NEUTRON STARS: GENERAL REVIEW

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In this talk I shall review the work on neutron stars that has been performed in the last five or six years. The general trend of my talk will be that of stressing the fact that today we seem to have reached a satisfactory agreement among theorists, observers, and any linear combination of the two. This clearly is not intended to imply that we have solved all the problems concerning neutron stars and that nothing is left to study in the future. What I'm referring to is the apparent clarification of at least one problem, that of the maximum value for the mass of a neutron star. In fact, I will show you in the rest of my talk that there is today general agreement on the value of the maximum mass for a neutron star, and that no great crisis seems to be lying ahead of us, unless evidently we are ready to say that the whole of nuclear physics is wrong.

In my mind, and in those of the nuclear physicists who have spent the last five or six years thinking about this problem, a fact has emerged very clearly: namely that a stable neutron star cannot have a mass higher than 2 or say 2.2 solar masses. Unless evidently you are ready again to throw out the window the general theory of relativity on which these computations are based, there is no way that we can possibly conceive of changing our theoretical framework, so as to get values much in excess of 2 or 2.2. I am not saying that the existence of a maximum mass is due to general relativity. Rather, the existence of the maximum mass is due to microscopic physics. What I'm saying is that the location and the specific value of the maximum depend on what kind of theory of relativity you use. We, and by we, I mean all the people whose work I'm going to make reference to and whose work I'm going to report today, we all have used the so-called TOV equations, the Tolman-Oppenheimer-Volkoff equations, which in turn are based on Einstein's equations. There are other alternatives to the theory of relativity, the ones that have been discussed in this meeting, and in the previous talk it was stressed that if you change the theory of relativity of Einstein with the one proposed for instance, by Rosen, then the maximum mass of a neutron star is much, much higher. In this talk I will assume that we believe in the Einstein theory, and I will therefore make no further reference to this point.

I would also like to go a little further in my talk and give you some ideas of what people have been thinking about the behavior of matter at densities much higher than neutron stars.[1,2] In fact, neutron stars, dense as they are, are by no means the densest objects in the universe. They can teach us only the behavior of matter as high as 10^{15} g/cm^3, namely about 10 or 20 times higher than the density of ordinary nuclei. Since we seem to have understood this part, it is understandable that astrophysicists, after having worked out the physics of neutron stars, asked themselves: What's next? What's next is shown in TABLE 1, which in a way shows the general plan of my talk.

After talking about neutron stars, which give us information on the density region up to and including perhaps 10^{15} g/cm,[3] and after checking our results using the maximum mass M of a star, and the moment of inertia I, I would like to discuss how the physics involved in a scattering process of two protons can teach us a lot about the behavior of matter at densities up to 10^{17} g/cm^3. It seems that the p-p scattering is offering a possibility of studying the behavior of matter in a density region 100 times higher than the one we find in neutron stars,[3] and I must remind you that p-p scattering is something that we can do in the lab, it is not only an astrophysical occurrence, and it is done routinely at CERN, and in the United States in many labs. The pertinent observational data are indicated in the last column of TABLE 1 under the heading n_s, which is the number of secondary particles coming out of the scattering, and the transverse momentum, p_T. As we shall discuss,[3] the scattering of two protons yields a good step in the ladder that goes from the surface of neutron stars all the way up to almost infinite densities. Unfortunately, after the p-p scattering, we don't seem to have any other observations on which to put our hands. The only other source of information is cosmology, in which, as you know, the density can go from infinity, at the moment of

TABLE 1
HIGH-DENSITY MATTER

Source of Information	Density	Observation
Neutron stars	$< 10^{15}$ g/cm^3	M,I
p-p Scattering	$> 10^{17}$ g/cm^3	n_s, $\langle p_T \rangle$
Cosmology	$> 10^{20}$ g/cm^3	Galaxy form., Black holes, etc.

the Big-Bang, all the way down to the very small values today. I say unfortunately not because cosmology is not a good branch of science, but rather because it is difficult, and insofar as I know no way has been found to pin down any phenomenon that, having occurred during the early evolution when the Universe was as dense as 10^{20} or 10^{25} g/cm^3, has left any detectable footprint today, so that we can be sure that what we measure depends on the density in the very early stages. Perhaps black holes have recently given a clue to this problem, and we shall discuss them later on.

