Research of G.E. Brown

I. Atomic Physics (Electronic Interactions from QED)

The Brown-Ravenhall paper [1] showed that projection operators had to be introduced in order to avoid self-ionization of the correlated two-electron system. The Brown-Ravenhall prescription is almost universally used now in calculations of the relativistic atomic many-body problems. In ref. [2] I calculated from QED the electron-electron interaction to be used in those calculations. These two papers serve as the basis for present treatments of the relativistic many-electron problem.

In refs. [3] and [4] I laid out the method of calculating the Lamb Shift in heavy atoms to all orders in $Z\alpha$, lowest order in α. Measurements of the Lamb Shift for Uranium atoms ionized down to their last two electrons are now being made in Livermore and Berkeley, and results check calculations with my method down to a fraction of an electron volt.

My contributions in atomic physics were realized only some decades after I made them, because it took that much time until computers had developed so that they could tackle the relevant problems.

II. Nuclear Physics

I converted nuclear physics from a qualitative study with models into a systematic program in which quantitative calculations could be compared with data. I received the American Physical Society Bonner Prize for ref. [5], which shows how collective vibrations can be calculated from the effective two-body interaction in nuclei. In ref. [6] I introduced the ω-dependence of the effective nucleon mass $m_n^*(\omega)$ into nuclear physics. Ref. [7] with Kuo, and many following papers showed that effective two-body interactions in nuclei (shell model matrix elements) could be systematically and quantitatively calculated, beginning from the elementary nucleon-nucleon interaction. Many-body effects, such as the polarization of the medium, were crucial in getting agreement between calculated and empirical matrix elements.

The work of graduate students Scott Bogner and Achim Schwenk, under the supervision of Tom Kuo and myself, has put the Kuo-Brown interactions into a renormalization group formalism, showing that they are the unique effective interaction from the various two-body forces which fit low-energy nucleon-nucleon scattering. The effective interaction called V_{low-k} results from integrating out the contributions of all momenta which lie above those probed by experiments used to determine the nucleon-nucleon interaction. It is almost universally used now in microscopic nuclear structure calculations.

III. The Meson Presence in Nuclei

I was the first to unambiguously identify the meson presence in nuclei. This was done through the construction of meson exchange currents, beginning with the paper with Riska [8] in 1972. Using chiral invariance and the Weinberg low energy expansion, we developed low energy theorems to calculate how photons interacted with pions which were being exchanged by nucleons. This led to many experiments which quantitatively confirmed our predictions.

IV. Superdeformed States in Nuclei

In ref. [9] together with Tony Green I made the first study (in $^{16}0$) of superdeformed states in nuclei.

V. Stellar Collapse

In ref. [10] with H.A. Bethe, J. Applegate and J.M. Lattimer I laid the basis, in nuclear physics, for stellar collapse. In ref. [11] I laid out the theory for supernova explosions (although much of this was already known more empirically). The paper with Bethe is universally used in discussing the collapse of large stars, especially the 18 $M_\odot$ star which resulted in Supernova 1987A.

VI. General Many Body Theory

In ref. [12] I invented the Induced Interaction Formalism for many body problems. This shows how to make microscopic calculations in Landau Fermi Liquid Theory so that sum rules are preserved. This has been widely applied, especially in liquid ^{3}He. In connection with the renormalization group approach to effective interactions discussed in II, new relations between Fermi liquid parameters have been discovered. It has also been realized that the induced interaction <u>must</u> be included in microscopic calculations of superfluid gaps in neutron stars, in order to obtain quantitative results. The induced interaction guarantees satisfaction of the Landau sum rule (antisymmetry) at each stage of a dynamical calculation. Refs. [13] and [14] show how short-range correlations can be introduced into the electron gas. Ref. [15] introduces the very rapid ω-dependence of the interaction into the theory of liquid ^{3}He.

VII. The Chiral Bag Model

In a series of papers [16] – [19] with Mannque Rho, I formulated the chiral bag model (often called the "little Brown bag") which connected a small core of valence quarks with the exterior pion cloud by making the axial vector current continuous across the boundary. We were the first to establish that the baryon number is fractioned between quarks in the core and the meson cloud [19]. Our nonperturbative version [18] spawned a series of perturbative models, but these lack the Casimir effects which are of critical importance for many quantities. Michael Mattis and collaborators [20] and Aneesh Manohar [21] have published papers showing that our chiral bag model is the solution of large-N_c QCD.

