Study of Quark-Gluon Plasma by suppression of heavy quarkonium

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Abstract: With this work we want to know the conditions in which is originated the Quark Gluon Plasma (QGP) from the collision between two atoms of lead. This QGP will act as a medium, in which a meson formed by charm or bottom quarks will move with a constant momentum p_T. We approach this study from two points of view: the first one from the perturbative Quantum Chromodynamics (that will define the weakly coupling regime) and the other one from the point of view of AdS/CFT theories (it will introduce some aspects from holography and it will work in the strongly coupling regime). The nuclear modification factor ,R_{AA}, will be the focus of our study, and will give us information about the probability of creating bound states within the plasma. To compute R_{AA} we will make use of the Glauber geometrical modeling for collisions.

I. INTRODUCTION

Currently, we know that matter is made up of atoms, which are at the same time composed of subatomic particles, as explained in the Standard Model.

This model divides fundamental particles into two large groups: bosons (carriers of the fundamental forces of the universe) and fermions (constituents of ordinary matter): the latter can be classified into quarks (which can be affected by the strong nuclear force) and leptons (which do not feel said interaction).

Quarks, moreover, can only be observed directly in nature forming various structures, such as baryons (three quarks) or mesons (a quark and an antiquark). We will focus the study of this work on mesons.

Although we can form mesons from the six flavors of existing quarks (up, down, strange, charm, bottom and top in increasing order of mass) it is quite interesting to focus on the three flavors of heavy quarks: $c\bar{c}$ and $b\bar{b}$ (the $t\bar{t}$ will be excluded due to its great instability). The group of these three mesons is known as heavy quarkonium.

We study mesons made out of quarks, so it is convenient to have as a tool a theory that explains the interactions of these particles with the strong force: this is Quantum Chromodynamics (QCD), a quantum theory of fields. These types of theories are the result of quantizing classical field theories, such as Electromagnetism. However, QCD is a non-linear theory (since the gluon has color unlike the photon, which has no charge): this complicates the calculations considerably.

At energies larger than the constant Λ_{QCD} the coupling constant of QCD is small, therefore perturbation theory will give accurate results. This property is known as asymptotic freedom. The regime in which QCD is perturbative is called the weak coupling regime.

If we study heavy quarkonium in the J/ψ and Υ forms ($c\bar{c}$ and $b\bar{b}$, respectively) the formation of the corresponding heavy quark pair and its decay will always be a perturbative process, since the mass of charm and bottom are much larger than Λ_{QCD}. This makes these systems very interesting objects of study, as we have said previously.

In fact, they will serve us as very powerful tools to extract properties of the Quark-Gluon Plasma (QGP). It is a state of matter that requires very high energy density (and therefore high temperatures), which are conditions reached by the collision of heavy ions (for example lead): these processes are performed nowadays at RHIC and LHC.

We will focus our analysis on the heavy quarkonium suppression: It is usually studied by calculating the R_{AA}, the nuclear modification factor [1], which is defined as $R_{AA} = \frac{\frac{dN^{AA}}{dp_T}}{<N_{coll}>\frac{dN^{PP}}{dp_T}}$, that relates the number of nucleon-nucleon collisions in a nucleus-nucleus collision in the Glauber model, the number of quarkonium states of a given species created in a nucleus-nucleus collision, proton-proton collisions and the transverse moment (N_{coll}, N_{AA}, N_{PP} and p_T, respectively).

We can also use the Holographic Principle to study the QGP: it says that under certain conditions a conformal quantum field theory (CFT), a type of theory that remains constant under transformations that keep the values of the angles invariant, at strong coupling is equivalent to classical gravity. The CFT to which we approximate QCD is supersymmetric Yang-Mills theory.

Therefore, we have seen two extreme visions of the suppression of heavy quarkonium to study the QGP: these will be the conditions that we study in this work. Nonetheless, in the necessary range of energies to study this phenomenon the coupling constant will have intermediate values, so we will not be in any of the extreme situations.

We will calculate the decay width ($\Gamma(v)$) of the quarkonium (which will be related to its half-life), depositing it in a QGP medium at rest with a velocity relative to this medium v, which we will vary. As the value of v varies, we will calculate the corresponding $\Gamma(v)$, with which we will obtain a relationship between the speed and the suppression of the quarkonium.

