THE UNIVERISTY OF ALABAMA IN HUNTSVILLE

# *Analysis of SOFCAL Calibration Data*

**FINAL REPORT**

Submitted by:

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# INTRODUCTION

## Supporting Studies for A Scintillating Optical Fiber Ionization Calorimeter (SOFIC)

Ionization calorimeters determine the total energy of a particle by absorbing within the mass of the calorimeter the entire energy of the particle or a significant (and determinable) fraction of it. The JACEE group has used passive ionization calorimetery, employing photographic emulsions as the detector medium, to measure the charge composition and energy spectrum of cosmic rays up to, and exceeding, $10^{14}$eV. The SOFIC approach depends similarly on the use of three-dimensional nuclear-electromagnetic shower theory to relate the ionization deposits obtained during a shower to the energy of the particle causing the shower. Bundles of thousands of scintillating optical fibers are read out using image-intensified CCD's. Such an event may be triggered by a fast shower detector placed under the instrument or if only heavy particles are of interest, from a fast primary Cerention detector placed above the calorimeter.

In the first study, fast Hammatsu photomultiplier tubes were purchased and tested for possible application for a triggering purpose.

In the second study, some refinements have been made to the theoretical treatment of hadronic interactions in the central collision region. These will be helpful in improving the simulations necessary for observations of high energy cosmic ray nuclei with a SOFIC.

# Report on Hamamatsu RA1250 Photo-multipliers

## CONTENTS

## 1.0 Introduction

The Hamamatsu RA1250 is a large (5 inch photo-cathode) photo-multiplier, which employs a liner focused 14 stage dynode geometry to produce fast (t_rise ~ 2.2 ns) response. The entrance window is borosilicate giving a spectral response from 300 to 650 nm. The quoted quantum efficiency of the Bialkali photo cathode is 22%. The results of measurements made on ten of these tubes with novel base electronic is presented.

## 2.0 Novel Base electronics

Photo-multipliers are conventional operated with a passive resistor base supplying appropriate bias voltage. Some experiments have been made with electronic bases which can offer low power consumption (ref 1), or high count rate capability (ref 2). In these measurements we have experimented with an active base using FET. The base circuit (ref 3, Fig 1), shows how the dynode chain is biased with FET, which also allow a slowly varying signal to be extracted via the dynode path as well as a fast anode signal. Such an arrangement is ideal suited to applications where fast, and slowly varying signals need to be measured with the same photo-multiplier. The dynode circuit performed satisfactorily.

## 3.0 Measured Performance

### 3.1 Linearity

The HM photo-tubes were stimulated with a light pulsar (241Am in NaI). The response as a function of voltage was linear as shown in Fig 2.

### 3.2 Relative gains

Although the tubes were purchased as a matched set there was a gain difference of two between the best and worst tubes (Fig 3).

### 3.3 Position response

The signal variation with photo cathode position was investigated by recording the photo tube output with the light pulsar placed at different positions across its surface (Fig 4).

### 3.4 After pulsing

Most of the tubes displayed after pulsing. Fig 5, and Fig 6 show examples of the best and worst. Five of the tubes were exchanged with Hamamatsu, but the replacements all had some after pulsing. It appeared that there is a problem which Hamamatsu could not correct.

### 3.5 Photo-tube oscillation

The Hamamatsu tubes were placed in a Lambertian sphere, and stimulated with a UV laser. Wavelength shifting aerials were employed to wavelength shift the light in to the tubes acceptance window. Typical photo tubes response is shown in Fig 7. The oscillatory structure shown is inherent to the photo tubes, and not associated with the FET base electronics: oscillations were still visible when the FET base was replaced with a passive resistor base constructed according to the prescription provided by Hamamatsu. Similar structure was also observed, with no external stimulus, when the tube was occasionally struck with a cosmic ray muon. It appears this tube design has a flaw.

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**Figure captions:**

Fig 1. The FET base bias circuit

Fig 2. The output response of the Hamamatsu RA 1250 photo-tubes as a function of bias voltage. The right hand scale refers to the Hamamatsu serial number.

Fig 3. Relative gain variations of the Hamamatsu RA 1250 photo tubes.

Fig 4. Position response of the Hamamatsu tube: serial number 37.

Fig 5. Best after pulsing response; tube number 80

Fig 6. Worst after pulsing response; tube number 74.