Let us now go back to neutron stars and consider FIGURE 1, where I have plotted the pressure versus density, the pressure in dynes/cm^2 and the density in g/cm^3. I have drawn two lines, one corresponding to a free system of particles and the other corresponding to the so-called causality limit, which corresponds to the hardest equation of state allowed by microphysics, namely the one with a velocity of sound equal to one. In the middle we have a display of all the relevant computations made in the last several years.[4-14] If you take out for a second the curves called L, N, O, and if you limit yourself to the curves that are labeled A-G, you will see that these curves bunch up rather nicely, thus indicating a general convergence of the results. I would like you to notice several things. First of

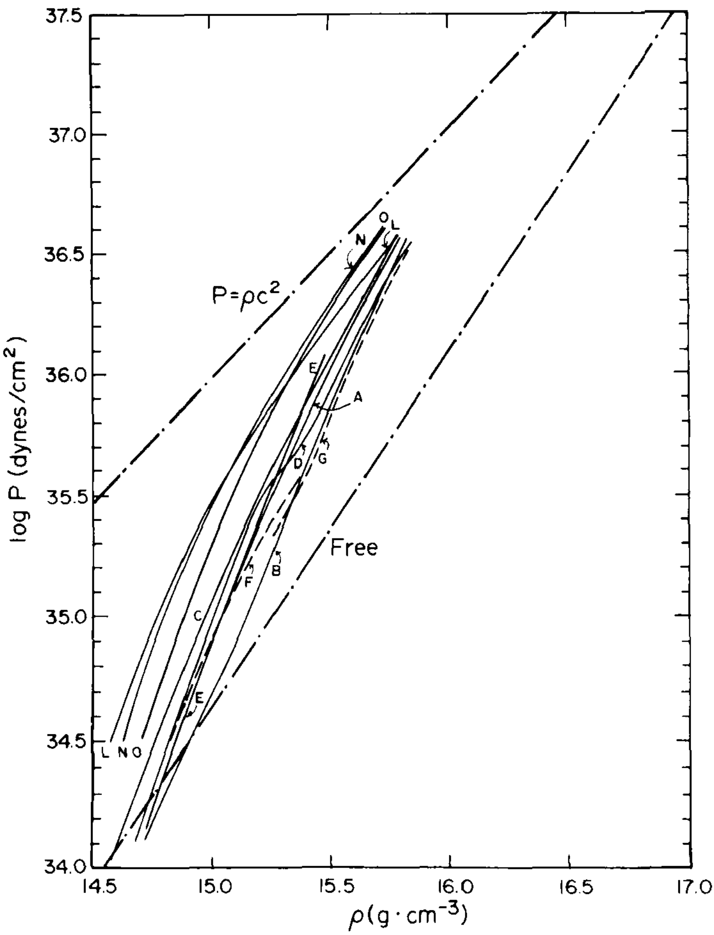


FIGURE 1. Pressure vs. density as from the most recent many body computations. See Reference 1 for details.

all, these results come from different people who have used different many body techniques and the best presently known nucleon-nucleon potentials. They are all based on non-relativistic many-body theories, and I would say that it is particularly comforting that everybody has obtained almost the same answer. I would also like to point out that almost all those curves yield a pressure that is larger than the one corresponding to the free system of particles at densities between 14.5 and 15 (in logarithmic scale), which means that only at those densities do we start filling the repulsive part of the nucleon-nucleon potential. At lower densities, the attractive nature of the nucleon-nucleon potential yields a pressure that is lower than the one corresponding to a free system. Finally, I would like to point out that the pressures with which we are dealing correspond to energy densities of the order of tens of MeV per every Fermi cube, namely energy densities of the same order of magnitude as the phenomenological constant (called B) introduced to keep the so-called MIT bag together.

Let me now turn to FIGURE 2, where I present the results corresponding to the value of the mass of a neutron star in units of solar masses versus the central density indicated by ρ_c. The lettering A, B, C all the way down to L, N, O corresponds to the notation used by Arnett and Bowers in their review paper published by the University of Texas two years ago. Let's have a close look at FIGURE 2. The L, N, O results, corresponding to stiff equations of state, yield values that are not higher than 2.7, whereas all the other equations, from A-G, yield values not higher than 1.84 solar masses. Now, there is something that I have to say about the equations of state indicated by L, N, O. Let me first start with the one indicated by L, which is due to Pandharipande and Smith.[12] A recent analysis of their work by G. Brown[15] has indicated that much of the repulsion included in Pandharipande and Smith's work is actually largely cancelled if one includes