Having the function $\Gamma(v)$ we can now extract R_{AA} as a function of quarkonium's transverse momentum, comparing it with those predicted by both models, and seeing which one is closer to the medium observed in heavy-ion collisions.

II. COMPARISON BETWEEN PQCD AND ADS/CFT

A. Coupling constant, g

We have talked about the different existing energy regimes (weak, intermediate and strong). All of them can be differentiated with the coupling constant g.

Depending on the energies involved in a process, g will take on different values.

When $g << 1$ we are in weak coupling conditions (pQCD), while strong coupling is achieved when $\frac{1}{g} << 1$ (the case that we model using AdS/CFT correspondence).

However, heavy quarkonium suppression will have a g value between both situations (intermediate regime). Our objective in this work will be to determine which conditions we will be closest to.

B. Screening length, L_s

Apart from the previously mentioned decay width, it is also necessary to take into account another mechanism related with quarkonium suppression: the screening length. This gives an idea of the distance beyond which bound states cannot exist for the quark-antiquark system that makes up our study, about the order of $L_s \sim \frac{1}{m_D}$ [2]. The m_D factor is the Debye's mass, and it is refered to the effective mass that a small frequency gluon adquires in a thermal medium.

If we observe the heavy quarkonium potential at finite temperature in pQCD we can observe this phenomenon:

$$V(r) = -\alpha_s \frac{e^{-m_D r}}{r} - i\alpha_s T\phi(m_D r), \tag{1}$$

where the imaginary term refers to the decay of the meson and the real term refers to the screening phenomenon. This expression for the potential is valid when $\frac{1}{r} \sim m_D$ [3].

Therefore, we could check that the temperature for which both parts of potential are equally large is smaller to the temperature for which screening becomes important. Hence, we can ignore screening when we study heavy quarkonium suppression in pQCD.

For L_s we have an analytical expression in the AdS/CFT approach. That follows the next dependence with T and v (the formula is written in the laboratory system):

$$L_s(v,T) \propto \frac{1}{T}(1-v^2)^{1/4}, \tag{2}$$

It can be seen that the screening length will become smaller when we increase T, and it will decrease with v [4].

There is a more significative consequence of this magnitude, that is known as the dissociation temperature T_{diss}; it is defined as the temperature above which mesons with a given velocity don't exist. That temperature will become important in our analysis [4]:

$$T_{diss}(v) = 2M(1-v^2)^{1/4} \tag{3}$$

Here M is the mass of the quarkonium, and we define the formula in the laboratory system.

C. Decay width, $\Gamma(v)$

It is interesting to see the expression of decay width for the heavy quarkonium dispersion process within the QGP, according to the perturbative regime [5]:

$$\Gamma_{pQCD}(v) = \frac{2\alpha_s C_F T m_D^2 a_0^2}{\sqrt{1-v^2}} log(\frac{2}{m_D a_0}), \tag{4}$$

where the equation is in the reference system where heavy quarkonium is in rest, and is valid for energies much smaller than the Debye's mass ($E << m_D$), and moderate velocities (v $\approx$ 1). The value a_0 is the Bohr radius (it variates its value for each meson).

The Debye's mass will depend also on T [5]:

$$m_D = \frac{2\pi T}{\sqrt{3log(\frac{2\pi T}{0{,}25})}} \tag{5}$$

In the other hand, we have the expression of thermal width for AdS/CFT theories (equivalent to decay width in pQCD):

$$\Gamma_{AdS/CFT}(v) = \frac{972\pi^5 T^4}{200 m_Q^2}(C_1+C_2v^2) = 1487\frac{T^4}{m_Q^2}(C_1+C_2v^2), \tag{6}$$

where $C_1 = 7{,}710^{-4}GeV^-1$ and $C_2 \approx 0$ (according with Figure 4 in [6]), and the formula is written in the frame of reference in which quarkonium is in rest. The expression will be useful for large temperatures (large energies).

We will have, therefore, the following parametric dependencies of the decay width with the velocity:

$$\Gamma_{pQCD}(v) \propto \frac{1}{\sqrt{1-v^2}} \tag{7}$$

$$\Gamma_{AdS/CFT}(v) \sim ctt \tag{8}$$

assuming the rest of the parameters to be invariant.

D. Glauber modeling

As we have said before, the QGP can be created in heavy-ion collisions.

