Crystal Detector R&D Proposal for Soft Photon Measurement in STAR

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We propose a crystal detector R&D study for soft photon measurement in STAR. Our study aims at developing suitable detector technology and physics program for soft photon measurement. The proposed soft photon program covers photon transverse momentum range of 20 MeV to 1000 MeV at mid-rapidity.

Our proposed physics program will focus on three aspects: 1) thermal photon radiation from the Quark Gluon Plasma (QGP) phase in nucleus-nucleus collisions at RHIC; 2) measurement of radiative decays of particles such as Σ^0 and χ_c states and explore spectroscopy of particles with soft photon and pi-0 in the final state; 3) soft photon radiations from bulk quark matter through processes such as jets traversing dense partonic matter, radiation from collective high angular momentum state and possible synchrotron radiation from high longitudinal E/B field from non-equilibrium stage during the transition from the Color Glass Condensate to Quark-Gluon Plasma. We should emphasize that the soft-photon physics regime proposed here is very exploratory. There is no established theoretical calculation or experimental detector technology for the proposed soft photon measurement. Existing STAR and PHENIX calorimeter detectors cannot cover the interested photons. We shall briefly illustrate the important physics in these topics.

1) **Thermal photon radiation from the QGP:** The initial temperature of the dense partonic matter formed in nucleus-nucleus collisions at RHIC is an outstanding question that we have to address. The thermal photon radiation is sensitive to the initial temperature of the QGP. Recent STAR white paper states the initial temperature measurement as one of the advances that we should make in our continued quest for the QGP study. For a partonic matter of temperature T, most thermal radiations emit photons of transverse momentum 2 to 3 times the temperature T, i.e. the thermal photons of typical p_T 500-750 MeV for a temperature of 250 MeV. Theoretically the calculation of thermal photon emission of the QGP involves non-perturbative process and the theoretical framework continues to be improved (e.g. see Peter Arnold, Guy Moore and L.G. Yaffe hep-ph/0111107). Experimentally though there have been several attempts to measure direct photons from thermal radiation from nucleus-nucleus collisions at the SPS (WA98) and at RHIC (PHENIX), no experiment has covered the soft photon region. Reference (P. Stankus, Annu. Rev. Nucl. Part. Sci. 2005 55:517) reviews the direct photon measurement from nucleus-nucleus collisions. Jack Sandweiss et al have proposed the measurement of direct photons through photon HBT correlations. It is important for STAR to develop detector technology capable of excellent photon measurement in the soft pT region from 200 to 1000 MeV.

2) **Particle measurement through radiative decays:** There are several particles which decay radiatively and have an important impact on dynamics of nuclear collisions at RHIC. Notably are Σ^0 and χ_c states. Σ^0 decays to $\Lambda\gamma$ and χ_c to $J/\psi\gamma$. The exact contribution of Σ state to Λ and χ_c to J/ψ is an important question to understand nuclear dynamics. For example, fragmentation models for hadron formation would predict the Σ^0/Λ ratio of 1/3 and thermal statistical models would predict the ratio approximately 2/3. Coalescence models would predict the ratio to be unity at the intermediate pT region. For J/ψ suppression in nuclear collisions at RHIC we have to understand the behavior of χ state because they have a large size and are believed to melt much easily than primordial J/ψ which does not melt at the critical temperature. The radiative decay photons tend to be very soft. A new STAR detector covering the soft photon region will significantly enhance our particle measurement capability. We can also explore particle spectroscopy with more particles involving photons in the final state.
3) **Soft photon radiation from bulk partonic matter through non-equilibrium processes:** Soft photons in the energy range of 20 to 70 MeV are particularly interesting because photon background from neutral pion decays is significantly reduced in this energy range. Previously excess of direct photons in the pT range of 5 to 90 MeV in hadron-nucleus collisions at incident beam energy of 70 to 450 GeV has been reported. Physical origin of these soft photons has not been established. In nucleus-nucleus collisions at RHIC there are several interesting possible soft photon production processes that we should investigate. A) Photon radiation from jets traversing dense partonic matter in central collisions at RHIC. The energy loss of quark jets in QCD color charged medium will induce bremsstrahlung photon radiations. We can study the radiation by correlating soft photons with high pT hadron production, which will allow us to probe the properties of the dense partonic matter. B) Photon radiations from bulk partonic matter due to high angular momentum of quarks from non-central collisions and synchrotron radiation from possible formation of longitudinal E/B fields.