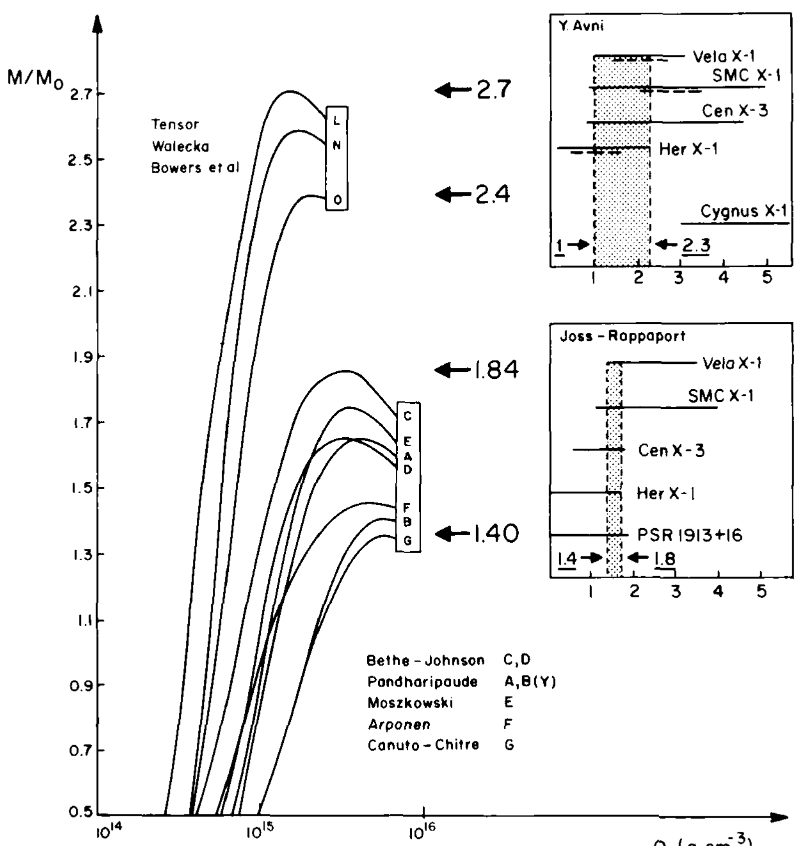


FIGURE 2. The mass of a neutron star vs. central density as predicted by the equations of state of FIGURE 1. Observational data are on the right.

higher order terms in the many-body treatment. In fact G. Brown has shown that those higher order terms give attraction, thus greatly lowering the pressure and therefore the value of M, thus bringing the result much closer to the lower set of curves. I will therefore consider that the equation of state L does not actually give a value 2.7, but a much lower value of the order of 2. As far as equations N and O are concerned, they are due to Walecka[13] (N) and Bowers *et al.*[14] (O), and they both include relativistic effects and therefore in a way you would expect slightly higher pressures and slightly higher masses. Walecka[13] has based his computation on a mean field approximation to the set of relativistic equations describing the motion of nucleons, sigma mesons, and omega mesons. However, recent work by Chin,[16] which improves Walecka's work by including higher order effects, indicates that the original pressure obtained by Walecka is also reduced, again bringing the curve N down much closer to the lower group A–G. As far as the work of Bowers *et al.*[14] is concerned, it is more difficult to assess the many-body structure. Indeed, they use Dyson equations for electrodynamics, and its many-body aspect is not as easily understandable as in the other two cases. However, my feeling is that what I would like to call the "Brown disease" is also lurking in Bowers' computations, and when properly taken into account, it will also reduce the value of 2.4 solar masses to a much lower value, around 2.