Fig 7. Typical oscillatory structure observed in the anode output of the RA 1250 tubes

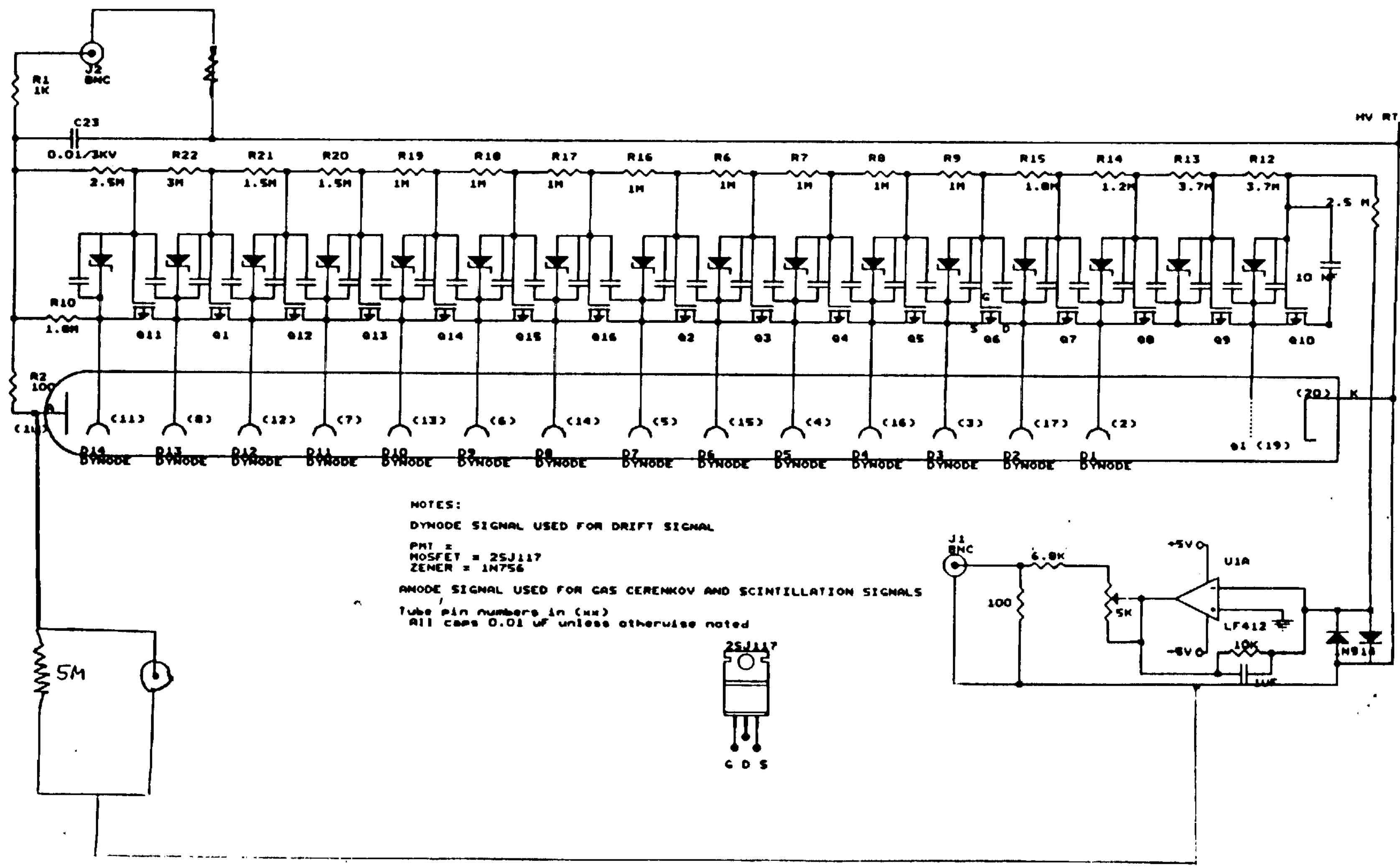


Figure 1

| | |
|---|---|
| Title | BUGS REGION B PMT BASE |
| Size B | Document Number BUGS.PMT |
| Date: | December 14, 1992 Sheet 1 of |