We propose to investigate CsI crystals as a possible photon detector candidate. We can develop the soft photon physics program in two phases. In phase-1 we can develop a short crystal detector to be sensitive to low energy photons possibly from 20 MeV up to an energy range around Tc and the exact upper energy reach will require more Monte Carlo simulations to be carried out during the R&D period. In phase-2 another long crystal detector can be added so the photon energy coverage may be extended to a few GeV. The proposed crystal detector will be a patch in the size of one or two TOF/BEMC modules depending on the acceptance requirement which will also be a simulation task. We envision that the phase-1 can be accomplished with a crystal detector array in place of a TOF module. The phase-2 may have to replace one existing BEMC module with CsI crystals. In phase-2 as one possible configuration the short crystals could be extended by gluing additional CsI crystal on the back side.

Possible Mechanical Integration within the STAR Configuration

For phase –1 the minimum crystal length will be 5.5X0 if crystal patch will be installed inside the TOF integration volume in place of a TOF module. The BEMC module will be used as a strongback to support crystals. For phase-2 the total length of a crystal module can be 16X0 (eta =0) if one BEMC module will be replaced by a crystal detector. In both cases it will be required to remove one TOF module to minimize dead materials in front of soft photon detector. The crystal detector module will be located at 6 o'clock at the east side of the STAR detector. It will have a projective geometry pointing to the center of the interaction point. We propose to use photo-diodes directly coupled to the crystals as our read-out system. The proposed front-end electronics will be located inside the same integration volume (inside the magnet). Mechanical integration was briefly discussed with R.Brown. There is no serious issue identified with the proposed mechanical set-up.

Choice of Crystal

Inorganic crystals are among the best choice for total absorption calorimeters to measure soft photons. The properties of several commonly used inorganic crystals are shown in table 1 below.

Table 1 Properties of several inorganic crystal scintillators

Crystal	NaI(Tl)	CsI(Tl)	BGO	$PbWO_4$
Density (g/cm^3)	3.67	4.51	7.13	8.28
Radiation length (cm)	2.59	1.85	1.12	0.89
Molière radius (cm)	4.8	3.8	2.3	2.0
DE/dx (Mev/cm)(per mip)	4.8	5.6	9.2	13.0
Nucl. Int. length (cm)	41.4	37	21.8	18
Refractive index (480 nm)	1.85	1.79	2.15	2.16
Peak emission λ (nm)	410	560	480	420-560
Relative light output	100	45(PMT) 140(PD)	15	0.01
Light yield temp.coef. ($\%/^0C$)	~0	0.3	-1.6	-1.9
Decay time (ns)	230	1000	300	10-50
Hygroscopic	strong	slight	no	no

We propose to use CsI(Tl) crystals as our detector of first choice for R&D for soft photon measurement in STAR. Large scale calorimeter detectors based on CsI(Tl) have been built for BaBar, Belle, BesII and KTeV all with excellent performance for photon measurements over a very broad energy range. These calorimeters have achieved energy resolution as good as 2.9% for photon energy as low as 20 MeV.

Simulation Task for Detector Performance

In the low energy region, the expected energy resolution follows $E^{-1/4}$ for a total absorption calorimeter. Unfortunately, it is not reliable to translate results obtained in these experiments directly to that in the STAR environment because optimizations of calorimeters to measure soft photons at the other facilities and RHIC are quite different. Contributions to the energy resolution for crystal calorimeters can be written as following:

$$\sigma / E = \sqrt{\sigma_{EC}^{2} + \sigma_{\gamma l}^{2} + \sigma_{noise}^{2} + \sigma_{PD}^{2} + \sigma_{CAL}^{2}},$$

Where σ_{EC} is the intrinsic resolution due to fluctuations of the energy deposition and the photon statistics; σ_{r1} is from the shower leakage including contributions from "dead material" in front of the crystal detector including the TPC and others; σ_{noise} is from electronic noise including "pile up" at high luminosities; σ_{PD} is from fake signals in photodiodes directly hit by charged particles; and σ_{cal} is from errors of calibration and non-uniformity of the system.

