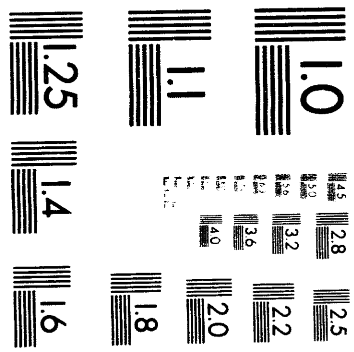

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DOE/ER/40764-1

THEORY OF ULTRA DENSE MATTER AND THE DYNAMICS OF HIGH ENERGY INTERACTIONS INVOLVING NUCLEI

Progress Report
for Period December 15, 1992 - December 14, 1993

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DISCLAIMER

1 Technical Progress

This report summarizes progress made on the research proposed under DOE agreement DE-FG02-93ER40764 from Dec 15,1992 to the present. The PI joined the faculty of Columbia University to initiate theoretical research and graduate student training in the field of nuclear physics with initial emphasis on the following topics:

1. pQCD radiative processes in dense matter,
2. non-perturbative models of deconfinement and chiral symmetry restoration,
3. QCD transport theories to describe the evolution of non-equilibrium phenomena in dense matter,
4. the development and testing of phenomenological models of high energy nuclear collisions,
5. the analysis of high energy hadron-nucleus data to constrain models of initial and final state interactions in cold nuclear matter,
6. the study of deep-inelastic lepton nucleus hadroproduction to test jet quenching and related formation zone physics,
7. the formulation of neurocomputing theory utilizing dynamical systems for information processing, and its applications to pattern recognition and classification problems in high energy and nuclear physics.

During the period covered by this progress report important advances were made in areas 1, 3, 4, as described below and discussed at several international conferences (see conferences below). One graduate student (see personnel) was taken on by the PI for thesis supervision during this time. One post-doctoral fellow will join the effort in October and another starting December 15. The work described below was carried out with long term visitors (see visitors), especially A.V. Selikhov and S.S. Padula, and collaborators at LBL. Below I highlight the technical progress in the above areas. A copy of each relevant papers is enclosed.

1.1 Radiative energy loss

Work on the problem of QCD multiple collision theory and the nonabelian generalization of the Landau-Pomeronchuck effect was completed in ref.3. This work was initiated to study the validity of parton cascade models used for predicting the evolution of the quark-gluon plasma produced at RHIC and higher energies. The first question studied was under what conditions do the interference effects in multiple collision QCD amplitude average out. Only if those conditions are met can a semiclassical parton cascade be used to calculate the evolution due to elastic final state scattering. The second question was whether the interference phenomena associated with induced gluon radiation amplitudes could be summarized by effective form factors specific to QCD.

These problems were investigated by calculating the amplitudes for scattering and radiation of an incident high energy jet scattering off a color neutral ensemble of heavy quarks with an effective screened potential, $V_i^a(\mathbf{q}) = g(T_i^a)_{c,c'}/(\mathbf{q}^2+\mu^2)$ where T_i^a is a d_i-dimensional generator of $SU(N)$ corresponding to the representation of the target parton at $\mathbf{x}_i$, and $\mu \sim gT$ is the infrared screening scale in the plasma. For an isolated at x_i this potential leads to

$$d\sigma_i/dq_{\perp i}^2 \approx C_i \frac{4\pi\alpha^2}{(q_{\perp i}^2+\mu^2)^2} \ , \tag{1}$$

where the color factor is $C_i = C_2 C_{2i}/d_A$ where C_2 and C_{2i} are the second order Casimir of the jet and struck parton. In the eikonal limit the coincidence amplitude to scatter sequentially with partons i through j was shown to be given by

$$\begin{aligned} M_{ji}(p_j,p_{i-1}) \ &\approx \ \delta(ji)(a_j\cdots a_i)(-ig)^{j-i+1}2E_0\int\left\{\prod_{k=i}^{j}\frac{d^2\mathbf{q}_{\perp k}}{(2\pi)^2}e^{-i\mathbf{q}_k\cdot\mathbf{x}_k}V_k^{a_k}(\mathbf{q}_k)\right\} \\ &\times(2\pi)^2\delta^2(\mathbf{Q}_{\perp ji}-\sum_{l=i}^{j}\mathbf{q}_{\perp l}) \ , \end{aligned} \tag{2}$$

