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HADRONIC J/ψ SUPPRESSION IN ULTRARELATIVISTIC NUCLEAR COLLISIONS†

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Abstract: One of the proposed signatures of quark-gluon plasma formation in ultrarelativistic nuclear collisions is a suppression of J/ψ production. We show that a similar reduction in the J/ψ signal can occur due to inelastic scattering of J/ψ's in a hadronic resonance gas. This collisional suppression can be substantial, provided that the hadronic densities are as large as the first CERN data suggest.

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Experiments with ultrarelativistic heavy ion beams at the CERN SPS at 200 GeV per nucleon, and at the Brookhaven AGS at 15 GeV per nucleon, are expected to produce hadronic matter at energy densities up to ~ 2 GeV fm^{-3}, perhaps a factor of ten higher than those achieved previously [1]. As these experiments explore a wider range of energies with heavier nuclei, changes that betray the novel character of matter expected at such energy densities can appear in the production of J/ψ and other heavy mesons [2-8]. The NA 38 collaboration at CERN is currently studying J/ψ production with ^{16}O and ^{32}S beams on heavy targets[9]. Matsui and Satz [2] proposed that a suppression of J/ψ formation, relative to that inferred from proton-nucleus scattering at the same energies, can be used as a signature of quark-gluon plasma production. The utility of any signature, however, depends on its uniqueness. In this paper we consider an alternate mechanism of J/ψ suppression that may forge such a signature — J/ψ absorption in a hadronic resonance gas.

We derive a simple formula for the survival probability $\mathcal{P}_H(p_\perp)$ of a J/ψ in an ultrarelativistic nuclear collision as a function of the transverse radius R_A of the projectile, and the total rapidity density of hadrons dN_H/dy. We find the average survival probability in the central region

$$\mathcal{P}_H(\vec{p}_\perp) \approx (t_{0\psi}/t_f)^\beta, \tag{1}$$

where $t_f \propto R_A$ is the last time that the J/ψ can interact, and $t_{0\psi}$ is the Lorentz-dilated J/ψ formation time. The absorption parameter β is the ratio of the absorption collision frequency to the expansion rate, and is given by

$$\beta \approx \overline{\sigma}(\pi {R_A}^2)^{-1} dN_H/dy, \tag{2}$$

in terms of the average absorption cross section $\overline{\sigma}$.

Inelastic scattering can absorb J/ψ's through a variety of channels in high-energy-density hadronic matter. If the gas is composed primarily of pions, then possible candidate reactions are $\psi\pi \to \eta_c\pi\pi$, with a threshold of 23 MeV, and $\psi\pi \to D\overline{D}$, with a threshold of ≈ 500 MeV [10], where the $\eta_c(2980)$ is a pseudoscalar $c\overline{c}$ state, and the $D(1870)$ is a $c\overline{u}$ or $c\overline{d}$ combination. In a high density hadronic gas, however, resonances such as the $\eta(549)$, $\rho(770)$, and $\omega(783)$ can constitute a large fraction of the hadronic matter. Exothermic reactions such as

$$\psi\rho \to \eta_c\pi + 750\,\text{MeV}, \tag{3a}$$

$$\psi\omega \rightarrow \eta_c\pi\pi + 620\,\mathrm{MeV}, \tag{3b}$$

$$\psi\eta \rightarrow \eta_c\pi\pi\pi + 250\,\mathrm{MeV}, \tag{3c}$$

and

$$\psi\omega \rightarrow D\overline{D} + 150\,\mathrm{MeV} \tag{3d}$$

are then possible. The cross sections for such reactions are unaffected by threshold factors and can be large, perhaps on the order of the measured[11,12,13,14] J/ψ-nucleon cross section $\sigma(\psi N) = 2.2 \pm 0.7$ mb.