Major simulations have to been carried out in order to provide detailed understanding of the crystal detector performance in the proposed STAR configuration. We will investigate in detail contributions from all sources to the energy resolution of a crystal calorimeter and optimize the detector configuration for best performance. The main difference in performance between a crystal detector in STAR and previously constructed crystal detectors at BaBar etc could arise from reconstruction of photons with a non total absorption calorimeter in the presence of possibly large pileup.

As an example, below we show some results for towers with transverse dimensions 2.54 x 2.54 cm^2 (this size is far from optimal to get best energy resolution, but close to what is required for detection of isolated photons) under the assumption that clustering will be limited by 3x3 crystal array. The lengths of crystal modules used in the MC were 5.5X0 and 15X0, where X0 is the radiation length of CsI crystal. Both limited cluster size and length will lead to shower leakages.

Fig.1 shows fraction of energy detected in 3x3 crystal array as a function of the incident photon energy for different crystal lengths. One special case is shown for short crystals with/without 1X0 tungsten converter located at the front surface of the crystal. The energy resolution presented is defined using (RMS visible)/(E visible). Since the amplitude spectra are strongly non Gaussian, the resolution values in the figure represent the worst case scenario. By using shower shape information and information from BTOW when short crystals were placed in front of the BTOW we expect the energy resolution can be significantly improved. At the end of this proposal (last page), we show two examples: one for raw amplitude spectra for 30 MeV photons and the other for correlations between BTOW and crystal patch. The energy resolution can be improved if we can reject events with significant leakage at the back of the crystal. That is one of the tasks of this R&D effort

Fig. 2 shows dependence of energy resolution vs. energy for the above configurations (again we would like to mention that numbers as they presented are very conservative). These simulation results are meant to demonstrate the dependence of energy resolution on leakage and dead materials. Much more simulations are needed to understand the crystal detector performance, and possible ways of rejecting events with substantial leakage (transversal and longitudinal) particularly with a short crystal array.

How well a short crystal detector will perform depends on how effective that we can use the shower cluster shape and the BTOW modules to identify gammas with large leakage. We also need to understand the background source of photons in the STAR configurations. These are the major goals of simulation tasks in this proposal. We should emphasize that the simulation tasks are a major component of the proposed R&D effort and we have requested budget to support a visiting scholar from Dubna to collaborate with the UCLA group on the effort.

The proposed crystal detector configuration is intended to be optimized for the soft photon energy range from 20 MeV to a few GeV. Simulations have to been carried out to understand the influence of particle multiplicity on the crystal detector performance. In addition, we also propose to carry out a beam testing using a 5x5 crystal detector array. We have previously used SLAC for calorimeter testing and SLAC will be a choice facility for our testing if it can be arranged. The test run will be required to measure response of crystals in final configuration with final electronics.

R&D on Crystal Detector System

In addition to R&D on individual crystal module performance, we propose to develop optimal detector configuration and physics analysis for the soft photon measurement in STAR. This includes the development of requirements on crystal granularity, energy resolution and uncertainty analysis necessary for physics measurement of soft photons. Uncertainties with reconstruction of photon energy due to limited cluster size, unknown dead materials in front of crystal detectors, background from pileup events, albedo from BTOW, background from TOF modules etc. need to be understood and estimated. This can be done only by comprehensive Monte Carlo simulations and will require support for visiting scientist from Dubna to do that. Dubna group is already doing analysis for soft photons using conversion technique (conversion within the TPC gas). The analysis and technique skills developed at Dubna can be applied when suitable in the crystal detector configuration for soft photon measurement.