where $a_j \equiv T_{a_j}$ are the color matrix vertices for the jet. Squaring this amplitude and averaging over initial and summing over final target wavefunctions using closure leads to

$$\langle|M_{ji}(p_{i-1},p_j)|^2\rangle \ \propto \ \int\left\{\prod_{k=i}^{j}\frac{d^2\mathbf{q}_{\perp k}}{(2\pi)^2}\frac{d^2\mathbf{q}'_{\perp k}}{(2\pi)^2}T_k(\mathbf{q}_{\perp k}-\mathbf{q}'_{\perp k})V_k^{a_k}(\mathbf{q}_k)(V_k^{a_k}(\mathbf{q}'_k))^*\right\}$$

$$\times(2\pi)^4\delta^2(\mathbf{Q}_{\perp ji} - \sum_{l=i}^{j} \mathbf{q}_{\perp l})\delta^2(\mathbf{Q}_{\perp ji} - \sum_{l=i}^{j} \mathbf{q}'_{\perp l}) \ , \qquad (3)$$

where $T_k(\mathbf{q}_\perp)$ is just the Fourier transform of the Glauber thickness function. The classical Glauber multiple collision formula emerges from above only if the ensemble is color neutral and the condition $1/\mu \ll \lambda \ll R$ is satisfied. At temperature T pQCD indicates that the mean free path $\lambda \sim 1/g^2T$ while $\mu \sim 1/gT$. we thus have shown that a parton cascade is classical only if $g \ll 1$. For attainable temperatures at RHIC $T < 500$ MeV, unfortunately $g \sim 1-2$ and thus the evolution is at best on the borderline of the semiclassical limit.

In the second major part of this research we showed that the gluon radiation induced by m sequential collisions can be factorized as

$$\frac{d^3n_m}{d^3k} \equiv C_m(k)\frac{d^3n_1}{d^3k} \ , \qquad (4)$$

where $\omega d^3n_1/d^3k = (\alpha_s C_A/\pi^2)\langle q_\perp^2/(k_\perp^2(\mathbf{k}_\perp - \mathbf{q}_\perp)^2)\rangle$ is the soft gluon radiation spectrum in an isolated collision. We showed that the "color formation factor" for soft gluons can be expressed in the following simple closed form:

$$C_m(k) = m - \frac{r_2}{1-r_2} Re \sum_{i=1}^{m}\sum_{j=1}^{i-1}(1-r_2)^{i-j}F_{ij}(k)e^{iL_{ij}/\tau(k)} \ , \qquad (5)$$

where $r_2 = N/(2C_2)$ is a color factor specific to the jet parton, $L_{ij} = z_i - z_j$ are the longitudinal distances between collision centers i and j, F_{ij} is a current correlation function, and $\tau(k) \approx \omega/k_\perp^2 \sim 2/\omega\theta^2$ is the same radiation formation time as in QED. Eq.(5) describes the nonabelian interference pattern due to the finite formation time of gluons. When L_{ij} are all large compared to $\tau(k)$, $C_m = m$ recovers the additive Bethe-Heitler limit. In the opposite limit, $C_m \approx 1/r_2$ becomes approximately independent of m and reduces to the factorization limit. In the intermediate case the formula interpolates between those limits.

Eq.(5) achieves our aim to derive a formula summarizing the QCD interference effects that can in principle be introduced into a parton shower monte carlo. As an important analytic check we also calculated the radiative energy loss

$$dE_{soft}/dz \approx \frac{1}{2}\alpha_s C_2\mu^2 \approx 2\pi\alpha_s^2 C_2 T^2 \ , \qquad (6)$$

which shows the sensitivity of the finite energy loss to the infrared screening scale. This provides confirmation of the ideas published last year (X.N. Wang and M. Gyulassy, Phys. Rev. Lett. 68 (1992) 1480) that jet quenching at RHIC should provide a way to measure that important scale in the minijet plasma produced nuclear collisions.