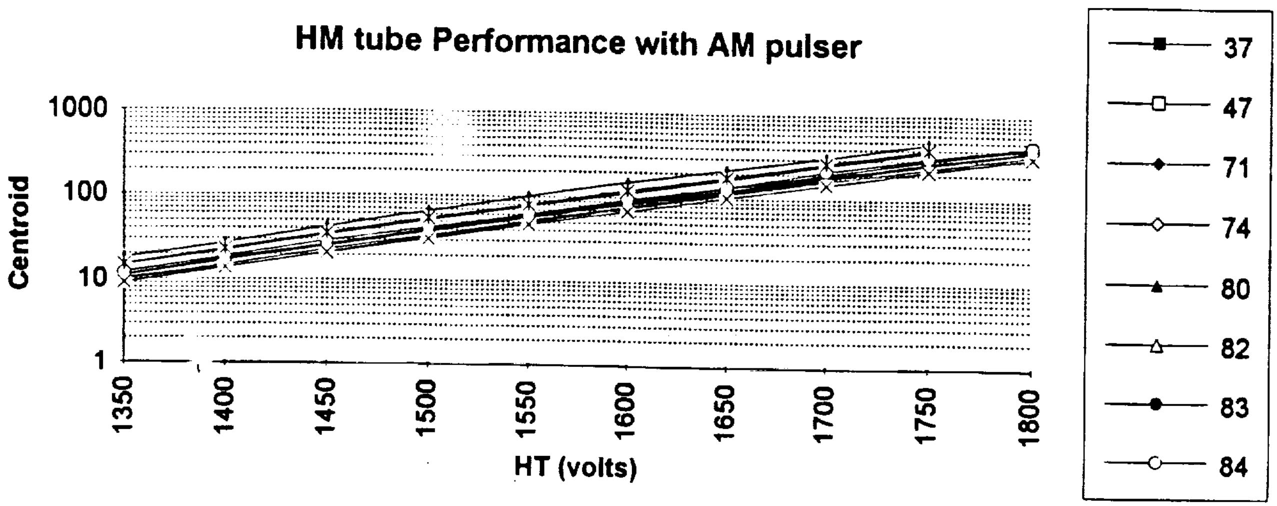
HM tube Performance with AM pulser
1000
100
10
1
Centroid
1350
1400
1450
1500
1550
1600
1650
1700
1750
1800
HT (volts)
37
47
71
74
80
82
83
84

Figure 2.

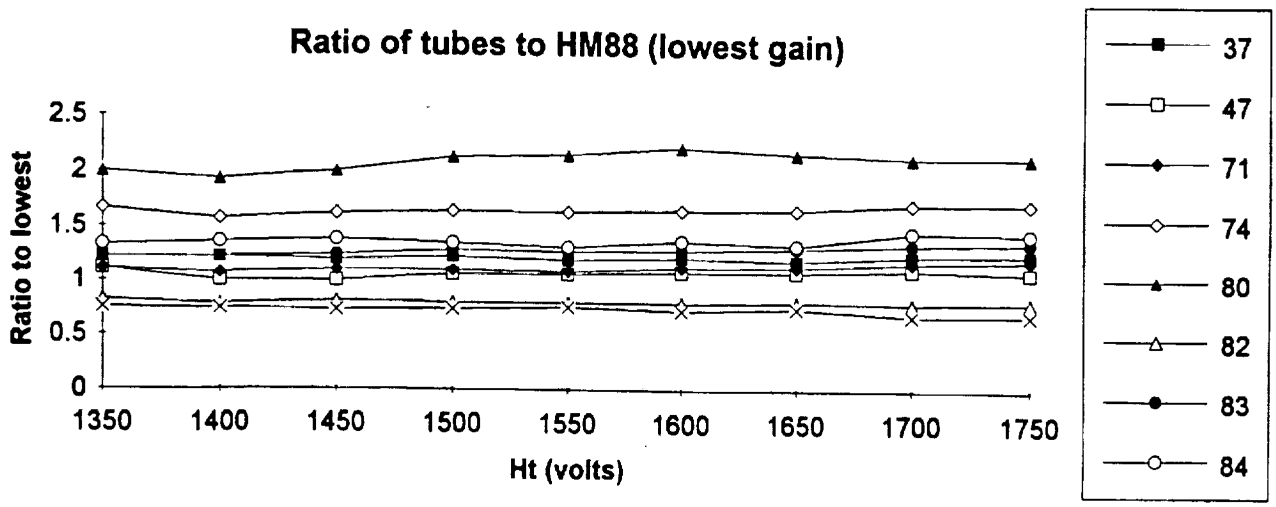
Ratio of tubes to HM88 (lowest gain)
Ratio to lowest
2.5
2
1.5
1
0.5
0
1350
1400
1450
1500
1550
1600
1650
1700
1750
Ht (volts)
37
47
71
74
80
82
83
84

Figure 3.

