CONF-901116--20

BNL-45257

Strong Field Effects and the Luminosity Lifetime of a Heavy–Ion Collider.*

M.J. Rhoades–Brown

Brookhaven National Laboratory, Upton, New York 11973, USA

BNL--45257

DE91 001720

Abstract

The Relativistic Heavy Ion Collider (RHIC) will accelerate fully stripped ions to beam kinetic energies of 250 (Z/A) GeV/u. For the heaviest nuclei, i.e., $^{179}Au^{79+}$, 10^9 ions per bunch will circulate in 57 bunches at a kinetic energy of 100 GeV/u. During bunch crossing, the peripheral interactions of the heavy ions generate a sufficiently large electromagnetic field that spontaneous e^+, e^-pair creations will occur. Up to 10^7 pairs per second are expected at RHIC luminosity values ($2 \times 10^{26} cm^{-2} sec^{-1}$). In addition, a produced electron may be captured by a heavy ion, thus strongly effecting the luminosity lifetime of a heavy ion collider.

* Work performed under the auspices of the U.S. Department of Energy. Invited paper at the 11th International Conference on the Application of Accelerators in Research and Industry, Denton, Texas, Nov. 5–8, 1990.

I. Introduction

By the spring of 1997, experiments will be performed using ultra- relativistic heavy ions in a collider mode. At the Brookhaven National Laboratory (BNL), the Relativistic Heavy Ion Collider (RHIC)[1] will accelerate fully stripped heavy ions to beam kinetic energies of 250 (Z/A) GeV/u. For the heaviest nuclei, i.e. $^{179}Au^{79+}$, 10^9 ions per bunch will circulate in 57 bunches at kinetic energies of 100 GeV/u. The beams will collide in up to six intersection regions at RHIC. Mainly because of detector stability, it is required that the beam at RHIC exist for several hours. For $^{179}Au^{79+}$ beams at 100 GeV/u, it is desired the beams exist in a collider mode for up to 10 hours with an average luminosity L value of $2 \times 10^{26} cm^{-2} sec^{-1}$[1].

Almost all the experimental users of the RHIC facility are interested in so-called central collisions of the heavy ions. These collisions are expected to form a new and exotic form of matter, known as a quark-gluon plasma. The cross section for this central collision is approximately 7 barns for $^{179}Au^{79+}$ ions. In addition to the central collisions, there are several new processes associated with the long-range or peripheral electromagnetic interactions of ultra-relativistic heavy ions [2]. These processes play a direct role on the overall performance of the collider, and are important considerations for detector designs.[3] At increasing relativistic energies, the electromagnetic field associated with the fully stripped heavy-ions becomes sharply peaked in a direction transverse to the heavy ion motion. Under these conditions, the electromagnetic interaction between the ions is sufficiently strong to induce copious amounts of electron- -positron pairs as the bunches cross. For comparison with the cross section for central collisions, the peripheral reaction cross section σ_c, for producing e^+, e^-pairs with $^{179}Au^{79+}$ ions at 100 GeV/u, has been reliably calculated to be $\sigma_c = 33,000$ barns[4]. Thus, using the expected luminosity value L at RHIC, it is easily estimated that up to $\sim 10^7$ pairs per second will be produced from the peripheral interaction alone. These pairs have to be considered in any detector design at a relativistic heavy ion collider[3].

In addition to the pair production, it is possible that a produced electron can be captured by a heavy ion in an atomic orbital[2,5]. This bound electron changes the charge state of the ion, and the ion is eventually lost from the beam. It is this mechanism that plays a major role in determining the luminosity lifetime of the heavy ion beam, and is something quite unique to heavy ions for the cross section of this process scales as $\sim Z^{6,7}$, where Z is the atomic number of the ion[5]. It is noted that there has already been a preliminary experimental study of both pair production and capture at CERN[6], and another experiment is planned with $^{179}Au^{79+}$ beams at Brookhaven's Alternating Gradient Synchrotron (AGS)[7]. So far there have been no definitive experimental measurements of this kind of capture process.

While it is possible to electromagnetically excite an internal resonance of a heavy ion[8], the mechanisms described above completely dominate the picture for the more interesting very heavy ions. In section 2, the momentum and geometrical distributions of the pairs are shown. In section 3, the capture problem is addressed together with its effect on the luminosity lifetime of a heavy ion collider. It is noted here that the perturbative capture cross section increases as a logarithm of the Lorentz γ of the beam, and thus will be important in estimating the optimum machine operation at other proposed heavy ion colliders, such as the Large Hadron Collider (LHC) at CERN.