In order to estimate the density of hadrons in the central region from the measured longitudinal-rapidity density dN/dy, we assume that their distribution is approximately invariant under longitudinal boosts. This approximation can apply in the central region in the interval $2 < y_{\mathrm{lab}} < 3$ for a 200 GeV per nucleon ^{16}O beam on a Au target, where the observed dN/dy is roughly independent of y [15]. Longitudinal boost invariance is manifest if we assume that matter in the central region forms at a proper time $\tau \equiv \sqrt{t^2 - z^2}$ of order $\tau_0 \sim 1$ fm, where $z = 0$ refers to the longitudinal position of the center of momentum at $y_{\mathrm{lab}} \approx 2.4$. For simplicity, we neglect the transverse motion of the system and, moreover, take the density n to be uniform in the transverse coordinate, so that [16]

$$dN_H/dy = \pi {R_A}^2 n(\tau_0)\tau_0. \tag{4}$$

If we take dN_H/dy to be three times the multiplicity of negative particles $dN_-/dy \sim 41$ observed at $y_{\mathrm{lab}} \sim 2.5$ in central ^{16}O + Au collisions by the NA 35 collaboration, then we find $n(\tau_0) \sim 4\ \mathrm{fm}^{-3}$, for $\tau_0 \sim 1$ fm and $R_A \approx 3.0$ fm. The large NA 35 multiplicity is consistent with the WA 80 and NA 34 results.

Proton-proton scattering experiments[17] suggest that resonances constitute a large fraction of the hadron gas. To estimate the initial density properly, we must correct (4) for the multi-pion decays of these resonances. We estimate the fraction of resonances in the system using the LUND FRITIOF/JETSET6.3 string fragmentation model[18], which successfully reproduces many features of the preliminary CERN data [15]. In a 200 GeV per nucleon reaction, the composition of the produced hadrons is

$$f_\pi \approx 0.25,\ f_{\eta+\eta'} \approx 0.07\ f_\rho \approx 0.21,\ f_\omega \approx 0.07,\ f_N \approx 0.15,\ f_{K+K^*} \approx 0.15, \cdots . \tag{5}$$

The measured pion rapidity density dN_π/dy is related to the total hadron rapidity density by

$$\frac{dN_H}{dy} \approx \frac{f_\pi + f_{\eta+\eta'} + f_\rho + f_\omega}{f_\pi + 2(f_{\eta+\eta'} + f_\rho) + 3f_\omega} \frac{dN_\pi}{dy} \approx 0.6 \frac{dN_\pi}{dy} \ , \tag{6}$$

where the factors of 2 and 3 in the denominator are the decay multiplicities into pions. The initial hadron density in this model is then reduced by a factor ~ 2 from the earlier estimate. A hadronic density $\sim 2 - 4$ fm^{-3} is quite large, since the hadrons would overlap. While matter in local equilibrium at such densities should be in a QCD mixed phase, or possibly even a plasma phase, we must nevertheless explore alternative possibilities, particularly in view of the non-equilibrium nature of matter produced in a collision. To identify a set of signals with quark matter formation, any hadronic counterfeiting must be ruled out. Our results indicate that J/ψ suppression is a generic feature of dense matter formation, and is not specific to plasma formation.

The familiar result (4) strictly describes the rapidity distribution in a central collision in which the decrease of density with proper time follows

$$n(\tau) = n(\tau_0)\tau_0/\tau, \tag{7}$$

so that the number of hadrons in a given rapidity interval $\propto n(\tau)\tau$ remains fixed as the system evolves from τ_0 to the proper time τ_F, where interactions effectively cease. The number $\Delta N = (dN/dy)\Delta y$ is roughly constant in the hydrodynamic expansion of a fluid dominated by particles of masses that are small compared with the temperature, since then ΔN is proportional to the entropy ΔS, which is conserved (except for viscous entropy generation, which is small near local equilibrium). The approximation $\Delta N \propto \Delta S$ is also applicable in a resonance-rich hadron gas that is not too near the deconfinement temperature [19]. A hydrodynamic description is relevant for the light mesons (although not for the J/ψ's) at the large density implied by the CERN experiments, since the mean free path for elastic meson-meson scattering, roughly $\lambda \sim (n\sigma_{\rm el})^{-1} < 0.3$ fm for a characteristic cross section $\sigma_{\rm el} \sim 20$ mb, is much smaller than R_A or τ_0. We emphasize, however, that (7) holds over a wider range of conditions, e.g., when interactions are completely absent, and follows mainly from the one-dimensional character of boost-invariant expansion.