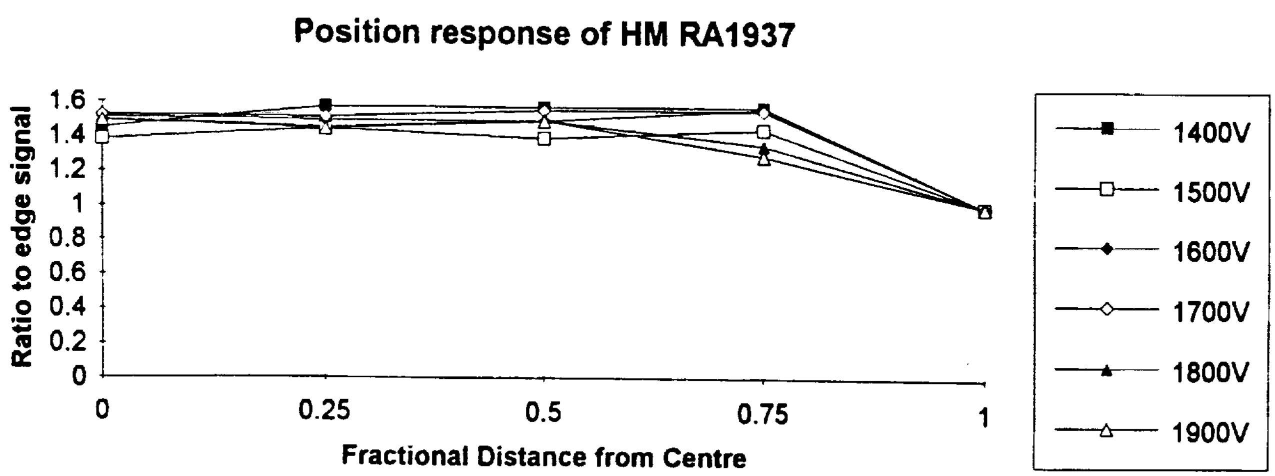
Position response of HM RA1937
Ratio to edge signal
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.25
0.5
0.75
1
Fractional Distance from Centre
1400V
1500V
1600V
1700V
1800V
1900V

Figure 4.

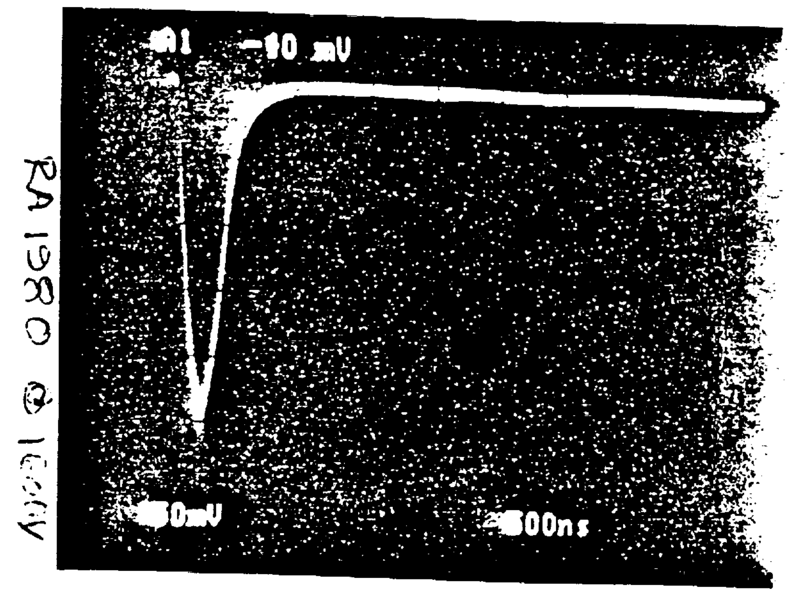

Figure 5.

Figure 6.