II. e^+, e^- Pair Production

Working in natural units ($\hbar$ = c = m = e = 1), and assuming a geometry in the cm or collider frame the pair production cross section in the first order perturbative limit is given by Bottcher and Strayer as [4],

$$\sigma_c = \frac{1}{(2\beta)^2} \sum_{\sigma_K, \sigma_q} \int \frac{d^3k\ d^3q\ d^2p_\perp}{(2\pi)^8} \mid A^{(+)}(k,\ q;\ \vec{p}_\perp)\ +\ A^{(-)}\left(k,\ q;\ \vec{k}_\perp + \vec{q}_\perp - \vec{p}_\perp\right) \mid^2 \quad (1)$$

where $\vec{q}$, $\vec{k}$ are the momenta of the positron and electron in the final state, $\vec{p}$ is the intermediate momenta, σ_q, σ_k run over spins of the positron and electron. The label k is short for quantum numbers $\vec{k}$, σ_k, S_k where $S_k = \pm 1$ for positive and negative energy states. The amplitude $A^{(+)}(k, q; \vec{p}_\perp)$ is expressed as a product,

$$A^{(+)}\ (k,q;\vec{p}_\perp) = F\,(k_\perp - p_\perp : \omega_a)\ F\,(q_\perp - p_\perp : \omega_b)\ T_{KQ}\,(p_\perp : \beta) \quad , \qquad (2)$$

where F is the scalar part of the field associated with a heavy ion,

$$F(u:\omega) = \frac{4\pi\ Z}{u^2 + (\omega/\beta\gamma)^2} \tag{3}$$

and ω_a, ω_b are the frequencies associated with the field of ions a and b. The amplitude T_{KQ} relates intermediate photon lines to outgoing fermion lines [4]. Monte Carlo evaluation of equation (1) gives the result $\sigma_c = 33{,}000$ barns for $^{179}Au^{79+}$ beams at $\gamma = 108$ (100 GeV/u). An evaluation of σ_c using an analytic formula due to Racah [9] gives essentially the same magnitude. As stated in the introduction, we may expect $\sim 10^7$ pairs/sec for $^{179}Au^{79+}$ beams at top RHIC energies with a machine luminosity value of 2×10^{26} cm^{-2} sec^{-1}.

Figure (1) shows the all important $dN/dp_\perp$ as a function of $p_\perp$ in GeV (velocity of light c put equal to 1), where N is the number of pairs per second. For the pair curve, $p_\perp$ is the perpendicular projection (relative to beam direction) of the total momentum of the produced e^+, e^-pair. For the singles, $p_\perp$ is the perpendicular projection (relative to beam direction) of a single lepton momentum value. The nuclear form factor used throughout this manuscript corresponds to a Fourier transform of a radial Woods–Saxon density distribution, that was fitted to electron scattering data.

Figure (1) also shows how soft the produced electrons are. As $p_\perp$ increases from 0 to 100 MeV, $dN/dp_\perp$ falls nearly six orders of magnitude for the pairs calculated including a nuclear form factor. In spite of the general rapid fall of in $dN/dp_\perp$, <u>some care must be taken with any detector design</u> for the absolute value of $dN/dp_\perp$ is still of considerable magnitude.

In Fig. (2), the differential cross sections $dN/dp_\parallel$ are plotted as a function of the longitudinal momentum $p_\parallel$. Once again for the pairs, $p_\parallel$ is the longitudinal projection (along the beam direction) of the total e^+, e^-pair momentum, and for the singles $p_\parallel$ is the longitudinal projection of a single lepton. The nuclear form factor has been included in the calculations, but is of negligible importance for this variable. Of course, the curves are symmetric around $p_\parallel = 0$ for this variable.

While there are a tremendous number of e^+, e^-pairs produced by heavy ion beam crossing, reliable estimates show very clearly [2] that production of the pairs has essentially negligible impact on the overall energy of the beam. The pairs are produced with very low momenta on average, as seen in Figs. (1) and (2), and are mostly in a direction along the beam direction[3].