We surmise that hadron-J/ψ scattering is dominated by absorptive processes, with a characteristic cross section of order one to two millibarns, from the information on J/ψ-nucleon scattering obtained in photoproduction experiments [11,12,13,14]. The EMC collaboration [13] found a total cross section of $\sigma_{\psi N} = 2.2 \pm 0.7$ mb, and in addition, determined the J/ψ-nucleon inclusive cross section $\sigma_{\psi N \to \psi X} = 79 \pm 12\,\mu$b. Reactions that do not absorb the J/ψ's account for only a small fraction, $\sim 3-4\%$, of the total J/ψ-N cross section. We estimate the J/ψ absorption cross section, averaged over all possible initial and final states, as

$$\overline{\sigma} \approx (2/3)\sigma_{\psi N} \approx 1 - 2\,\text{mb}, \tag{8}$$

and neglect reactions of the form $\psi X \to \psi Y$, which do not deplete the J/ψ (i.e. dimuon) yield. Threshold effects, which tend to reduce the effective cross section, are discussed by Vogt *et al.* for the case of J/ψ's in a gas of pions and nucleons [20]. To properly account for threshold and resonant-scattering effects in a resonance gas, one must replace (8) with an average over the experimentally-unknown partial cross sections for each of the plethora of possible reactions such as $\pi\psi \to X$ and $\rho\psi \to X$, together with the appropriate threshold for each final state X. In the light of the exothermic reactions (3a-d), (8) may be an *under*estimate.

We illustrate how the hadronic suppression in a central collision varies with the overall dN/dy, and with the transverse momentum $p_\perp$ of the J/ψ, by estimating the probability that a J/ψ formed on the central slice with $y = 0$ escapes absorption by the expanding hadronic medium. We assume that the J/ψ's form primarily in the hard N-N scatterings that occur as the nuclei first strike one another, and neglect additional sources of J/ψ's such as the decay of heavier resonances. First we calculate the probability $P(\vec{p}_\perp, \vec{r}_{\perp 0})$ that a J/ψ formed at a time $t_{0\psi}$ due to a hard collision at a transverse position $\vec{r}_{\perp 0}$, survives for a time t_f, and then obtain the total survival probability by averaging over $|\vec{r}_{\perp 0}| \leq R_A$. We write

$$P(\vec{p}_\perp, \vec{r}_{\perp 0}) = \mathrm{e}^{-\mathcal{N}} \tag{9}$$

in terms of the mean number of collisions

$$\mathcal{N}(\vec{p}_\perp, \vec{r}_{\perp 0}) \equiv \int_{t_{0\psi}}^{t_f} \nu(\vec{p}_\perp, \vec{r}_\perp(t), t) dt, \tag{10}$$

where $\vec{r}_\perp(t)$ is the J/ψ's trajectory, and we assume that each collision leads to absorption. The collision frequency $\nu = n\langle\sigma v_{\rm rel}\rangle \approx \overline{\sigma} v_{\rm rel} n$, where $\overline{\sigma}$ is the momentum-independent cross section given by (8), and $v_{\rm rel}$ is the average meson-J/ψ relative velocity. On the central slice, ν varies with time through the total hadron density n, and is approximately uniform for transverse positions $\leq R_A$. Therefore,

$$\mathcal{N}(\vec{p}_\perp, \vec{r}_{\perp 0}) \approx \overline{\sigma} v_{\rm rel} \int_{t_{0\psi}}^{t_f} n(t) dt = \beta \log(t_f / t_{0\psi}), \tag{11}$$

where we have used (7), and defined the absorption parameter

$$\beta \equiv \overline{\sigma} v_{\rm rel} t_0 n(t_0), \tag{12}$$

and have taken $v_{\rm rel}$ to be constant, for reasons discussed below. We see that the absorption parameter is the ratio of the collision frequency ν to the expansion rate $n^{-1} \,|dn/dt| \sim t^{-1}$.

The probability P depends on the initial transverse position $\vec{r}_{\perp 0}$ through the time t_f at which the J/ψ escapes the medium. The average time needed for a high-$p_\perp$ particle of transverse velocity $v_\perp = p_\perp / m_\perp$ to escape the collision volume is $\langle t_f \rangle = {v_\perp}^{-1} \langle ({R_A}^2 - {r_{\perp 0}}^2 + (\vec{r}_{\perp 0} \cdot \vec{v}_\perp / v_\perp)^2)^{1/2} \rangle = (8/3\pi) m_\perp R_A / p_\perp \approx m_\perp R_A / p_\perp$, where we have averaged over $\vec{r}_{\perp 0}$. On the other hand, a low-$p_\perp$ J/ψ will remain in the gas until freezeout at time τ_F. We conclude that