This phenomenon can be studied using the Glauber's collision modeling, a model that takes in count the geometry of the reaction, and that was made to deal the problem of high energy scattering with composite particles [8].

There is a limit in the model at which the calculations become analytically tractable: it is known as the "Optical Limit".[9].

We will use this limit to reach some conclusions in this work.

III. ANALYTICAL STUDY OF THE HEAVY QUARKONIUM SUPPRESSION

Having all the previous points clear we can propose a mathematical model for study the heavy ion collision.

A. Glauber's approach to the problem. Monte Carlo simulation

Let us assume both lead nuclei to be two identical spheres of radius R, with a given intersection volume. To simplify the analysis we will study it from a plane transverse to the collision axis, so it will become a two-dimensional problem.

Furthermore, we define an arbitrary impact parameter: although this value varies for each collision we take b=R/5 (as an example).

In the intersection area we have two regions: the central area (with temperature T) and the periferical (with T/5). The remaining area is at T=0.

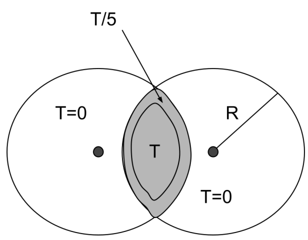

FIG. 1: Two-dimensional model described for the collision

In order to know the temperature in each point of the space and time we will use the Relativistic Hydrodynamics.

In this theory, and supposing a very large nucleus, we will have the following dependence of T with time (Bjorken's model):

$$tT^3 = t_0 T_0^3, \tag{9}$$

where the values of T_0 and t_0 can be extracted comparing calculations using this model with experimental values (560 MeV and 0'6 fm respectively).

Starting from this model and using Fortran we will program a Monte Carlo simulation, to study the evolution of heavy quarkonium in QGP (in the J/ψ or Υ form).

First of all we will generate a random point, contained within the grey region of *Figure 1*. If this point falls into the central region the heavy quarkonium will be at temperature T, and if it falls into the external will have T/5. In both regions we will check if $T > T_{diss}$: if this condition is met the quarkonium will melt, due to screening phenomenon.

Once we have the quarkonium formed, we associate a transverse moment to it, which will follow the experimental distribution

$$f(p_T) \approx \frac{p_T}{p_T^2 + M_{qrknm}^2}, \tag{10}$$

Assuming that the quarkonium and the medium have the same longitudinal velocity, we can say that the velocity of the former will be given only by the transverse velocity (which comes from the transverse momentum generated).

Taking an angle between [0,2π) we can define the evolution of the quarkonium along the region, given by $\vec{v}$.

We will evolve quarkonium using a time step dt (the time will be given by t=t+dt). For each value of t we will check whether decay or screening acts.

Regarding screening, we will check if T¿T_{diss}. As we have said, we will only take this into account for Ad-S/CFT, and not for pQCD.

The decay width, on the other hand, will define the probability that the heavy quarkonium will disappear in a given time interval:

$$P = \Gamma(T, v)dt \tag{11}$$

Having defined the value of P, we will only have to generate a random number, and compare it with P. If this number is greater than P the quarkonium will survive.

This multiple analysis will be repeated until reaching a temperature at which QGP cannot exist (phase transition temperature, around T_{PhTr}=0,25 GeV). When we reach this point, we generate another random point and repeat the process.

When we finish studying all the quarkoniums we will have defined a value for the coefficient R_{AA}:

$$R_{AA} = \frac{\#\text{ of quarkonium that survives}}{\#\text{ of quarkonium initially produced}} \tag{12}$$

B. Study of R_{AA} in two different models

Therefore, we will have two different suppression simulations: one for pQCD, and the other one for AdS/CFT.

With the objective of finding which situation is closest to reality we will start checking the values of R_{AA} as a function of the transverse momentum p_T for J/ψ and Υ.

IV. RESULTS

A. R_{AA} with moment p_T for J/ψ and Υ

The experimentally observed distributions of R_{AA} with p_T are shown in fig. 2

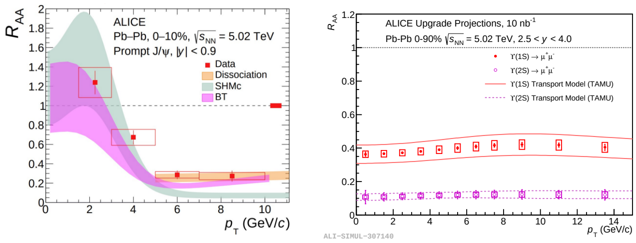

FIG. 2: Distribution of the coefficient R_{AA} with p_T for J/ψ[14] and Υ[15] (left and right).