1.2 Color Conductive Evolution of Mini Jet Plasmas

In ref.(2) work was completed on how the copious minijets produced in nuclear collisions could couple to the soft beam jet fragments via color conduction. Present models of beam jet fragmentation assume that a color field is left in the wake of the two interacting nuclei that decays on a relatively slow time scale $\tau_s \sim 1$ fm/c due to pair production. However the mini jets on the scale of $p_T \sim 2$ GeV are formed on a much shorter time scale ~ 0.1 fm/c. Therefore, their evolution could be influenced by the large chromo-electric fields before they have a chance to decay. As in EM plasmas such a background field could lead to ohmic heating of the minijet plasma. That heating would of course also serve to damp the background field because of the induced polarization of the plasma. We investigated the order of magnitude of such a coupling between the high frequency (minijet) modes and the low frequency modes by following the evolution with chromo-viscous-hydrodynamics:

$$\begin{aligned}\frac{d\epsilon_g}{d\tau}+\frac{\epsilon_g}{\tau} &= -\left\{\frac{P_g(\tau)}{\tau}-\frac{4}{3}\frac{\eta_g(\tau)}{\tau^2}\right\}\Theta(P_g\geq\frac{4\eta_g}{3\tau})+2\epsilon_f\left\{\kappa_g(2\epsilon_f)^{1/4}+\sigma_c^g(\tau)\right\}\\ &\quad +\epsilon_h^g\frac{\tau_h}{\tau}\cdot\frac{\Theta(\tau_h\leq\tau\leq\tau_h+\delta)}{\delta},\end{aligned} \tag{7}$$

$$\frac{d\epsilon_q}{d\tau}+\frac{\epsilon_q}{\tau} = \kappa(2\epsilon_f)^{5/4}+\epsilon_h^q\frac{\tau_h}{\tau}\cdot\frac{\Theta(\tau_h\leq\tau\leq\tau_h+\delta)}{\delta}, \tag{8}$$

$$\frac{d\epsilon_f}{d\tau} = -2\epsilon_f\left\{\kappa(2\epsilon_f)^{1/4}+\sigma_c^g(T_g)\right\}+\epsilon_s\frac{1}{\tau_f}\Theta(\tau_h\leq\tau\leq\tau_f), \tag{9}$$

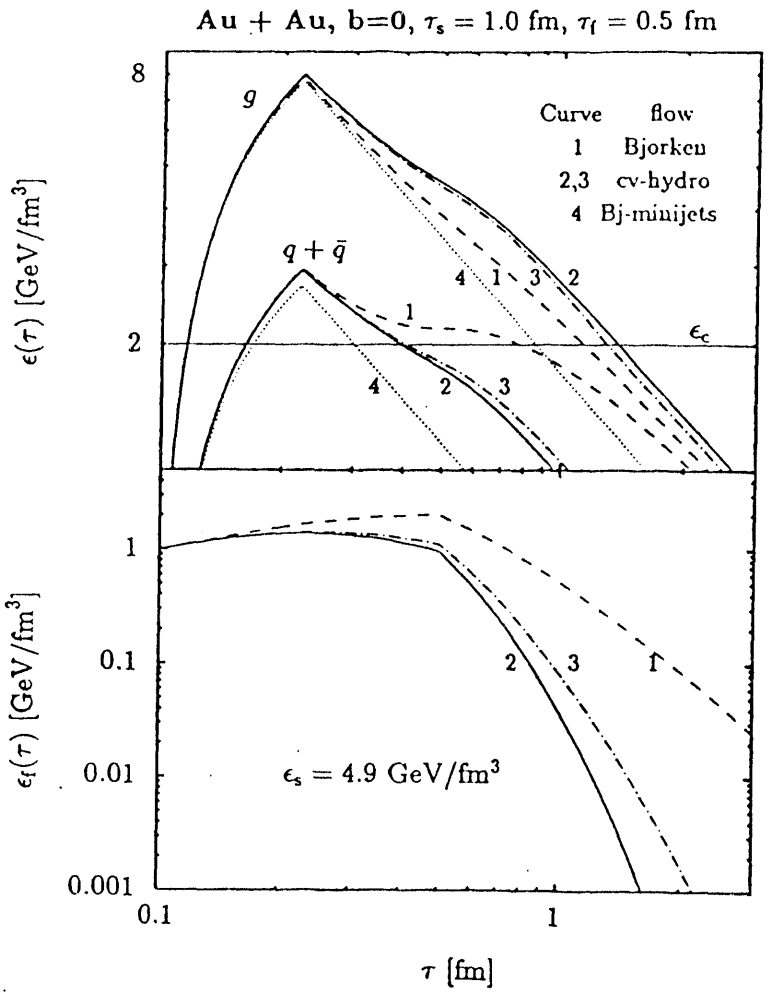
where $\epsilon_{g,q,f}$ are the energy densities of gluons quarks and the background field and P_g is the gluon partial pressure. The finite relaxation times in the plasma are incorporated in terms of a viscosity, $\eta_g \approx T^3/(3\alpha_s^2\ln 1/\alpha_s)$, and a color conductivity $\sigma_c^g(T) = \tau_g\omega_{\rm pl}^2 \approx (4\alpha_s^2\ln(1/\alpha_s)T)^{-1}(4\pi\alpha_s T^2/3) \approx$