$$\langle t_f \rangle \approx \begin{cases} \tau_F & \text{for } p_\perp < (p_\perp)_{\rm min}; \\ m_\perp R_A / p_\perp & \text{for } p_\perp > (p_\perp)_{\rm min}, \end{cases} \tag{13}$$

since particles of $p_\perp$ up to

$$(p_\perp)_{\rm min} = M (R_A / \tau_F) \{1 - (R_A / \tau_F)^2\}^{-1/2} \tag{14}$$

remain in the central region until freezeout. We find the average survival probability

$$\mathcal{P}_H(\vec{p}_\perp) \equiv \langle P(\vec{p}_\perp, \vec{r}_\perp) \rangle \approx (t_{0\psi} / \langle t_f \rangle)^\beta, \tag{15}$$

where $\langle t_f \rangle$ is given by (13) (cf. eq. (1)). We find the same result by solving a Boltzmann equation for the phase-space distribution of J/ψ's.

We estimate the formation time by assuming that all J/ψ's form at a fixed proper time $\tau_{0\psi}$, so that a particle of momentum $p_\perp$ will appear on the central slice at a time

$$t_{0\psi} = \tau_{0\psi}\sqrt{(p_\perp/M)^2 + 1}. \tag{16}$$

[Karsch and Petronzio [5], and Blaizot and Ollitrault [6] apply a similar time dilation argument to describe the dissociation of $c\bar{c}$ pairs in a plasma.] As a consequence of (16), a J/ψ of a $p_\perp$ beyond a value $(p_\perp)_{\max}$ must form at a transverse position outside the collision volume. Such a particle has no opportunity to scatter and be absorbed, so that $\mathcal{P}_H(p_\perp > (p_\perp)_{\max}) \equiv 1$. This maximum $p_\perp$,

$$(p_\perp)_{\max} = MR_A/\tau_{0\psi}, \tag{17}$$

is determined by the condition $R_A \sim p_\perp t_{0\psi}/m_\perp$ at $y = 0$.

In fig. 1, we show $\mathcal{P}_H(p_\perp)$ for values of the parameters discussed presently, for 200 GeV per nucleon ^{16}O + U and ^{32}S + U collisions. The absorption due to J/ψ-hadron scattering becomes less effective for increasing $p_\perp$, as is reflected in the increase of $\mathcal{P}_H$ from the zero-$p_\perp$ value of $(\tau_{0\psi}/\tau_F)^\beta$, to unity. In a quark-gluon plasma, the J/ψ suppression should take on a similar transverse-momentum dependence [5,6,7], since for a J/ψ to survive either medium, it must escape before it is absorbed — escape is more likely for a J/ψ (or $c\bar{c}$ pair) of higher transverse momentum.

The absorption parameter β depends on $\overline{\sigma}$, $v_{\rm rel}$, and the product $n(t_0)t_0$, where $n(t_0)$ is the total hadron density produced initially at $z = 0$. We extract $n(t_0)t_0 \equiv n(\tau_0)\tau_0$ from (4), to find

$$\beta = \overline{\sigma} v_{\rm rel}\tau_0 n(\tau_0) = \overline{\sigma} v_{\rm rel}\,(\pi {R_A}^2)^{-1} dN/dy, \tag{18}$$

where we emphasize that dN/dy is the *total* hadron multiplicity. To estimate the relative velocity, we assume that J/ψ's are removed primarily by ρ and ω scattering through the strongly exothermic reactions (3a) and (3b)(cf. also eq. (5)). If we take the ρ's and ω's to have a $\langle p_\perp\rangle \approx 0.5$ GeV, then $v_{\rm rel} \approx 0.6$. By including the pions in this estimate, we increase $v_{\rm rel}$. We take $(\pi {R_A}^2)^{-1} dN/dy \approx 4.3$, for $dN/dy \approx (1.5-3)dN_-/dy \approx 60-120$, and $R_A = 1.2A^{1/3}$ fm, using the NA 35 results for ^{16}O + Au. In an $A-B$ collision, the ratio $A^{-2/3}dN/dy \propto B^{1/3}$, since most of the particle production occurs in soft processes, so that

$$\beta \approx (0.13-0.26)\,(\overline{\sigma}/1\,\text{mb})\,(B/197)^{1/3}, \tag{19}$$

where $\overline{\sigma}$ is given by (8). The absorption parameter is practically independent of A when $A \ll B$.