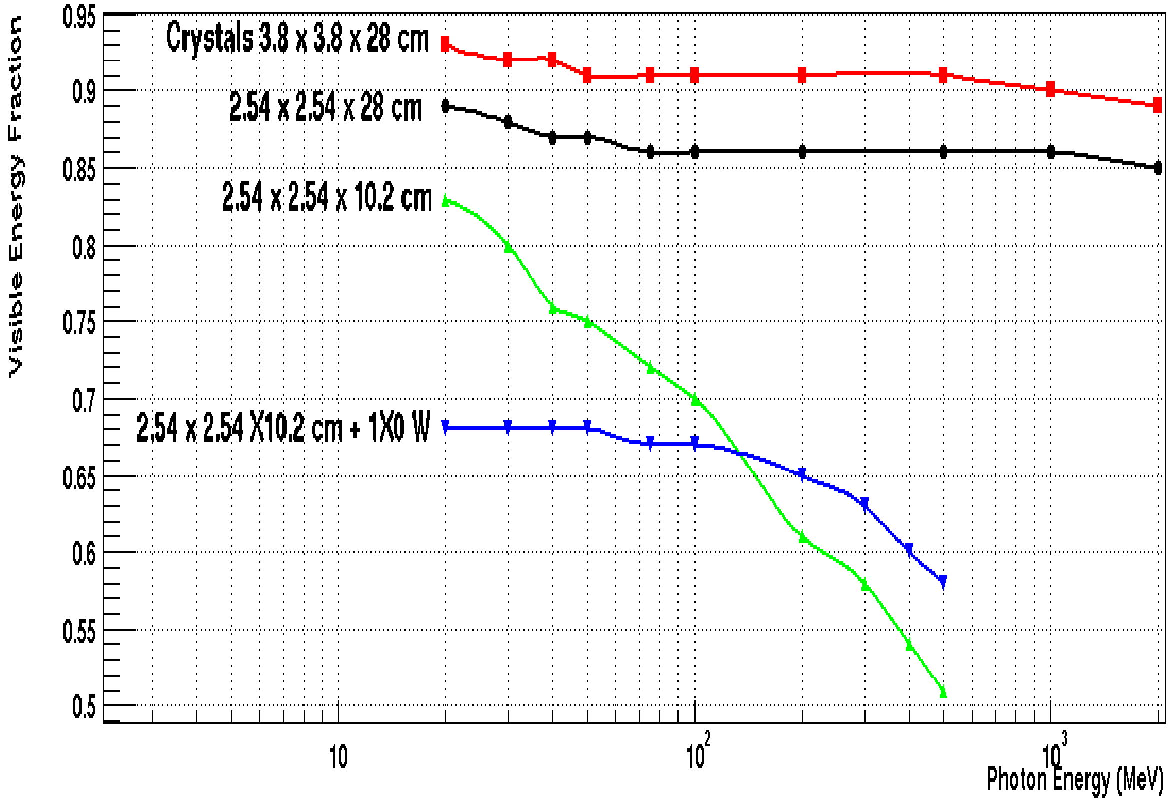
We will need to acquire a CsI crystal array and Hamamatsu photo diodes for bench test and test run measurements. We plan to learn from experiences of other collaborations from their extensive R&D results and actual CsI crystal calorimeter operations. Results from BaBar, BESII and BELLE have been well documented. The type of reflective wrappings, glues, method of coupling of photo diodes to crystals, nonuniformities of light yield along the crystals etc. are known and will not require re-inventions. But the first hand experience is important. Some members of Dubna group have prior experience working with CsI crystals. The UCLA group has well equipped laboratory to do such test. A 22Na source will be needed to do bench-test measurements with crystals.