$T/(\alpha_s \ln(1/\alpha_s))$. The initial minijet energy density ϵ_h and time $\tau_h = 0.1$ fm/c are determined from pQCD including an estimate for nuclear shadowing integrating above $p_T > 2$ GeV/c. The initial background field energy density, ϵ_s is derived by fitting the net transverse energy production in the HIJING model (X.N. Wang and M. Gyulassy, PRD44 (1991) 3501; PRD45 (1992) 844.). The decay rate parameter κ and the field formation time τ_f are estimated.

The main result is shown in the Figure 1. The strongest effect of conductive flow in our calculation is the suppression of $q\bar{q}$ production from the background field and thus the hindrance of chemical equilibration by reducing the beam jet source of $q\bar{q}$ pairs. Without conductivity the background color field produces sufficiently many $q\bar{q}$ pairs that near ϵ_c chemical equilibrium is more likely. However, with the enhanced minijet conductivity the ratio of q to g densities remain far below equilibrium at least above the critical temperature. This calculation provides therefore an explicit dynamical realization of the van Hove-Pokorski picture of high energy reactions as dominated by gluonic interactions.

Most studies of dilepton and direct photon production (Kajantie et al 1989 - Kapusta, McLerran 1992) have assumed chemical equilibration in computing $q\bar{q}$ annihilation from the quark-gluon plasma. We showed that the minijet gluon plasma has difficulty achieving chemical equilibration during the pure plasma phase $\tau < 2$ fm at least at RHIC energies. The reduced density of quarks and anti-quarks may therefore reduce significantly the number of hard photons and dilepton pairs relative to those equilibrium estimates. This is an important topic for further work because of its implication for proposed RHIC experiments.

Figure 1: The evolution of the the total energy density of quarks and gluons with minijet initial conditions at RHIC energies for Au+Au. Curves 1 correspond to non-conductive, non-viscous free flow. Curves 4 show the pure minijet contribution to curve 1. Curves 2 show the solution of the equations with the perturbative estimates for the viscosity and conductivity. Curves 3 show the solution when the momentum relaxation time τ_g is reduced by a factor of two. The evolution of the field energy density is shown.



1.3 Color Diffusion and QCD Transport Theory

Another major research project completed under this grant was the discovery of a new transport process in nonabelian plasmas we call color diffusion in refs(4,7). We derived the characteristic color relaxation time scale, $t_c \approx (3\alpha_s T \log(m_E/m_M))^{-1}$, showing its sensitivity to the ratio of the static color electric and magnetic screening masses. This leads to a surprisingly small color conductivity, $\sigma_c \approx 2T/\log(m_E/m_M)$, which in fact vanishes in the semi-classical (1-loop) limit. The relevance of t_c can be seen most clearly in the context of color conductivity. In the relaxation time approximation, classical non-abelian transport theory leads to the following formula for the static color conductivity $\sigma_c = t_c\omega_{pl}^2$ where $\omega_{\rm pl}^2 = 4\pi\alpha_s T^2(1+N_f/6)/3$ the color plasmon frequency. As noted in the previous section the color conductive coupling between the mini jet plasma and the beam jet background field can lead to significant observational consequences for dilepton production.

Our analysis reveals the surprising result that t_c formally vanishes in the semiclassical limit because long range color magnetic fluctuations make the parton color precess wildly. We derived t_c in two independent ways with the result that

$$\frac{1}{t_c} = -2\pi g^2 NT \int \frac{(dk)}{(ku)} \frac{k^2}{(ku)^2-k^2} \delta\left(\frac{kv}{vu}\right) \mathrm{Im}\left(\frac{1}{k^2-\Pi_L} - \frac{1}{k^2-\Pi_T}\right) \quad (10)$$

In ref(4) this was derived starting from the Heinz classical QCD transport equations. In ref.(7) we showed that the same (divergent) result could be derived starting from quantum color dynamics of the QCD Wigner densities.