Let us now look at the right-hand side of FIGURE 2, where I quote the observational results. The figure at the top is due to Avni,[17] and the one on the bottom is due to Joss and Rappaport.[18] This last one has recently been published in *Nature*, and this morning we heard Rappaport himself present the same data. The one by Avni will be published in the Proceedings of the IAU Symposium held last summer in France. As you can see, the values allowed for the mass of a neutron star by the work of Joss and Rappaport lie between 1.4 and 1.8 solar masses. If I understand Rappaport correctly, the large uncertainty in the second case from the top, the Small Magellenic Cloud, has recently been reduced to a much smaller interval, and therefore one has more confidence in the result just quoted. The work of Avni also indicates that the maximum mass of a neutron star lies between 1 and 2.3 solar masses. However, Avni has used a more stringent criterion than Joss and Rappaport, and that's why the interval is slightly wider. In any event I would like to stress the fact that both observational works have given us results that are in really excellent agreement with our theoretical understanding if we recall that only a few years ago we were very confused about the values of the mass of a neutron star. FIGURE 2 is indeed very rewarding because it does indicate a very satisfactory agreement between theoretical understanding of a structure of a neutron star and the results that we obtained from observations. This is why at the beginning I said that all we theorists who have worked in this field seem to agree that once we will have reduced the value of the curve L, N, O, we shall conclude that the maximum mass of a neutron star cannot be higher than say 2 plus or minus 10% solar masses.

In FIGURE 3, I show the value of the moment of inertia vs. the mass of a neutron star corresponding to the equations of state just shown. Again, the curves L, N, and O give high moments of inertia, whereas the other curves from A–G bunch together nicely around a value of 10^{45}. The two arrows indicate the value of the moment of inertia needed if a neutron star is to be held responsible for not only the luminosity of the Crab Nebula but also for the kinetic energy of the expanding gas. The demand is rather strict, because it requires that the moment of inertia be higher than some 8×10^{45}. If so, then the equations of state G and B are excluded. Only equations of state A, C, D, E, and F satisfy that criterion. Again, we can use the moment of inertia to discriminate against several equations of state, but notice that almost all of them do satisfy that criterion, which again makes the model of the exploding supernova and the neutron star as a powerhouse for both the luminosity and the kinetic energy of the expanding envelope a reliable one. (See Ref. 19.)

In FIGURE 4, the mass of a neutron star is shown as a function of the radius, measured in kilometers. It is commonly accepted that the radius of a neutron

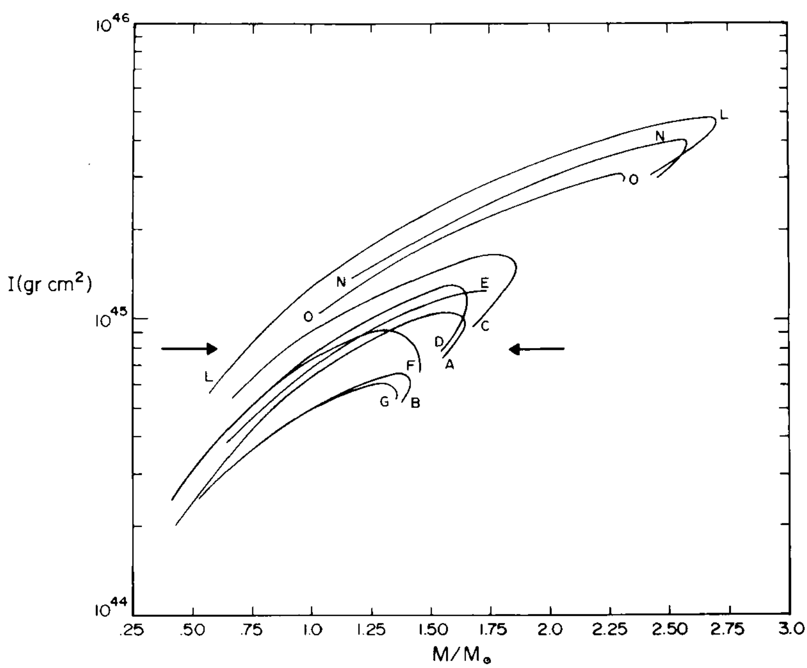


FIGURE 3. Moment of inertia vs. mass as from the equations of state of FIGURE 1.

star is of the order of some 10 km. Recently, however, there has been some dispute about this statement,[20] since one equation of state, especially the one indicated by L, produces much fatter stars with radii of the order of, or higher than, 15 or 18 km. However, as we have indicated before, since the equation of state L, N, and O suffers from the Brown disease, I would prefer to stick to the other group and therefore to continue thinking that the most reliable value for the radius of a neutron star is of the order of 10 km.

This in a way concludes my summary. As I've shown you, the general agreement is indeed satisfactory, and a comparison with the observational data is rather good.