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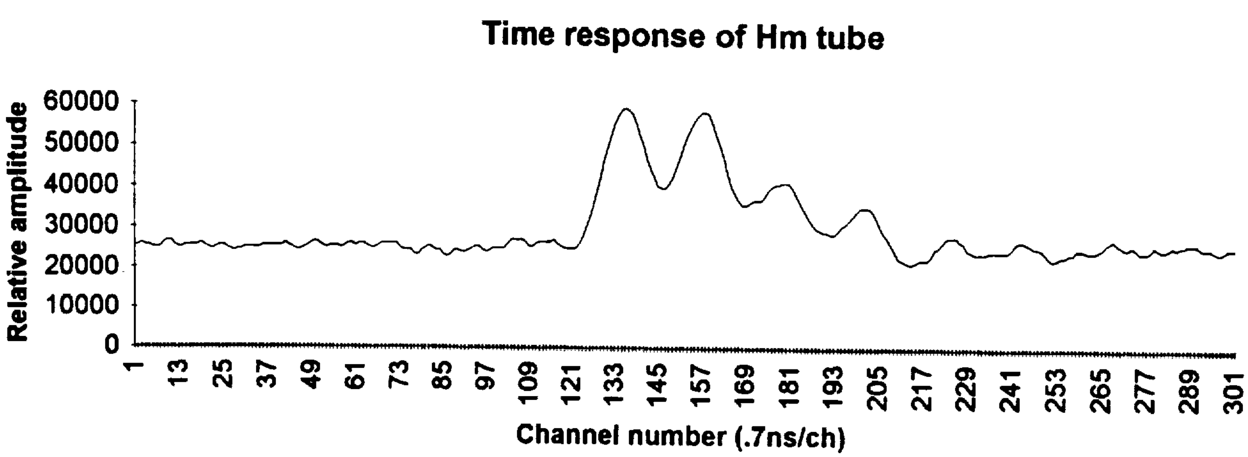
Time response of Hm tube
Relative amplitude
60000
50000
40000
30000
20000
10000
0
1
13
25
37
49
61
73
85
97
109
121
133
145
157
169
181
193
205
217
229
241
253
265
277
289
301
Channel number (.7ns/ch)

Figure 7.

**Gluon Clusters Formation and Their Subsequent Decay Into Hadrons in a High Energy Nuclear Collision For a Scintillation-Fiber-Calorimeter**

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## Abstract

When two heavy nuclei collide with extremely high energy, a large number of hadrons will be created. In this report, we use a simple thermal model to predict the number of gluons produced in the central collision region in a high energy nuclear collision. We then use a simple symmetry model to calculate the formation of two-gluon and three-gluon clusters and their subsequent decay into mesons and baryon-antibaryon pairs. The developed scheme of hadronic interactions will help improving a simulation program for observations of cosmic nuclei with a Scintillation-Fiber-Calorimeter.

## I. Introduction

When two heavy nuclei collide with extremely high energy, it is expected that a part of their energy will be carried away by the leading particles which have the baryon number of the colliding nuclei, and a large portion of their kinetic energy will be converted into heat so that a quark-gluon plasma will be created in the collision region.[1] This plasma subsequently hadronizes into baryon-antibaryon pairs and mesons as it cools. This so called central rapidity region has been the interest of many recent theoretical and experimental studies.[2-6] This report outlines our recent theoretical study. We use a very simple thermal model for the gluon production and a simple cluster model for the formation of gluon clusters and their subsequent decay into hadrons. With a simple assumption of thermal equilibrium, the number of gluons produced and their energy distribution are calculated in terms of the incident energy of the colliding nuclei and their interaction volume. The gluons produced subsequently form colorless clusters. The number of two-gluon and three-gluon clusters and their mass distribution are calculated from a simple symmetry model. The decay of these clusters into baryon-antibaryon pairs and mesons are then calculated using an SU(3) flavor symmetry Lagrangian. The particle composition in the central rapidity region can be completely predicted without any adjustable parameter and can be easily compared with experimental results. This work is still in progress and shall be completed very soon.

