right)^2 \left(\frac{1 + \cos \theta^*}{1 - \cos \theta^*} \right)^2 + \left(\frac{1 - \cos \theta^*}{2} \right)^2 + \left(\frac{2}{1 - \cos \theta^*} \right)^2 \right] \end{aligned}$$

This cross section diverges as the electron scattering angle $\theta^* \rightarrow 0$. In this limit, the factors $1 - \cos \theta^*$ will have correction terms of order m^2/s (although an unshielded Coulomb cross section will always diverge at zero degrees). The integrated cross section in the interval $|\cos \theta^*| \leq \cos \theta_{Min}$ is:

$$\sigma(\theta_{Min}) = \frac{\pi\alpha^2}{s} \left[16 \frac{\cos \theta_{Min}}{1 - \cos^2 \theta_{Min}} - 8 \ln \frac{1 + \cos \theta_{Min}}{1 - \cos \theta_{Min}} + 9 \cos \theta_{Min} + \frac{1}{3} \cos^3 \theta_{Min} \right] \quad (6)$$

The BABAR CsI(Th) calorimeter subtends the (electron) laboratory scattering angles of 15.8° to 141.8° . With incident electron and positron momenta of $9.0 \text{ GeV}/c$ and $3.1 \text{ GeV}/c$, the CM angular acceptance is $|\cos \theta_{CM}| \leq 0.9$. The total Bhabha cross section within the calorimeter is

$$\sigma_{BABAR}^{Bhabha} = \frac{65 \text{ nb GeV}^2}{(10.56 \text{ GeV})^2} \left[16 \frac{0.9}{1 - 0.81} - 8 \ln \frac{1.9}{0.1} + (9)(0.9) + (0.9)^3/3 \right] \quad (7)$$

$$= 35 \text{ nb} \quad (8)$$

The final operational luminosity was $\approx 10^{34}/\text{cm}^2/\text{s} = 10 \text{ Hz}/\text{nb}$ with a collision frequency of 4.2 ns . This yields a Bhabha rate of 350 Hz , or $< 10^{-3}$ per $2 \mu\text{sec}$ emission/shaping time of the CsI crystal and front end electronics.

In addition to the Bhabha events at the full CM energy of the collider, there is also an important flux of radiative Bhabha events. In this case, the CM acceptance varies with the effective collision energy. For given positron and electron radiated energies k_- and k_+ , respectively, the minimum and maximum CM scattering angle for the electron and positrons

and positrons in BABAR are:

$$\begin{aligned}\cos\theta_{Min}^*(electron) &= \frac{\cos\theta_{Min}^{Lab} - \beta(k_-, k_+)}{1 - \beta(k_-, k_+) \cos\theta_{Min}^{Lab}} \\ \beta(k_-, k_+) &= \frac{k_- - k_+}{k_- + k_+} \\ \cos\theta_{Min}^*(Positron) &= \frac{-\cos\theta_{Max}^{Lab} + \beta(k_-, k_+)}{1 - \beta(k_-, k_+) \cos\theta_{Max}^{Lab}} \cap\end{aligned}$$

We can anticipate that the total Bhabha rate from radiative return will be comparable to the di-muon rate.

C. Electron Proton Collider

The dominant hadron production rate in electron proton collisions comes from quasi-real photo-production. This cross section can be approximated by the Δ -resonance plus an approximately constant $100\mu\text{b}$ total cross section. Thus the total hadron cross section is

$$\begin{aligned}\sigma_{ep} &\approx \int_{Th}^k \frac{t^V dk_\gamma}{k_\gamma} [\sigma_\Delta (W^2 = 2k_\gamma(E + P)) + 100\mu\text{b}] \\ &\approx \int_{(M+m)^2}^s \frac{t^V dW^2}{W^2} \left[\frac{(500\mu\text{b})(M_\Delta^2 \Gamma^2/4)}{(W^2 - M_\Delta^2)^2 + M_\Delta^2 \Gamma^2/4} + 100\mu\text{b} \right] \\ &= t^V (100\mu\text{b}) \ln \frac{s}{(M+m)^2} + t^V \sigma_\Delta\end{aligned}$$

This cross section is approximately 4 times greater than the e^+e^- cross section integrated over the BABAR acceptance. Since cross sections fall with s the larger ep rate reflects the flux of quarks inside the proton at less than the full proton momentum. Although both the mean charge and mean square charge of the

At very small angles, the cross section is dominated by elastic scattering. The cross section on the proton is:

$$\begin{aligned}\frac{d\sigma}{d\Omega_{Lab}} &= \frac{\alpha^2 \cos^2 \theta/2}{4E^2 \sin^4 \theta/2} \frac{E'}{E} \left[\frac{G_E^2 + \tau G_M^2}{1 + \tau} + 2\tau G_M^2 \tan^2 \theta/2 \right] \\ \frac{d\sigma}{dQ^2} &= \frac{4\pi\alpha^2 \cos^2 \theta/2}{Q^4} \left[\frac{E'}{E} \right] \left[\frac{G_E^2 + \tau G_M^2}{1 + \tau} + 2\tau G_M^2 \tan^2 \theta/2 \right] \\ &\rightarrow \frac{4\pi\alpha^2}{Q^4}\end{aligned}$$

At small angles, the Bhabha cross section reduces to

$$\frac{d\sigma}{d\Omega^*} \rightarrow \frac{4\alpha}{s} \frac{1}{(1 - \cos \theta^*)^2} = \frac{\alpha s}{(-t)^2}$$

$$\frac{d\sigma}{dt} \rightarrow \frac{4\pi\alpha^2}{(-t)^2}$$

From these formulae, I conclude that at extreme forward angles the Bhabha cross section is dominated by scattering (rather than annihilation) and e^-e^+ and e^-p cross sections are therefore of necessity identical. This means that secondary background induced by extreme forward angle scattering events will be identical in an electron-positron or electron-proton collider (if both have the same detector).

1. DIS background

What is the relative importance of small angle inclusive scattering to elastic scattering in an electron-proton collider? The DIS cross section is

$$\frac{d^3\sigma}{d\Omega k'} = \frac{\alpha^2 \cos^2 \theta/2}{4E^2 \sin^4 \theta/2} \left[\frac{2}{M} F_1(x_B) \tan^2 \theta/2 + \frac{1}{\nu} F_2(x_B) \right].$$

Imposing the Callen-Gross relation $2xF_1 \rightarrow F_2$:

$$\frac{d^3\sigma}{d\Omega k'} = \frac{\alpha^2 \cos^2 \theta/2}{4E^2 \sin^4 \theta/2} \left[\frac{1}{Mx} \tan^2 \theta/2 + \frac{1}{\nu} \right] F_2(x_B).$$

To be continued.