Let us now go on to the next topic and ask ourselves how does matter behave at

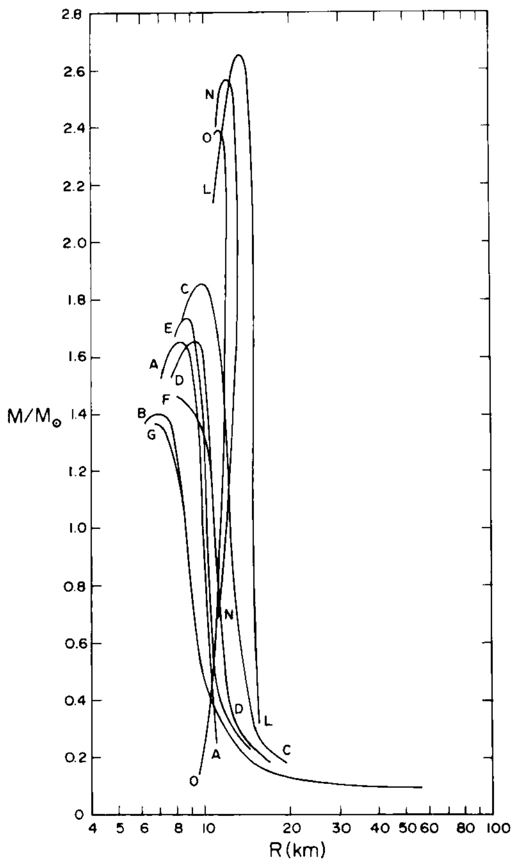
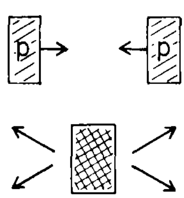


FIGURE 4. Masses vs. radii as from the equations of state of FIGURE 1.

densities higher than nuclear densities, or higher than 100 times nuclear densities. The topic I have chosen to discuss is the high-energy scattering between two protons.[3] The necessary mathematical background is sketched on TABLE 2, where we see two protons colliding, and where I have depicted the protons not as spheres but as contracted disks because of the Lorentz contraction. The Lorentz contraction is in fact the most important fact in my argument here. Let us now consider what is happening during the process. After the two protons have collided, they form a very hot blob of matter. We are not considering the protons as point sources, but rather the proton is thought of as a gas say of pions, which are contracted during the motion. Upon smashing one against the other, the two protons occupy a volume which is the cube of the Compton wavelength reduced by the Lorentz factor, which goes like one over the center of mass energy. The higher the energy, the smaller the volume. The corresponding density ρ can be worked out to be 1.5×10^{14} times the lab energy measured in Gev. For a typical lab energy of 1000 Gev, the density corresponds to some 10^{17} g/cm^3, therefore a factor of 100 higher than the density we found in the core of a neutron star. The equation of state of such an initial blob of gas is clearly unknown. In order to understand the time evolution of the process, we have to study the hydrodynamic flow for this initial blob by solving the relativistic Euler equations, or Navier-Stocks equation if we include viscosity. Many years ago Landau solved the one-dimensional Euler's equations exactly by using an equation of state corresponding to a free Fermi gas. However, if we repeat Landau's computation[3] leaving the pressure versus energy density as an unknown, we can try to fit the observational data by appropriately choosing the value of the equation of state.

FIGURE 5 shows the results of the work that John Lodenquai and I did a few years ago.[3] FIGURE 5a gives the value of the transverse momentum versus the lab energy. It is a well-known fact, both in high-energy physics as well as in cosmic physics, that the value of the transverse momentum p_T is fairly constant (≈ 400 Mev/c) over a wide range of lab energies. FIGURE 5b gives the other experimental datum, namely n_s, the number of charged secondary particles that are coming out after the blob has diffused. Three curves are indicated there, one corresponding to the Pomeranchuk model, a second corresponding to the Fermi model, and a third corresponding to a nonhydrodynamic model. The small table in FIGURE 5 gives the results for both p_T and n_s. Depending on specific choices of the velocity of sound and the viscosity η, we have several possibilities. Let's begin from the bottom. If we choose the velocity of sound to be 1, namely the hardest possible equation of state and a viscosity proportional to the cube of the