## II. Gluons Production

When two relativistic heavy nuclei collide head-on, viewing in the center of mass system, we have two highly Lorentz contracted pan cakes passing each other.[1] Shortly just before and after they pass through each other in a time of the order of one fermi/c, the quarks and gluons in the nuclei are excited and a large portion of their kinetic energy is converted into heat within a small cylindrical volume bounded by the two receding nuclei. Within the volume, it is expected that a thermal equilibrium is reached and this volume can be treated as a black body cavity. Since the gluons are produced more easily than the quarks, and they are spin 1 massless particles, they, like the photons, satisfy the photon statistics and their energy distribution is governed by the Planck formula

$$U(E,T) = \frac{8E^3}{\pi^2\left(e^{\beta E} - 1\right)} \qquad (1)$$

where ß = 1/k T. A factor of 8 is included in Eq(1) due to the fact that there are eight kind of gluons instead of one kind of photon. Integrating Eq (1) gives the energy density:

$$U(T)=\frac{8\pi^2}{15}\frac{1}{\beta^4} \tag{2}$$

Eq (2) can be used to estimate the temperature of the cavity. Let us assume a 160 GeV/n lead beam on lead in the laboratory system, or a total center of mass energy W=3600 GeV. Let us assume a third of this energy is carried away by the products of each of the two receding nuclei and the remaining one third is left in the central collision region. Therefore,

$$U\,V = 1200\text{ GeV} \tag{3}$$

where V is the cavity volume. Let the radius of the cavity be the lead nuclear radius, 7 fm., and the length be 2 fm. From Eqs (3) and (2), the temperature of the gluon plasma is estimated to be 270 MeV. With the temperature worked out, Eq (1) can be used to calculate the gluons average energy and their energy dispersion:

$$Eg=\frac{\int E\,U(E,T)dE}{U(T)}=1.03GeV \tag{4}$$

and similarly, ΔEg = 0.55 GeV.

Eq (4) and Eq (3) tell us that for a 160 GeV/n lead on lead head-on collision, one expects that a total of about 1166 gluons are produced in the central collision region with an average energy Eg = 1.03 GeV and ΔEg = 0.55 GeV.

## III. Clusters Formation

In the last section, we estimated the number of gluons and their average energy produced in a high energy nuclear collision. In this section we study the formation of gluon clusters and their properties. Since gluons carry color, they cannot decay into hadrons directly, but they may form colorless clusters and then decay into hadrons. We expect the most abundant clusters will be formed by low number of gluons, namely, two-gluon clusters, $C\varepsilon$ and three-gluon clusters, $C\omega$.[7,8]

$C\varepsilon$ : $C\varepsilon$ is formed when one gluon is combined with another gluon of opposite color, for example a b$\bar{r}$ gluon is combined with a r$\bar{b}$ gluon. We may calculate the probability of such a formation as follows. Let f be the frequency of one gluon in the vicinity of another gluon. Then there is a 1/8 chance it will meet the right gluon and form a $C\varepsilon$, and a 7/8 chance it will meet the wrong kind and stay as a single. If it does not meet the right gluon on the first time, it may meet the right gluon on the second, or on the third time . . . So the total probability of forming a $C\varepsilon$ is:

$$P(C\varepsilon) = \frac{1}{8}f + \frac{7}{8}f \times \frac{1}{8}f + \left(\frac{7}{8}f\right)^2 \times \frac{1}{8}f + \ldots = \frac{f}{8-7f} \tag{5}$$

$C\omega$: $C\omega$ is formed when one gluon, say $b\bar{r}$, is combined with two gluons of the right color, $r\bar{g}$ and $g\bar{b}$. This calculation is more complicated than the previous one. We may proceed as follows. Say a $b\bar{r}$ gluon, if it meets either a $r\bar{g}$ or a $g\bar{b}$ on the first encounter, it needs to add a $g\bar{b}$ or a $r\bar{g}$ on the second encounter or on the third encounter .... Hence, the probability of forming a $C\omega$ if it has met one of the two right gluons on its first encounter is :

$$P = \frac{2}{8}f\left[\frac{1}{8}f + \frac{7}{8}f \times \frac{1}{8}f + \left(\frac{7}{8}f\right)^2 \times \frac{1}{8}f + \ldots\right] = \frac{f^2}{4(8-7f)}$$

But there is also a $\frac{6}{8}$ chance it meets neither a $r\bar{g}$ nor a $g\bar{b}$ on the first time. Out of this $\frac{6}{8}$ chance, there is a $\frac{1}{8}$ chance it will meet a $r\bar{b}$ gluon and leave as a $C\varepsilon$ cluster, a $\frac{5}{8}$ chance it will meet the others and will stay as a single. If it stays as a single, it always has a chance to form a $C\omega$ by meeting the right gluons. Hence the total probability of forming a $C\omega$ is

$$P(Cw) = \frac{f^2}{4(8-7f)} + \frac{5f}{8} \times \frac{f^2}{4(8-7f)} + \left(\frac{5f}{8}\right)^2 \frac{f^2}{4(8-7f)} + \ldots = \frac{2f^2}{(8-7f)(8-5f)} \tag{6}$$