III. Electron Capture in Heavy Ion Colliders

The cross section for electron capture in the perturbative limit is obtained from eqs. (1) – (3) by convoluting the amplitude into the momentum representation of the bound state wave- -function $\Phi_T(s_k,\ k)$. Most of the capture is into the K- -shell ($1s_{1/2}$ state), for which Φ_T is independent of the usual Dirac hydrogenic quantum numbers σ_T and m_T. In this way, our expression for the capture cross section derived from (1) becomes[5]

$$\sigma_{\text{cap}} = \frac{1}{(2\beta)^2} \sum_{\sigma_q} \int \frac{d^3q d^2p_\perp}{(2\pi)^5} \times \mid \sum_{s_k} \int \frac{d^3k}{(2\pi)^3} \tilde{\Phi}_T \left(s_k, \vec{k}\right) B\left(k, q; \vec{p}_\perp\right) \mid^2 \quad , \tag{4}$$

where $s_q = -1$, $s_k = \pm$, $\sigma_q = \pm$ and $\sigma_k = \sigma_T$. The bound state wavefunction $\tilde{\Phi}(s_k, \mathbf{k})$ is expressed here in the collider frame, and is reexpressed in terms of Φ_T by a Lorentz transformation[5]. We shall evaluate (4) by Monte Carlo methods[5].

In Fig. 3, the capture cross section is plotted for Au + Au collision as a function of the collider energy. The scale of the cross section is given by $\sigma_0 = \left(\gamma Z_a Z_b \alpha^2\right)^2$ where γ is the Compton wavelength of the electron, and α is the fine structure constant. The value of σ_0 for Au + Au is 164.7 b. Fig. 3 shows three calculations: the full Monte Carlo evaluation of (4), an approximate Monte Carlo calculation assuming the electron and ion have the same velocity, and a Weizsäcker–Williams approximate calculation from Bauer and Bertulani[10]. The error bars reflect the remaining statistical errors in the Monte Carlo evaluation of the integral. The Weizsäcker–Williams curve is consistently lower than the Monte Carlo method by a factor of 3.

From the perspective of RHIC accelerator performance, at the top RHIC energy for Au, the perturbative capture cross section is 72 b per beam.

In Fig. 4, the capture cross sections are shown for a sample of symmetric heavy-ion collisions used in the design of RHIC. The results are scaled with $\lambda^2 = 1.49kb$. As can be seen from this figure, the capture process scales dramatically with the atomic number Z of the ion. Very few heavy ions would be lost to this mechanism for A$\leq$ 100. The perturbative calculation discussed here corresponds to a beam loss of 0.032/hour for ^{197}Au in RHIC. This is acceptable over a proposed ten hour beam lifetime with six intersection regions.

The increase of the capture cross section with beam energy is also seen from Figs. (3)–(4). This increase is easily understood on realizing the perturbative pair production cross section itself increases as $(ln(\gamma))^3$[4], where γ is the Lorentz gamma of the beam. As γ increases, there are simply more electrons to capture. Calculations show the perturbative capture cross section increases approximately as $ln\gamma$[5].

IV. Discussion

In this paper we have investigated the unique strong electromagnetic field phenomena present at a relativistic heavy ion collider. For detector design, the important background question is the nature of the e^+, e^-particles produced by beam crossing. Figures (1) and (2) show most of these particles are soft, or have relatively low momentum. Further calculations have shown most of these particles travel in the beam direction. There should be relatively little problem in distinguishing these soft pairs from the hard ones produced in the plasma. However, some care should be taken to ensure the pairs do not spiral and accumulate into the electronics of any detector.

The ultimate luminosity performance of RHIC will be strongly influenced by the capture mechanism of a produced electron into an atomic orbital. The perturbative calculations shown here are harmonious with a desired ten hour beam lifetime, but further theoretical studies of higher order perturbation terms, are needed[11,12]. These, together with experimental measurements, are required to produce a definitive answer to the capture problem.

The proposal to inject heavy ions into the LHC, or even the possibility of heavy ions in the SSC, requires a detailed understanding of the capture mechanism in order to ensure an ultimate machine performance.

References

[1] Conceptual Design of the Relativistic Heavy Ion Collider RHIC, May 1989, BNL 52195.

[2] "Can RHIC be used to test Q.E.D.?", Workshop at Brookhaven National Laboratory, Upton, New York 11973, April 20- -21, 1990, M. Fatyga, M.J. Rhoades-Brown, M. Tannenbaum, editors, BNL52247.