TABLE 2
HIGH-ENERGY P-P SCATTERING



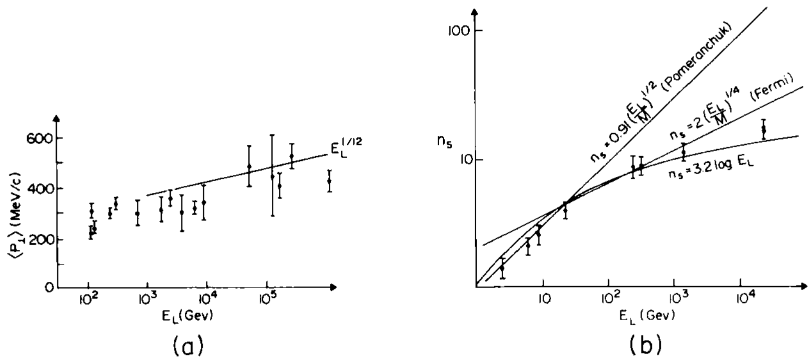
$$V = \frac{4\pi}{3}\left(\frac{\hbar}{m_\pi c}\right)^3 \left(\frac{2Mc^2}{E_{cm}}\right)$$

$$\rho = \frac{\epsilon}{c^2} = \frac{1}{c^2}\,\frac{E}{V} = 1.5 \quad 10^{14}\ E_L\,(\mathrm{Gev})\ (\mathrm{gr/cm^3})$$

$$E_L = 10^3\ \mathrm{Gev}\ ;\ \boxed{\rho \sim 10^{17}\ \mathrm{gr/cm^3}}$$

$$T_{\mu\nu} = p\,\delta_{\mu\nu} + (p+\epsilon)\,U_\mu U_\nu$$

$$\boxed{p = p(\epsilon)}$$



$\boxed{p = c_s^2 \epsilon}$

c_s^2	η	n_s	$\langle p_T \rangle$
1/3	0	$E^{1/4}$	$E^{1/12}$
1	0	lg E	lg E
1/3	T^3	$E^{1/3}$	lg E
1	T^3	$E^{1/3}$	$E^{-1/3}$

$\boxed{E = E_L}$

FIGURE 5. Transverse momentum and multiplicity vs. lab energy for p-p scattering.

temperature, we find that the transverse momentum decreases with the energy. Since this is certainly not the case, as we can see from FIGURE 5a, we can immediately discard that possibility. If we take the other possibility, namely that the velocity of sound corresponds to that of a free Fermi gas, and a viscosity still proportional to the cube of the temperature, we find that the transverse momentum goes like log E, which is quite acceptable. However, the number of secondary particles increases like the cubic root of the energy. Looking at FIGURE 5b, we find that this would correspond to a curve between the one of Pomeranchuk and the one of Fermi, and that would certainly not fit the data. We are therefore forced to exclude that possibility too. The other possibilities correspond to the value of the velocity of sound again equal 1, but zero viscosity. In that case we find that both n_s and p_T go like log E. This result is perfectly acceptable, since it simply means that those quantities are very slowly varying functions of the energy, as they actually are. I would like to make a further remark at this point. For many years it was believed that the hydrodynamic model would not be able to produce a logarithmic term, but only a power law type of behavior. The logarithmic behavior of FIGURE 5b is the one given by a theoretical model which is not based on the idea of an hydrodynamic expansion, but rather on the idea that the two protons exchange several intermediate particles (Regge trajectories) during their interactions. As we can see, the hydrodynamic model can yield the same result if the velocity of sound is properly chosen. Therefore this combination certainly fits the data very well. The other combination, which corresponds to zero viscosity and velocity of sound equal to one-third, in other words, free particles, gives a transverse momentum that fits the data rather well. As a matter of fact, the theoretical curve in FIGURE 5a is precisely the one corresponding to this case. However, the number of secondary particles increases with the one-fourth power of the energy, which is what is usually known as the Fermi model. As we can see from FIGURE 5b, the Fermi model, up to an energy of 1000 Gev, is indistinguishable from the model that gives the log term. There is, however, one extra experimental point at an energy higher than 10,000 Gev which lies definitely lower than the Fermi curve, and I would therefore tentatively suggest that this combination gives a number of secondary particles that increase too fast with the lab energy. I would then conclude that perhaps the most reliable combination is the one with the velocity of sound equal to 1 and the viscosity equal to zero. If we believe in such a scenario, we can conclude that the equation of state when continued up to 10^{17} seems to correspond to that of a gas of strongly interacting particles.