We proposed that the same infrared regulation mechanism must work in this case as necessary to regulate the divergent gluon and quark damping rates in high T pQCD. We therefore introduced a nonperturbative color magnetic screening cutoff via the Pisarski modification:

$$\mathrm{Im}\left(\frac{1}{\omega^2\epsilon_T(k)-k^2}\right) \approx -\frac{a\omega/k}{(k^2+m_M^2)^2+(a\omega/k)^2}\ , \quad (11)$$

where $a = 3\pi\omega_{pl}^2/4 \approx m_E^2$. This lead to the finite color relaxation time noted above.

The influence of this new time scale on QCD plasma transport was derived in ref(7). It was shown that the nonabelian dynamical equation for the plasma reduce to Fokker-Planck type equations

$$p^\mu\partial_\mu\Delta Q + gp^\mu\partial_p^\nu\Delta F^a_{\nu\mu}t^aQ_{eq} = -d_c[t^a,[t^a,\Delta Q]] + \partial_p^\mu\left((-a_\mu + b_{\mu\nu}\partial_p^\nu)\{t^a,\{t^a,\Delta Q\}\}\right)$$

and similar equations for the antiquark and gluon Wigner densities. This system describes the transport of small deviations in a color neutral quark-gluon plasma in terms of the transport coefficients, $d_c = (pu)/(Nt_c), a_\mu = -b_{\mu\nu}u^\nu/T = -bp_\mu/T$ with $b \approx \alpha_s^2T^3\log(1/g)$. The new term associated with color diffusion is the double commutator proportional to d_c.

One of the interesting consequences of these equations is that they show that the damping of collective modes in a non-abelian plasma is controlled by the (perturbatively divergent) parton damping rates. This suggests that color collective modes may be over-damped in quark-gluon plasmas. This is of interest in connection with constructing parton shower codes for RHIC since it essentially justifies the neglect of color in such models. Several further developments along these lines are currently under investigation and will be published.

1.4 Phenomenological Studies

Work was initiated on the analysis of new AGS data on pion interferometry (see ref 1 of conf.proc.) We performed a 2D chi^2 analysis of the data to test whether the data could differentiate widely different reaction geometries with or without long lived resonance production. Earlier studies (S.S. Padula, M.Gyulassy, Phys. Lett. B217 (1989) 181) showed the ambiguity of the pion source size at CERN energies due to unknown resonance contributions. We found that the present AGS data were also consistent with both dynamical models. In fact systematic errors in the data at high relative momentum difference induce a poor chi^2 for all theoretical models at present. Work on this project continues with close contact with the experimentalists at the NEVIS lab.

Work utilizing the HIJING model continues to map out possible observables at RHIC energies. Recently the documentation for HIJING was completed ref(5) and the code has been widely distributed to experimentalist working both at RHIC and LHC.

2 Refereed Papers

1. Neural Filters for Jet Analysis, Dawei W Dong and Miklos Gyulassy, Phys.Rev. E47 (1993) 2913.

2. Color Conductivity and the Evolution of the Minijet Plasma at RHIC, K.J. Eskola and M. Gyulassy, Phys.Rev. C47 (1993) 2329.

3. Multiple Collisions and Induced Gluon Bremsstrahlung in QCD, M.Gyulassy and X.N. Wang, CU-TP-597, 1993, submitted to Nucl. Phys. B

4. Color Diffusion and Conductivity in a Quak-Gluon Plasma, A. Selikhov and M. Gyulassy, CU-TP-598, 1993, Phys.Lett.B in press.

5. HIJING 1.0: A Monte Carlo Program for Parton and Particle Production in High Energy Hadronic and Nuclear Collisions X.N. Wang and M. Gyulassy, LBL-34246 (1993), submitted to Comp. Phys. Comm.