It is interesting to see the values between which momenta p_{Tmax} are plotted. The maximum values for momenta given on the figure are:

$$p_{Tmax,J/\psi} = 10GeV/c; p_{Tmax,\Upsilon} = 14GeV/c \quad (13)$$

Hence, the corresponding maximum speeds v_{max} are:

$$v_{max,J/\psi} = 0,96; v_{max,\Upsilon} = 0,81 \quad (14)$$

These values correspond to observations made at CERN, where lead atoms collide at high energies. Both distributions are similar to each other, which we expected to obtain since J/ψ and Υ are the same type of system (heavy quark mesons).

However, the peak J/ψ is much higher than that of Υ: this is due to the phenomenon of recombination: this process consists of the quark and antiquark resulting from the suppression can recombine with others quarks. It becomes more probable at J/ψ, since there will be much more charm quarks than bottom of the medium.

This may also explain the position of the maximum of R_{AA}, closer to zero in J/ψ and more centered in Υ. We did not take into account recombination in this study.

B. Computational values for pQCD

We have plotted ($R_{AA}(p_T)$) for pQCD, with the data obtained through the simulation detailed in the third point of the report. We have used the tabulated values of $M_{J/\psi}$ and M_Υ, 3097 MeV and 9460 MeV respectively:

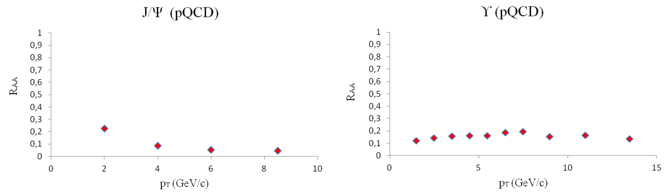

FIG. 3: Obtained distribution of the coefficient R_{AA} with p_T for J/ψ and Υ according to pQCD (left and right).

These plots are histograms of all the data, so we have divided the intervals of p_T in the same way as $IV.A$ has been divided.

We obtain distributions very similar to the experimental results, although all factors are lower. Furthermore, we can see that R_{AA} doesn't have such a sharp jump as in the case of *FIG.2.A*. The values of momenta that define R_{AA}'s maximums correspond to the expected.

C. AdS/CFT approach

We can repeat the study for this case:

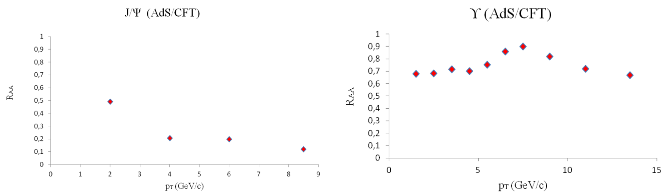

FIG. 4: Obtained distribution of the coefficient R_{AA} with p_T for J/ψ and Υ according to AdS/CFT approach (left and right).

In the AdS/CFT approach we obtain distributions that are similar to the previous ones. However, we see that all values of R_{AA} are higher (having a higher increment in Υ's).

Therefore, we can finally observe how both experimental distributions are closer (numerically speaking) to the case of pQCD than to that of AdS/CFT. More specifically in the case of upsilon we can see how the curve is less pronounced (smoother), while in *FIG.3.B.* we have a differentiated pick.

Still, we can observe how R_{AA} decays faster with lower momenta for charmonium in pQCD than for AdS/CFT. It would be useful to conduct another study to know exactly the influence of recombination on heavy quarkonium suppression.