Turning now to FIGURE 6—the future of our equation of state—here again I have plotted the pressure, this time versus the baryonic density, which is the physical density. In the left corner I drew a curve called Best Nuclear Equation of State, and we have seen what that means. What can we do at higher densities? We have essentially three possibilities, or more exactly all the possibilities are included in this figure. If we believe the argument just given about the proton-proton scattering, we would conclude that the equation of state follows the upper curve, the one that is marked Slavery and that represents the equation of state $p = \rho$. We could, however, also claim that there is another possibility, namely that the

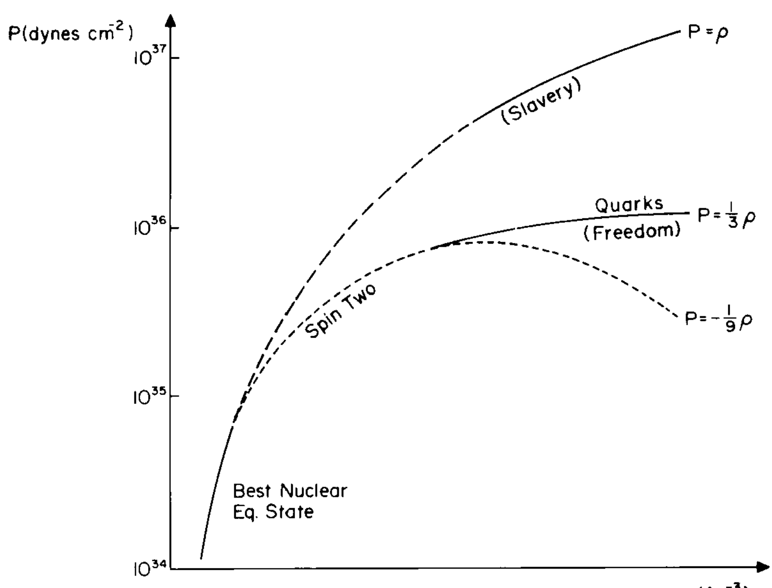


FIGURE 6. Three possible equations of state at superhigh densities as discussed in the text. The spin two curve is from the work of Canuto, Datta, and Kalman.[21]

particles are not actually slaves, but they become free (asymptotic freedom), in which case they would have an equation of state of the type $p = \frac{1}{3} \rho$. This is indeed what we learn from high-energy physics. If matter is composed of quarks, and they seem to be an accepted theoretical and experimental result, at very high densities, perhaps higher than 10^{17}, particles become free again, and that is what is called asymptotic freedom. Another possibility is that at very high densities some other kind of particle should come into the game, and the interaction between two nucleons should actually be mediated by a spin two meson. If that is the case, the spin two meson will produce attraction, and at very high densities that will produce a negative pressure, indicated here by the lower curve. Indeed, recent work[21] has indicated that such an equation of state is actually feasible, that the pressure can become negative at high densities if and only if the spin two becomes the dominant interacting force between two nucleons. In the light of what has been

TABLE 3
FORMATION OF INHOMOGENEITIES

$$\delta(t) = \delta(0)t^{s}, \qquad s \approx 1$$

$$\begin{array}{l} \delta^2(0) = \left(\dfrac{kT}{V}\right)K \\[2em] K^{-1} = n\left(\dfrac{dp}{dn}\right) \end{array} \left\{ \begin{array}{l} \text{1) Free gas} \quad p = nkT \\[0.5em] \qquad \boxed{\delta(0) = N^{-1/2}} \\[1.5em] \text{2)} \ \dfrac{dp}{dn} \to 0 \quad \text{At } n^{*} \\[0.5em] \qquad \boxed{\delta(0) \sim N^{-1/6}} \end{array} \right.$$

done recently on quarks and gauge fields,[22] however, I would like to believe that the true behavior of matter at high densities corresponds to the intermediate line, namely the one marked quarks,[23] which is telling us that at very high density matter again becomes free. Spin two interactions are perhaps relevant in a smaller interval where they soften and bend what I call the Best Nuclear equation of state into the quarks region, as indicated by the middle figure. My general feeling is therefore that the most reliable curve is that composed of what we have called the Best Nuclear Equation of state at around 10^{15}, followed by a rather stiff equation of state corresponding to a velocity of sound of the order of 1, as we have seen from the p-p scattering. After that, spin two interactions start softening and bending the pressure until they bring it into the region where quarks dominate.