If we assume that eventually all gluons form colorless clusters and decay into hadrons and they only form two-gluon and three-gluon clusters, we have

$$\mathrm{P}(C\varepsilon) + \mathrm{P}(C\omega) = 1 \tag{7}$$

Eq (7) determines $f$ uniquely. Substitute the value of $f$ into Eqs (5) and (6), we find

$$\mathrm{P}(C\varepsilon) = 0.64 \text{ and } \mathrm{P}(C\omega) = 0.36$$

With 1166 gluons on hand, they will form 316 two-gluon clusters $C\varepsilon$ and 178 three-gluon clusters $C\omega$.

The mass distribution of $C\varepsilon$ and $C\omega$ : $C\varepsilon$ is formed by two gluons each having an energy Eg and width $\Delta$ Eg. The combined mass of $C\varepsilon$ is $\sqrt{2Eg^2(1-\cos\theta)}$ where $\theta$ is the angle between the momentum vectors of the two gluons. Hence the average mass of $C\varepsilon$ is

$$M(C\varepsilon) = \left\langle \sqrt{2Eg^2(1-\cos\theta)} \right\rangle = \frac{4}{3} Eg = 1.37 GeV$$

The total width of $C\varepsilon$ is partly due to the energy uncertainty of the gluon, $\Delta$Eg, and partly due to various possible values of the angle $\theta$. The part of $\Delta$M due to the uncertainty of the angle $\theta$ can be worked out just like that for M($C\varepsilon$) and is $\frac{\sqrt{2}}{3} Eg$. The total width of $C\varepsilon$ is therefore:

$$\Delta M(C\varepsilon) = \sqrt{\frac{2}{9} Eg^2 + 2(\Delta Eg)^2} = 0.92 Ge\mathrm{V}$$

$C\omega$ is formed by three gluons. Its average mass and width can be calculated in a similar way. The calculation is straight forward but lengthy, one needs to take an average over the angles between the three momentum vectors of the gluons. The final results are

$$\mathrm{M}(C\omega) = 2.47 \text{ GeV}$$
$$\Delta\mathrm{M}(C\omega) = 1.06 \text{ GeV}$$

We note here that the widths of $C\varepsilon$ and $C\omega$ are comparable to their masses and are about 1GeV which are large enough to prevent them from being observed as resonances and small enough for them to be considered as clusters.

## IV. Hadronization

In this section we study the decay of $C\varepsilon$ and $C\omega$ into mesons and baryon-antibaryon pairs. It is commonly proposed that if gluons combine to form clusters, they are likely to be formed with low orbital angular momentum between gluons. This means that $C\varepsilon$ and $C\omega$ shall have the quantum number $J^{PC} = 0^{++}$ and $1^{--}$, respectively. Furthermore, they are colorless, quark neutral and flavor singlet. $C\varepsilon$, being made of two gluons, can only decay into two mesons. $C\omega$, being made of three gluons, can decay either into three mesons or a baryon-antibaryon pair. If we assume an SU(3) flavor symmetry, the effective Lagrangrian for various gluon cluster decay processes can be written out, for example, for the $C\varepsilon \rightarrow$ PP and $C\varepsilon \rightarrow$ VV decay processes.

$$L_{eff} = g[\, C\varepsilon \; \mathrm{Tr}\,(PP) + C\varepsilon \, \mathrm{Tr}\,(V\mu \; V\mu)]$$

where $g$ is the coupling constant, P and $V\mu$ are the well known 3 x 3 SU(3) matrices for the pseudo-scalar meson octet and vector meson nonet. Once we have these Lagrangians, the branch ratios for various decay processes can be easily worked out. They depend on the product of two factors, the SU(3) symmetry factor and the available phase space. Knowing the masses of the gluon clusters and the number of these clusters, we can finally calculate the hadron composition in the central rapidity region in a high energy nuclear collision.

The last stage of this calculation is still in progress. It shall be completed soon.

In conclusion, we used a simple thermal model to predict the number of gluons produced in the central collision region in a high energy nuclear head-on collision. We then used a simple symmetry model to calculate the formation of gluon clusters and their subsequent decay into hadrons.

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