V. CONCLUSIONS

- The heavy quarkonium system corresponds to a meson, formed by the union between one heavy quark and its corresponding antiquark. These quarks are charm and bottom, and they form the J/ψ and Υ states.
- Quantum Chromodynamics (QCD) is the theory that study the interaction among different types of quark: it introduces the color charge, and it has the gluon as its fundamental interaction carrier. To be able to develop calculations in this theory it is possible to convert QCD in a perturbation theory (pQCD), that works into the weak coupling regime.
- Under strong coupling conditions we can approximate QCD to super Yang Mills theory (SYM), a Conformal Field Theory (AdS/CFT approach). With this approximation we can make calculations, using the General Relativity mathematical formalism.
- It is interesting to note that the decay width becomes approximately constant with changing velocities in AdS/CFT and depends on them for pQCD, whereas if we look at the evolution of quarkonium in the laboratory reference system (and not where the quarkonium is in rest) both results are exchanged. We have to remember that to go from one reference system to another we have to divide by the factor $\gamma = \frac{1}{\sqrt{1-v^2}}$). From here we can see how extreme both models are, where in one the probability of decay does not depend on time and in the other it does.
- The real situation does not correspond to any model presented in the previous points of the report. However, we could conclude that this is happening in a regime closer to the conditions of pQCD than to those of AdS/CFT.
- We confirm that the Quark Gluon plasma created from a collision between two lead atoms is in a medium regime, closer to the weakly coupled regime in which pQCD is developed. However, we have made many approximations, so the result may not be very accurated.
- It would be interesting to realize a second study, analyzing the impact of recombination in J/ψ, to explain the difference between its pQCD's and AdS/CFT's distribution.

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[1] Hohler, Paul M. and Yin, Yi, Charmonium moving through a strongly coupled QCD plasma: a holographic perspective" Phys. Rev. D **88** (2013), 020

[2] Qudsia J. Ejaz, Thomas Faulkner, Hong Liu, Krishna Rajagopal and Urs Achim Wiedemann, A limiting velocity for quarkonium propagation in a strongly coupled plasma via AdS/CFT" JHEP **04** (2008), 008

[3] Sebastian, Jobin and Jamal, Mohammad Yousuf and Haque, Najmul, Liénard-Wiechert potential of a heavy quarkonium moving in QGP medium" Phys. Rev. D **107** (2023), 016

[4] Hong Liu, Krishna Rajagopal, Urs Achim Wiedemann, An AdS/CFT Calculation of Screening in a Hot Wind" Phys.Rev.Lett. **98** (2007), 003

[5] Miguel Angel Escobedo, Floriana Giannuzzi, Massimo Mannarelli and Joan Soto, Heavy Quarkonium moving in a Quark-Gluon Plasma" Phys.Rev.D **87** (2013), 009

[6] Patra, Binoy Krishna and Khanchandani, Himanshu and Thakur, Lata, Velocity-induced Heavy Quarkonium Dissociation using the gauge-gravity correspondence" Phys.Rev.D **92** (2015) 8, 085034

[7] Myers, Robert C. and Sinha, Aninda, The Fast life of holographic mesons" JHEP **06** (2008), 052

[8] Michael L. Miller, Klaus Reygers, Stephen J. Sanders, Peter Steinberg, Glauber modeling in high energy nuclear collisions" Ann.Rev.Nucl.Part.Sci. **57** (2007), 052

[9] Bialas A, Bleszy´nski M, Czy´z W., Multiplicity Distributions in Nucleus-Nucleus Collisions at High-Energies" Nucl. Phys. B **111** (1976), 461

[10] Finazzo, Stefano I. and Noronha, Jorge, Thermal suppression of moving heavy quark pairs in a strongly coupled plasma" JHEP **01** (2015), 051

[11] Ali-Akbari, M. and Giataganas, D. and Rezaei, Z., Imaginary potential of heavy quarkonia moving in strongly coupled plasma" Phys. Rev. D **90** (2014), 086

[12] Giataganas, Dimitrios, Velocity Laws for Bound States in Asymptotically AdS Geometries" Fortsch. Phys. **71** (2023), 023-030

[13] Tahery, Sara and Chen, Xurong and Zhang, Zi-qiang, Holographic imaginary potential of a quark antiquark pair in the presence of gluon condensation" JHEP **03** (2023), 207

[14] Arsene, ALICE Overview" Quark Matter 2023 (2023), 032

[15] Anonymous, Projection nb-1" CERN's website (2018)

VI. APPENDIX

Here is the program I have done for simulations:

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C
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C------------------------------------------------------------
C-----------------------PROGRAMA----------------------------
C------------------------------------------------------------
C------------------------------------------------------------

PROGRAM SUPPRESSION
C Simularem la supressio del quarkonium
C pesant dins de un plasma de quarks i
C gluons. Usarem el model de Glauber per
C construir la geometria de la colisio
C que generara el plasma.