Let me now go to the final part of my talk, which is sketched in TABLE 3. If, as you have seen from FIGURE 6, there is a softening of the equation of state at a certain point or during a certain region, there could well be a point at which the derivative of the pressure with respect to the density is very small, if not zero. If that occurs, there are some interesting cosmological consequences, which I would like to discuss.

As we know, one very poorly understood phenomenon in astrophysics is the formation of galaxies. It was shown by Sir Jeans more than 40 years ago that any initial fluctuation of a random nature would grow exponentially in time if the Universe were not expanding. Later Lifschitz and Khalaktinov showed that if the Universe is expanding, as we now believe, the exponential growth is reduced to a power law, represented here by t^s, where s is of the order 1 (Ref. 2). That has killed all hopes of forming galaxies out of an initial random fluctuation, simply because a power law is too slow and the Universe is too young for that small fluctuation to grow to be of order unity. There is still some hope, however, that we could change the initial value, $\delta(o)$. In fact, from statistical mechanics it is known that $\delta(o)$ is given in terms of the compressibility by the equation shown in TABLE 3. Now, if we suppose that the system of particles that we are dealing with is a free gas, then it is simple to show that the initial fluctuation is one over the square root of the number of particles, $N^{-1/2}$. For a galaxy, the number of particles is of the order of 10^{68}, thus giving a $\delta(o)$ of the order of 10^{-34}, a value to small to grow to unity within the presently known age of the Universe. However, the $N^{-1/2}$ expression is valid "only" if we are dealing with a free gas. If it happens that our equation of state, as we have shown in FIGURE 6, softens at high densities, namely dp/dn becomes zero or very close to zero at a certain point, then clearly the compressibility will be extremely large and so will the initial fluctuation. Landau showed that if there is a point, say n^*, where the pressure has zero derivative with respect to the density, i.e., if there is such a phase transition, then $\delta(o)$ is not given by $N^{-1/2}$, but rather by $N^{-1/6}$ (Ref. 2). For N of the order of 10^{68} we can gain an enormous amount, therefore making the model of galaxy formation still possible. However, if this indeed occurred, it would have happened at densities higher than 10^{18} or 10^{20} g/cm^3. At that time, the Universe was very young, and the mass within the horizon was certainly not larger than the mass of the earth. If such a phase transition occurred, the enhancement so achieved would then correspond perhaps to a black hole, a miniblack hole, but certainly not a galaxy. We cannot claim to have solved the problems of formation of galaxies, but we can certainly say that there is great hope that a lot of inhomogeneities did indeed form in the early Universe if such an equation of state is true. This inhomogeneity, which we can call loosely miniblack holes, can possibly be considered as the seed for future condensation into what we know today as galaxies. Work along these lines has been performed by several people at Cambridge, England, but as far as I know, I have never seen discussed the possibility of a phase transition and therefore an enormous enhancement of the initial density fluctuation. In the light of this more recent equation of state, such a possibility seems indeed to be a real one, and therefore the formation of miniblack holes is put into a more reliable theoretical framework. The work of the people at Cambridge should be extended in this direction, and the observational consequences of having miniblack holes, their possible explosion via the Hawking mechanism, the possible emission of a spectrum of gamma rays, and its consequent observational constraints, could be a way to backtrack our knowledge on the behavior of matter at high density.

I would therefore like to conclude my talk by saying that we have reached a state in which due to the dedicated work of many nuclear physicists in the last six years, the general scenario of neutron stars seems to be understood, at least as far as the constituents of the stars are concerned. Many problems remain in this field because we do not yet understand the radiation mechanism, but that doesn't belong to my talk. We do not expect any great surprises as far as the mass of the star is concerned, and the feeling of those of us who work in this field is that the mass of a neutron star will not in the future come out to be any higher than 2 (plus or minus 10%) solar masses.

However, the interest now has been displaced from neutron stars to higher densities, where, by doing a kind of patchwork we seem to have been able to tentatively construct an equation of state that, starting from a neutron star, can be extrapolated to much higher densities through the use of the data on proton-proton scattering and on black holes. Evidently, neutron stars constitute the basis on which we would like to pin down our equation of state, passing then through the region of proton-proton scattering all the way up to the physics of black holes. It is rather interesting that black holes, with a new mechanism of explosion and therefore the possible link to observational data on the gamma ray background, can lead us all the way back to the early stages of evolution at densities 1 million times higher than nuclear density, and therefore allow us to make some definite statement about the behavior of matter at super high densities.

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