The survival probability tends to unity at $(p_\perp)_{\max} = MR_A/\tau_{0\psi}$, which is ~ 9 GeV for a 200 MeV per nucleon ^{16}O beam on a U target, assuming that $\tau_{0\psi} \sim \tau_0 \sim 1$ fm. We expect the freezeout time τ_F to be $\sim R_A/c_s$, where c_s is the sound speed of the hadron gas [21]. The preliminary results of cascade simulations are consistent with the scaling of τ_F with R_A. We take $c_s \approx 1/\sqrt{3} \approx 0.58$, as applies for a gas massless particles, although the sound speed in an interacting resonance gas can be somewhat smaller, roughly 0.45 [22]. We find

$$\mathcal{P}_H = (c_s t_{0\psi}/R_A)^\beta \approx (0.19)^\beta (A/16)^{-\beta/3}\{1 + (p_\perp/M)^2\}^{\beta/2}, \tag{20}$$

for $p_\perp < (p_\perp)_{\min}$, which is $\approx Mc_s/\sqrt{1-c_s{}^2} \sim 2.2$ GeV, for $c_s \sim 0.58$. Decreasing the sound speed to 0.45 reduces the probability at zero momentum by about 15%. In fig. 1, we show the A-dependence of (20) by comparing the suppression in ^{16}O + U to that in ^{32}S + U. We find that the relative survival probability for $p_\perp \approx 0$ is $\mathcal{P}_H[^{32}\mathrm{S}]/\mathcal{P}_H[^{16}\mathrm{O}] \approx 0.88 - 0.97$ for β in the range from $\beta \sim 0.14 - 0.55$, while $\mathcal{P}_H[^{208}\mathrm{Pb}]/\mathcal{P}_H[^{16}\mathrm{O}] \approx 0.63 - 0.89$. In a quark-gluon plasma, one expects the suppression of low-$p_\perp$ J/ψ's to be roughly A-independent, since the dimensionless parameter that controls the plasma survival probability at small momenta is proportional to $(\pi(R_A)^2)^{-1}dN/dy$, which is roughly independent of A [6].

The large overall suppression evident in fig. 1 owes primarily to our estimate of the initial density taken from the NA 35 data. We expect the hadron gas to be initially resonance rich, as is consistent with the observation that up to 70% of the pions produced in $p-p$ collisions above $\sqrt{s} \sim 10$ GeV come from the decays of resonances (cf. eqs. (5) and (6)). The resulting ambiguity in the initial hadronic density is incorporated in (19) within the factor-of-two uncertainty. This ambiguity, together with the uncertainties in $\overline{\sigma}$ and $v_{\rm rel}$, result in the factor-of-four uncertainty in the absorption parameter illustrated by the shaded region in fig. 1. Preliminary NA 38 results suggest a suppression of $\sim 30\%$, which falls in this range. To reduce the present uncertainties we require a much better knowledge of the hadronic physics, which includes cross sections for processes such as (3), the composition of the resonance gas (5), and its spacetime evolution (7).

We have shown that within present uncertanties, hadronic final state interactions can lead to a substantial suppression of J/ψ production in nuclear collisions, with a similar $p_\perp$ dependence to that expected assuming plasma formation. The burden of proof has therefore shifted to *systematic* studies of J/ψ suppression, together with other observables[1], in order to demonstrate the existence of quark-gluon plasma. To disentangle plasma-induced from collisional suppression, one must study how the suppression changes as a function of target and projectile masses, and beam energy.

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[Note added in proof: After completion of this work, a Bratislava preprint by J. Ftáčnik, P. Lichard, and J. Pišút was brought to our attention by G. Roche. In that paper, only $\psi\pi \rightarrow D\overline{D}$ processes are considered, and the effects of expansion are neglected.]