IMPLICIT NONE
C Passem les funcions com a external, per
C tal d'utilitzar-les a les diferents
C subrutines

EXTERNAL DWIDTHPQCD,TEMPDIS,DWIDTHADS
DOUBLE PRECISION PI,TEMP0,T0,DT,R,R2,A,PTU
DOUBLE PRECISION TEMPP,RCENT2,CIRC1,CIRC2
DOUBLE PRECISION TDIS,DECPROB,TEMP,T,X,Y
DOUBLE PRECISION TMAX,TEMPTF,A0,ALPHAS,PT
DOUBLE PRECISION M,THETA,TEMPDIS,P,V,GAMMA
DOUBLE PRECISION CD,XT,GAMMAU,MQ,DWIDTHADS
DOUBLE PRECISION DWIDTHP
INTEGER I,J,JMAX

C------------------------------------------------------------
C---------------DEFINICIO DE VARIABLES----------------------
C------------------------------------------------------------

C Introduim el valor de la massa (GeV) i el
C radi (amstrongs), tambe la separacio A del
C centre del segon cercle: A deu estar entre
C R i 3R perque hi hagi interseccio (pel cas
C del Pb 1'75<A<5'25)
C El parametre d'impacte sera R-A
M=9.46D0
MQ=4.19D0
R=1.75D0
A=2.D0
ALPHAS=0.41D0
A0=0.74D0


C Definim les variables necessaries
PI=4.D0*ATAN(1.D0)
RCENT2=(81.D0/100.D0)*R**2.D0

C Obrim l'arxiu on guardarem les dades
OPEN(1,FILE='UpsilonPQCDDEF.dat')

C Nom de les variables
WRITE(1,*) 'pT (GeV), Compte (adim)'

C Imposem les Condicions Inicials
TEMP0=0.56D0
T0=0.6D0*10**(-5.D0)
TEMPTF=0.25D0
C El pas de temps sera arbitrariament
C petit.
C Definim gamma amb l'expressio per
C pQCD donada a la memoria del treball
DT=0.5D0*10**(-5.D0)

C------------------------------------------------------------
C-----------------------BUCLE-------------------------------
C------------------------------------------------------------

C Generem 500 punts, amb valors dels
C moments aleatoris
DO I=1,500
C Calculem un punt aleatori (X,Y) en el
C interval requerit.
C Generem punts aleatoris en un rectangle
C de costats 2R i a+R amb vertex a (0,0)
1       X=(A+R)*RAND(0)
    Y=2.D0*R*RAND(0)

C I calculem els parametres dels cercles
C dependents de (X,Y)
    CIRC1=(X-R)**2.D0+(Y-R)**2.D0
    CIRC2=(X-A)**2.D0+(Y-R)**2.D0
    R2=R**2.D0

C Si el punt pertany a la interseccio
C seguim. Si no el programa acaba (el
C quarkonium pesant mor)
    IF ((CIRC1.LT.R2).AND.(CIRC2.LT.R2))
    THEN
        CONTINUE

    ELSE
        GO TO 1

    ENDIF

C Definim la temperatura del punt, acord
C amb el model especificat a la memoria
    IF ((CIRC1.LT.RCENT2).AND.
    (CIRC2.LT.RCENT2)) THEN
        TEMPP=TEMP0

    ELSE
        TEMPP=TEMP0/5.D0

    ENDIF

C Associem un moment lineal transversal
C pT al quarkonium pesant que ha
C sobreviscut a (X,Y)
    PTU=RAND(0)
    PT=M*SQRT(PTU/(1-PTU))

C De pT, i utilitzant la expressio
C relativista del moment, treiem la
```

```
C velocitat. Escrivim tambe la
C temperatura de dissociacio:
     V=(PT)/SQRT(PT**2.D0+M**2.D0)
     TDIS=TEMPDIS(M,V)/10.D0

C Falta donar notacio vectorial a la
C velocitat
     THETA=2*PI*RAND(0)

C Iterem el temps fins poder arribar a la
C temperatura de la Transicio de Fase
     TMAX=T0*(TEMP0/TEMPTF)**3.D0
     JMAX=INT((TMAX)/DT)+1

C Introduim el valor al bucle
     DO J=0,JMAX
          T=T0+J*DT
          TEMP=TEMP0*(T0/T)**0.33D0