[3] M.J. Rhoades-Brown, T. Ludlam, J. Wu, C. Bottcher, M. Strayer, Invited talk at the Fourth Workshop on Experiments and Detectors for RHIC, Brookhaven National Laboratory, Upton, New York, 11973, July 2–7, 1990, M. Fatyga and B. Moskowitz, editors, in press.

[4] C. Bottcher and M.R. Strayer, Phys. Rev. D39, 1330 (1989).

[5] M.J. Rhoades-Brown, C. Bottcher, M. Strayer, Phys. Rev. A40, 2831 (1989).

[6] S. Datz, et al., Measurements of pair production and electron capture from the continuum in heavy particle collisions, proposal to CERN SPS, 1989.

[7] H. Gould, et al., Letter of Intent submitted to AGS program committee, 1990.

[8] M.J. Rhoades-Brown, C. Bottcher, M. Strayer, Nuclear Instruments and Methods B43, 301 (1989).

[9] G. Racah, Nuovo Cimento 14, 70 (1937).

[10] G. Baur and C. Bertulani, Phys. Rev. 163, 299 (1988).

[11] M.J. Rhoades-Brown and J. Weneser, to be published.

[12] K. Momberger, N. Grun and W. Scheid, Preprint, University of Giessen, August 1990.

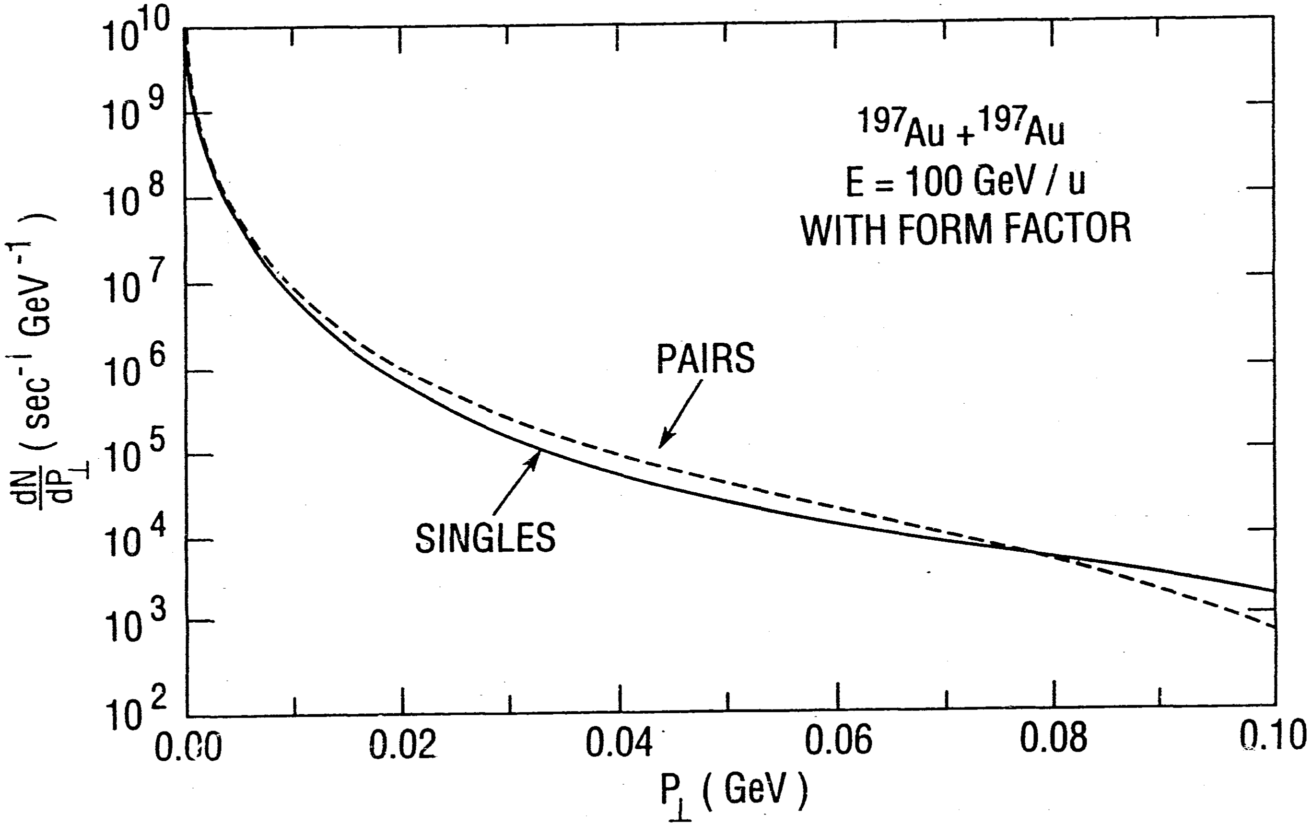
Figure Captions

Fig. 1 Comparison of $dN/dp_\perp$ as function of $p_\perp$, for both pairs and singles, with a nuclear form factor.