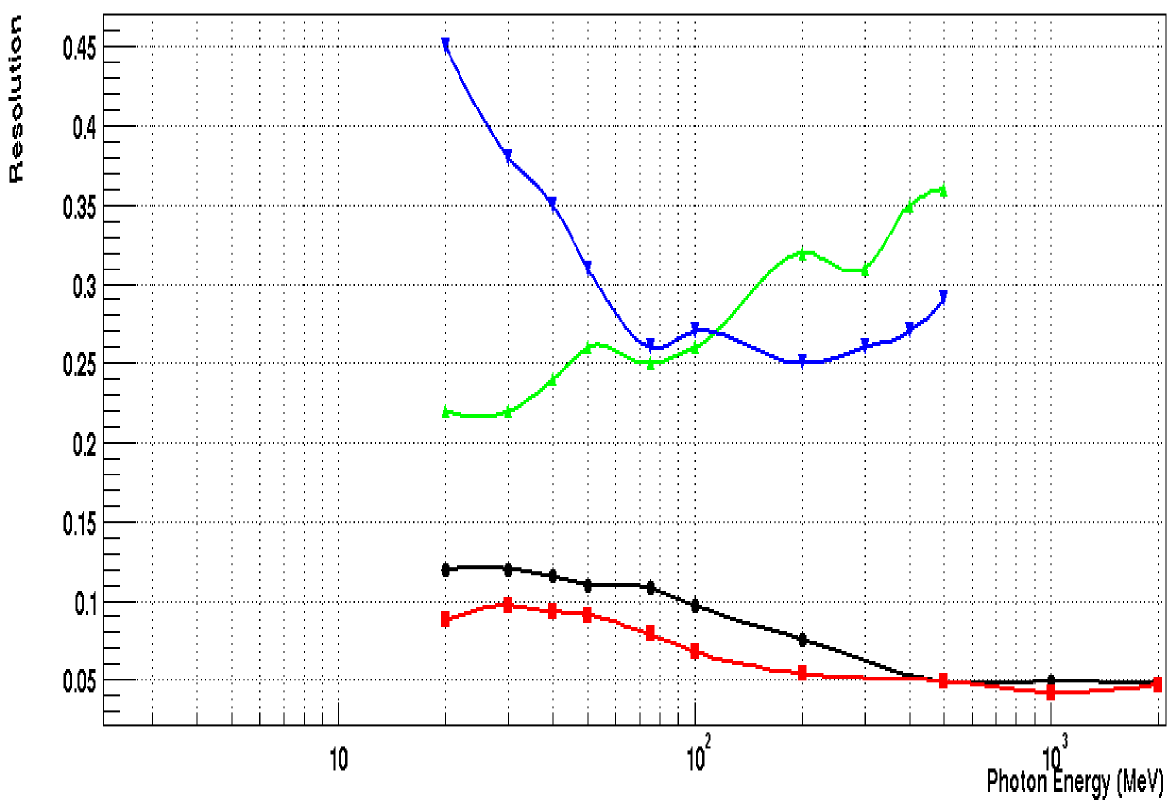
We plan to complete the R&D of the CsI crystal detector in FY2007. Successful development of the detector technology and the physics program for soft photons in STAR may lead to a full proposal for such a crystal detector in STAR to be constructed in FY2008-2010.

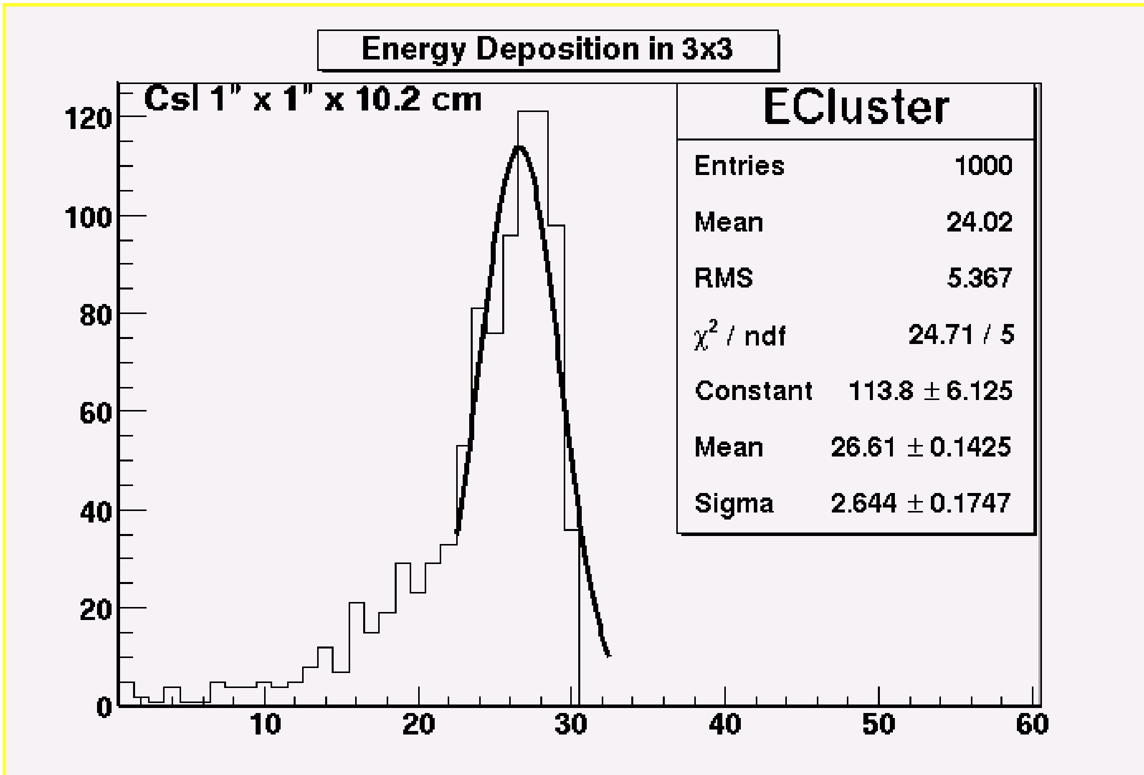
Budget Breakdown:

CsI crystals	\$25k	(FY07)
Photodetectors and FEE for 16 channels	\$15k	(FY07)
Test Run SLAC FFTB	\$15k	(FY07)
Supplies	\$5k	(FY07)
Mechanical Support Structure	\$10K	(FY07)
Simulations and Visiting Scholars	\$40K	(FY06-07)
Travel	\$10K	(FY07)
Total	\$120K	

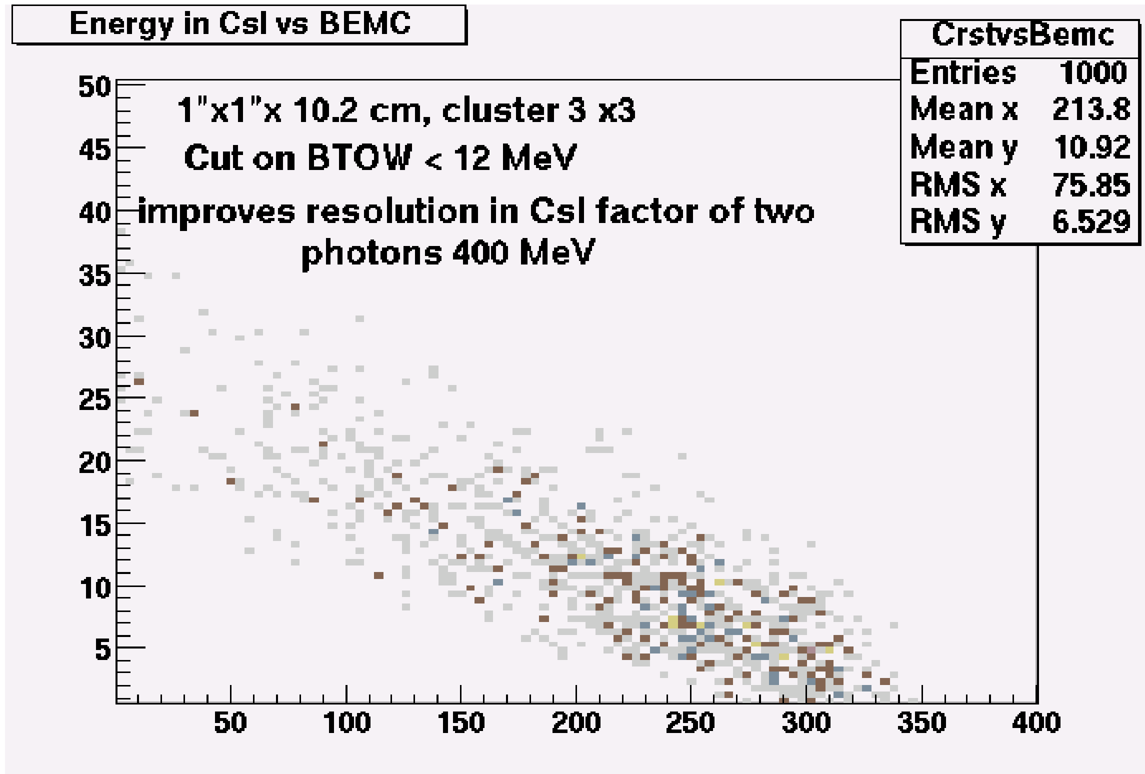
Cluster 3 x 3 towers, CsI, Fraction of energy visible in cluster and Energy resolution.







R&D question – can we reject events with large leakage? And improve resolution factor of two for short crystals?



R&D question – can BTOW/BPSD/BSMD be effectively used to reject events with large longitudional leakage?