C Redefinim les coordenades (X,Y) del
C quarkonium,
C i comprovem si mor
          X=X+V*COS(THETA)*T
          Y=Y+V*SIN(THETA)*T

C Actualitzem la equacio de la
C circumferencia
          CIRC1=(X-R)**2.D0+(Y-R)**2.D0
          CIRC2=(X-A)**2.D0+(Y-R)**2.D0

C Definim la temperatura al nou punt
          IF ((CIRC1.LT.RCENT2).AND.
          (CIRC2.LT.RCENT2)) THEN
               TEMPP=TEMP

          ELSEIF ((CIRC1.LT.R2).AND.
          (CIRC2.LT.R2)) THEN
               TEMPP=TEMP/5.D0

          ELSE
               WRITE(1,*) PT,'1.0'
               EXIT

          ENDIF

C Calculem la decay width especificada a la
C memoria del treball i la probabilitat de
C que el quarkonium decaigui. Generem un
C nombre aleatori per veure si el fem
C decaure o no
          GAMMA=DWIDTHPQCD(TEMP,V,A0,ALPHAS)
          DECPROB=GAMMA*DT*10**(6.D0)
          GAMMAU=RAND(0)
C CONDICIONS PER SOBREVIURE TENINT (X,Y)
C AMB V(THETA) DONADA
          IF (J.EQ.JMAX) THEN
               WRITE(1,*) PT,'1.0'
               EXIT

C Si la temperatura es superior a la
C temperatura de dissociacio mor.
C Aquesta condicio la usarem per la
C AdS/CFT approach (no per pQCD)
          ELSEIF (TEMPP.GT.TDIS) THEN
               WRITE(1,*) PT,'0.0'
               EXIT

C Comparem el nombre aleatori creat amb
C la probabilitat de decaiment.
C Si es inferior mor
          ELSEIF (GAMMAU.LT.DECPROB) THEN
               WRITE(1,*) PT,'0.0'
               EXIT

C En qualsevol altre cas el quarkonium
C viu
          ELSE
               CONTINUE
          ENDIF
          ENDDO
     ENDDO

C Tanquem el document
CLOSE(1)

          END PROGRAM SUPPRESSION

C-----------------------------------------------------
C-----------------------------------------------------
C-----------DEFINICIO DE FUNCIONS---------------------
C-----------------------------------------------------
C-----------------------------------------------------

C Decay width pQCD
DOUBLE PRECISION FUNCTION
DWIDTHPQCD(TEMP,V,A0,ALPHAS)

IMPLICIT NONE
DOUBLE PRECISION TEMP,V,MD,A0,PI,ALPHAS
DOUBLE PRECISION LOGTM

C Definim la decay width per pQCD per una
C temperatura i velocitat donades. La
C possem en el SR Laboratori
PI=4.D0*ATAN(1.D0)
MD=2*PI*TEMP/SQRT(3.D0
     *LOG(2*PI*TEMP/0.25D0))
LOGTM=LOG(2.D0/(MD*A0))

DWIDTHPQCD=(8.D0/3.D0)*ALPHAS*TEMP*MD**2.D0
          *A0**2.D0*LOGTM

RETURN
END FUNCTION DWIDTHPQCD
```

```
C Decay width AdS/CFT
DOUBLE PRECISION FUNCTION
DWIDTHADS(TEMP,V,MQ)

IMPLICIT NONE
DOUBLE PRECISION TEMP,V,K,MQ,PI

C Definim la decay width per AdS/CFT per
C una temperatura, velocitat i massa de
C quark donades. La formula esta escrita
C al sistema laboratori.
PI=4.D0*ATAN(1.D0)
K=(972.D0*PI**5.D0*TEMP**4.D0)/(200*MQ**2.D0)

DWIDTHADS=K*7.6D0*10.D0**(-4.D0)
          *SQRT(1-V**2.D0)

RETURN
END FUNCTION DWIDTHADS
```

```
C Temperatura de dissociacio
DOUBLE PRECISION FUNCTION TEMPDIS(M,V)
IMPLICIT NONE
DOUBLE PRECISION M,V

C Definim la temperatura de dissociacio
C del quarkonium a M i V donades al
C sistema laboratori
TEMPDIS=2.D0*M*(ABS(1.D0-V**2.D0))**0.25D0

RETURN
END FUNCTION TEMPDIS
```

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