Fig. 2 Plot of $dN/dp_{||}$ as function of $p_{||}$, for both pairs and singles, with nuclear form factor.

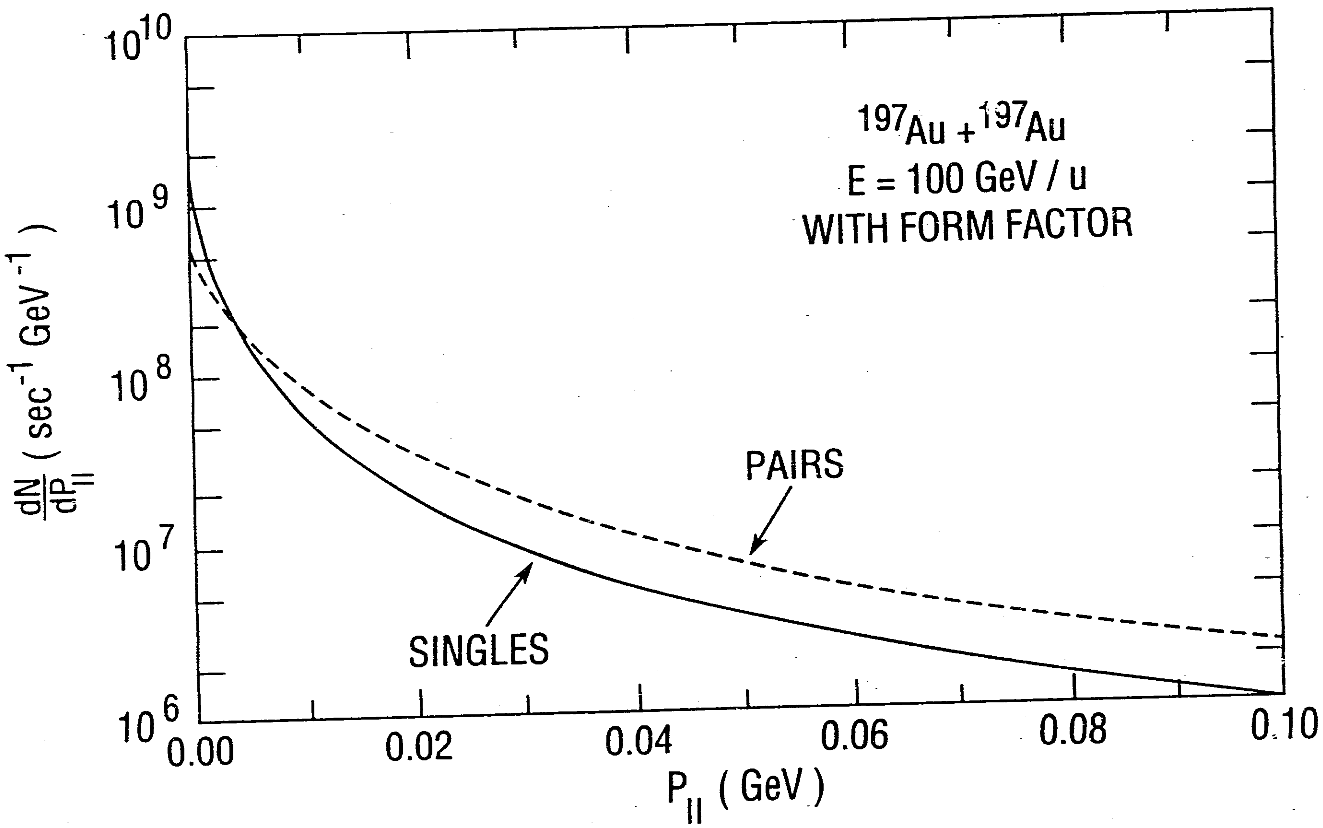
Fig. 3 Scaled capture cross section for Au + Au. The scaling factor σ_o = 164.7b. Full line and dashed line are Monte Carlo calculations described in text. Chain dashed line is the Weizsächer–Williams approximation method.