6. Non-Abelian Bresstrahlung in a Quark-Gluon Plasma, Alexei V. Selikhov, CU-TP-602 (1993), submitted to Phys.Rev. C

7. QCD Fokker-Planck Equations with Color Diffusion A. Selikhov and M. Gyulassy, CU-TP-610 , 1993, submitted to PRL

3 Papers in Preparation

1. Pion Interferometric Analysis of Nuclear Collisions at 14 AGeV, M. Gyulassy and S.S Padula

2. Classical versus Quantal Color Transport Dynamics, A.V. Selikhov and M. Gyulassy

3. Sensitivity of Minijet Plasma Evolution to the Color Diffusion Time Scale, K.J. Eskola and M. Gyulassy

4 Conference Proceedings

1. 2D-Chi2 Analysis of Recent AGS interferometry data, M. Gyulassy, S.S Padula, preprint CU-TH-593 (93), Proc.of HIPAGS Workshop, January 13-15, 1993, MIT, Boston, MA

2. Gluon Shadowing and Jet Quenching on hadron-hadron and hadron-nucleus collisions, M. Gyulassy, Proc. BNL Conference on Future Directions...Multi GeV Hadron Facilities, March 4-6, 1993, BNL, LI, NY

3. Multiparton Dynamics at Extreme Energy Densities, M. Gyulassy, K.J. Eskola, A.V. Selikhov, and X.N. Wang, Proc. CCAST Symposium on Particle Physics at the Fermi Scale, Beijing, China, May 27-June 4,1993, CU-TP-598 (Gordon-Breach)

4. Developments in QCD Transport Theory, M. Gyulassy, Columbia preprint CU-TP-612, to appear in Proc. Quark Matter '93, Borlange, Sweden, June 1993, and Proc. of NATO Advanced Study Institute on Hot and Dense Nuclear Matter, Sept 26-Oct. 9, 1993, Bodrum, Turkey.

5. Effects of Color Conductivity in the Evolution of the Minijet Plasma, K.J. Eskola and M. Gyulassy, Proc. Quark Matter '93, Borlange, Sweden, June 1993, LBL-34474

6. High Pt Physics at RHIC, M. Gyulassy, Proc. RHIC School 1993, BNL, Aug.23-27,1993

5 Professional Activities

1. Co-organizer of Workshop on Meson Interferometry in Relativistic Heavy Ion Collisions April 16-17, 1993 Brookhaven National Lab with George Bertsch and Carl Dover

2. Co-Organizer of Workshop on Pre-equilibrium Parton Dynamics at LBL, Aug. 23 - Sept. 3, 1993 with Xin-nian Wang and B. Mueller

3. Co-organizer of RHIC School 1993 at BNL Aug. 23 - Aug. 27, with T. Ludlam and H. Gutbrod

6 Personnel

Joining the PI under this contract were the following personnel:

1. Ziwei Lin, graduate student, started June 1 under my thesis supervision

2. Dirk Heumann, post-doctoral fellow from Univ. Giessen will start Oct. 12 under a Humbold Lynen Fellowship with partial support ($1000/mo.) from this DOE grant

3. Dirk Rischke, post-doctoral fellow from University Frankfurt will start Dec. 16 under a NATO research fellowship with partial support ($1000/mo.) from this DOE grant

4. A second thesis graduate student will be taken under this grant on or about Jan. 1994

7 Visitors

Short and long term visitors to Columbia University partially paid for travel and living expenses under the budget heading Domestic travel total $7986 to date.

1. Alexei Selikhov, Kurchatov Institute, Feb 16-Aug 16, QCD transport, paid by BNL

2. Sandra Padula, U. Sau Paulo, Brazil, March 14-april 19, pion interferometry.

3. Herbert Weigert, U. Regensburg, Germany, April 9-11, QCD transport theory

4. Asayuki Asakawa, Texas A&M, April 25-26, dilepton production

5. Larisa Bravina, University of Bergen, Bergen, Norway, April 20-23, hydrodynamics.

6. Tamas Csorgo, KFKI, Budapest, Hungary, Aug. 18-24, pion interferometry

7. Klaus Geiger, U. Minn., Oct. 11-14, parton cascade.
8. Carsten Greiner, Duke Univ., Nov?, strangelets

8 Equipment

Under this grant I purchased thus far the following computer equipment for a total price of $22,288. The system manager was contracted with GeNUA corporation based in Munich for $3,988 for this year.

1. Sparc 10 Model 41 sytem, 64MB memory, 1GB disc, operating system, professional fortran: $14,866
2. Sun tape backup unit: $2625
3. 2 NCD 15in B/W Xwindows terminals: $1500
4. Texas Instrument TM4000 WINDX2/50, 200MB, poratble pc: $3158
5. 14.4KB Modem and cables: 139

Planned purchase items include a tape backup for pc, an external monitor, keyboard, and an ethernet connection.

Budget received,
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