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Figure Captions

1. The survival probability of a J/ψ, is shown for central ^{16}O + U (solid curves), and for ^{32}S + U (dashed curves) at 200 GeV per nucleon. The shaded region indicates the uncertainty in the oxygen result that arises from the uncertainty in $\beta \sim 0.14 - 0.55$, and is bounded below by the $\beta = 0.55$ curve. The lower dashed line is the sulphur prediction for $\beta = 0.55$, and should be compared to the lower solid curve. The transition between low- and high-$p_\perp$ behavior occurs at $(p_\perp)_{\rm min}$, which is given by (14).

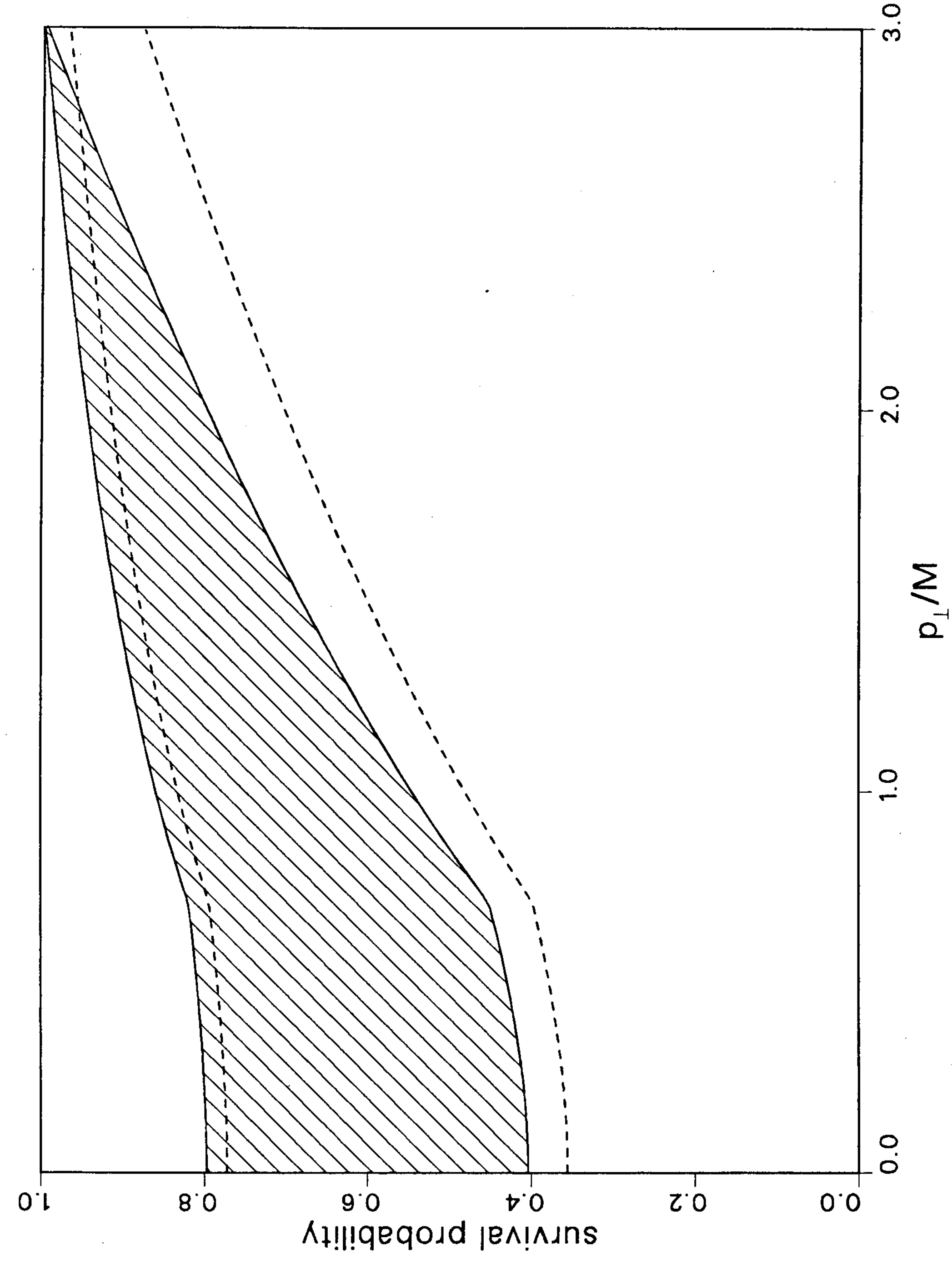

Fig. 1

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