Fig. 4 Capture cross section for symmetric $A_z + A_z$ collisions.



197Au + 197Au
E = 100 GeV / u
WITH FORM FACTOR
PAIRS
SINGLES
dN/dP⊥ (sec-1 GeV-1)
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
0.00
0.02
0.04
0.06
0.08
0.10
P⊥ (GeV)

Fig. 1



197Au + 197Au
E = 100 GeV / u
WITH FORM FACTOR
PAIRS
SINGLES
10^10
10^9
10^8
10^7
10^6
dN/dP|| (sec^-1 GeV^-1)
0.00
0.02
0.04
0.06
0.08
0.10
P|| (GeV)

Fig. 2

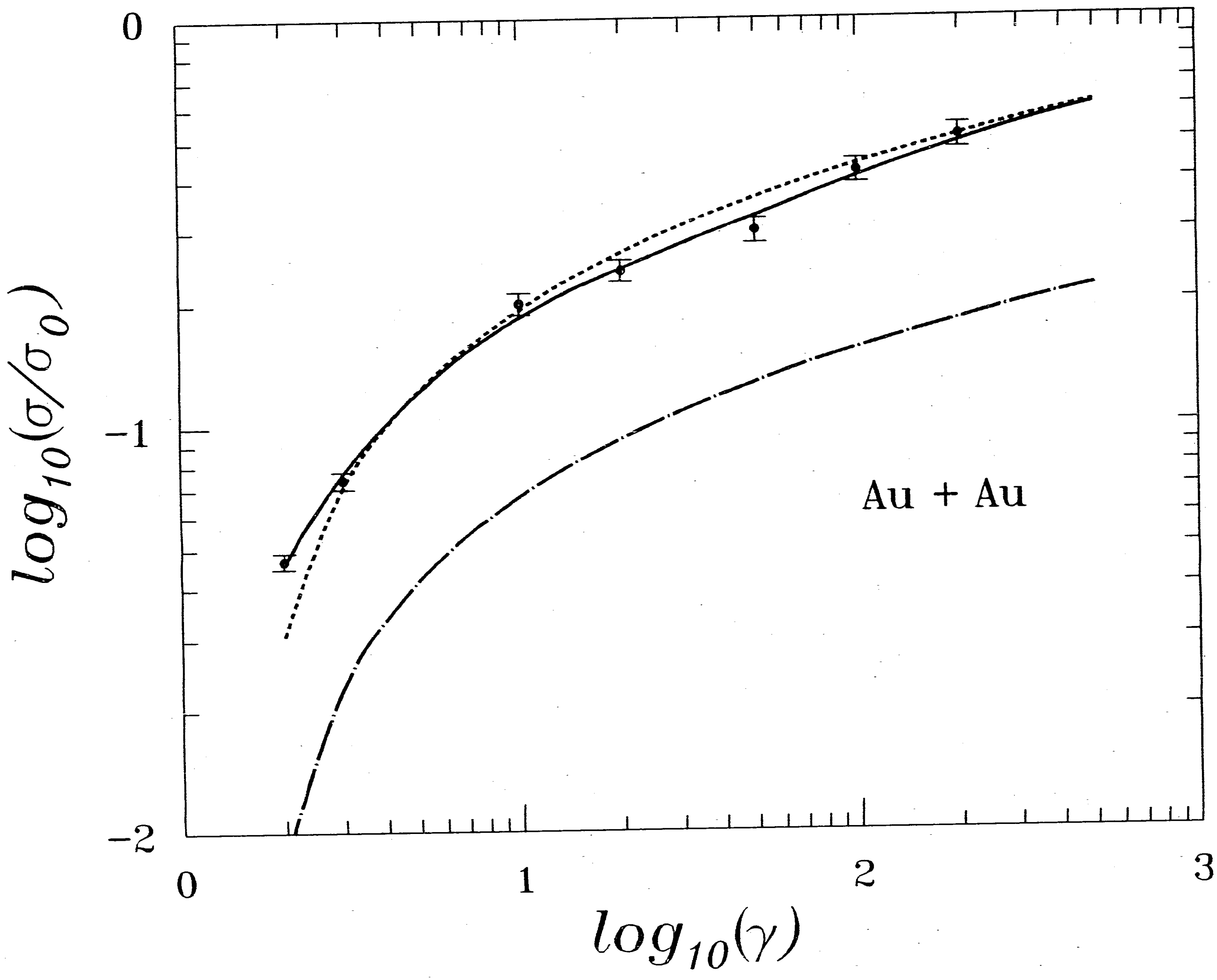


Fig. 3

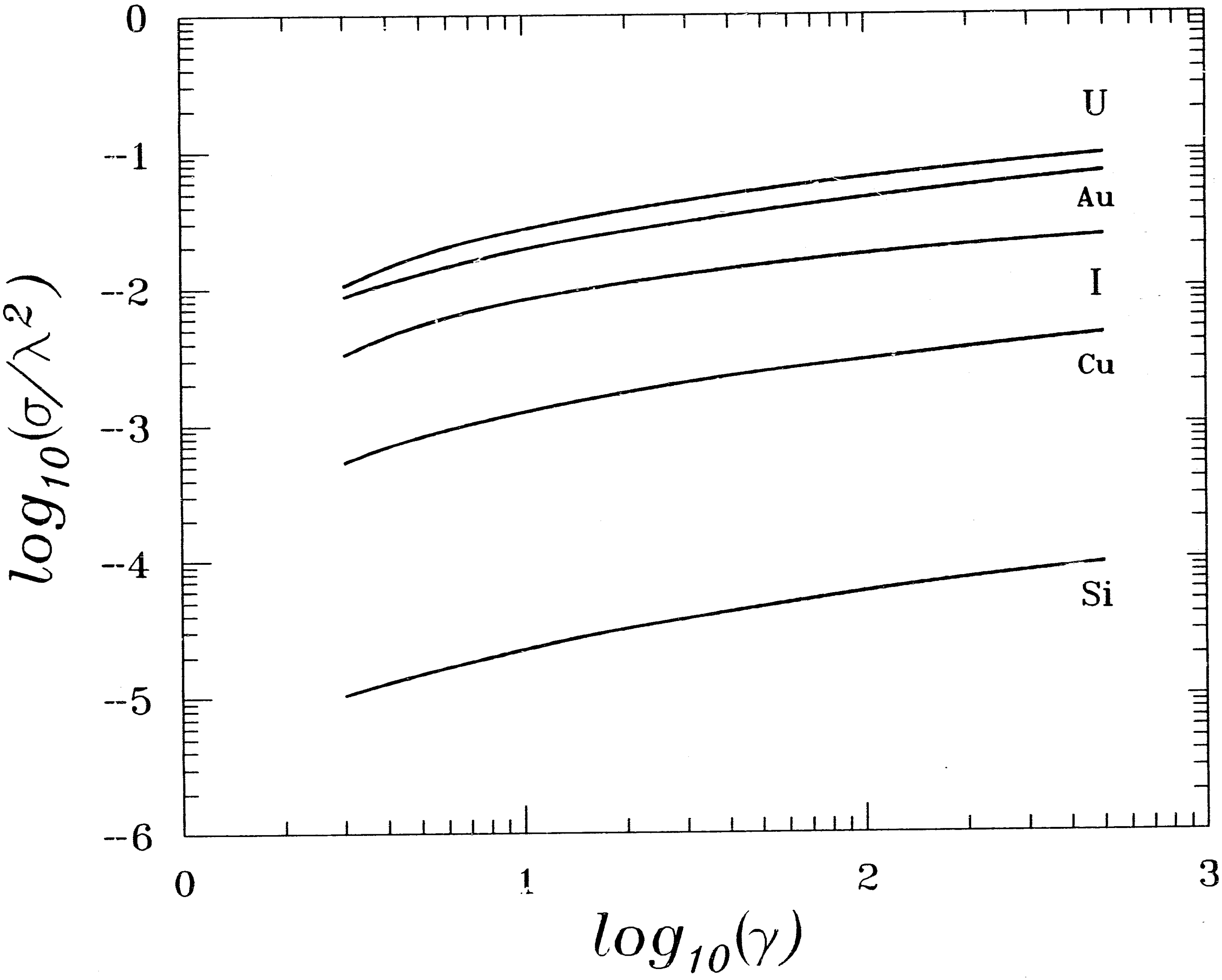


Fig. 4

END

DATE FILMED

11 / 16 / 90