VIII. Kaon Condensed Equation of State of Dense Matter

I proposed that in the collapse of large stars, as the density in the compact core became high (2-4ρ_o , where ρ_o is nuclear matter density) the energy of the K^- meson would become low enough, so that electrons would then go into a Bose condensate of antikaons. This softens the equation of state of dense matter considerably, so that the maximum neutron star mass is ~ 1.5$M_\odot$ [22,23]. This is currently particularly interesting because of the indications that the compact object in Supernova 1987A went into a black hole [24]. The work of Brown and Weingartner [25] shows that if a neutron star were present, then radiation from the accretion falling onto it would be about 100 times greater than the present bolometric luminosity (which comes from radioactivity, transformed into light, from the outer shells blown off in the supernova explosion).

The concept of low-mass (~ 1.5 $M_\odot$) black holes was new, as was the scenario in which there could first be an explosion, returning matter to the galaxy, followed by collapse into a low-mass black hole. This scenario depended on the kaon condensed equation of state.

With kaon condensation, many protons have to be present in order to neutralize the negative charge on the kaons. Brown and Bethe [23] showed that a more proper name for the compact objects is “nucleon stars” rather than neutron stars, because of the nearly equal numbers of protons and neutrons.

IX. Evolution of Relativistic Binary Pulsars

In paper [26] I showed that in the conventional scenario for binary pulsar formation, the neutron star from the first explosion nearly always goes into a black hole after entering the envelope of the companion star.

I consequently formulated an alternative scenario for the formation of relativistic binary pulsars. This begins from double helium star progenitors. In order to burn helium at the same time, the original main sequence stars must be within ~ 4% in mass. This scenario explains why neutron stars in a given binary tend to be very nearly equal in mass, whereas their masses differ appreciably between binaries.

Given this double helium star progenitor for the binary pulsars, I showed that accretion on to the neutron star during the helium-star, neutron-star binary stage brings the magnetic field of the neutron star down, so that it is slower to spin down. Building this “observability premium” into the evolution of binary pulsars explains why two of the four observed binary neutron star systems are narrow, with periods of only ~ 8 hours [27,28].

X. Matter Under Extreme Condition

With Mannque Rho, I suggested [29] that by incorporating the scaling property of QCD in low-energy effective chiral Lagrangians, the approximate *in-medium* scaling law

$$m_\sigma^* / m_\sigma \approx m_N^* / m_N \approx m_\rho^* / m_\rho \approx f_\pi^* / f_\pi$$

where the m_N^* is the nucleon *effective mass,* defined by the momentum-velocity relation

$$p / m_N^* = v ,$$

where v is the nucleon velocity, and f_π is the pion decay constant.

We have applied these ideas extensively in nuclei in order to explain many discrepancies [30]. We have also made a number of applications to the hot matter, studied by lattice gauge calculations or formed in relativistic heavy ion reactions [31]. These ideas have motivated at least two multimillion dollar experiments, KAOS and HADES at GSI, Darmstadt.

The excess dileptons found in the CERES experiments carried out in the last few years can be explained only by the dropping masses. However, Rapp and Wambach [32] proposed what was thought to be an alternative theory, phrased in ordinary hadronic variables.

Extensive work by Harada and Yamawaki [33] has, however, firmly established that the Brown/Rho prescription of introducing the effective hadron mass, e.g., m_ρ^*, parametrically into the Lagrangian and then using this Lagrangian in dynamical calculations such as the Rapp/Wambach configuration mixing is the correct approach. Thus, the two descriptions of medium dependent masses should be “fused”. The original Brown/Rho Phys. Rev. Lett. [29] has ~ 500 citations.

XI. Evolution of Black Holes in the Galaxy

Black holes are observed only in binaries. A companion star, which pours matter through the Lagrange point so that it circles the black hole is necessary. The black hole can then be observed through the visual X-ray or gamma-ray emission emitted from the accretion disk, which is heated by viscosity.

The critical stellar mass needed for formation of black holes in theoretical evolutions has steadily increased over the past years as investigators have calculated that only ever more massive stars ended up as neutron stars, not black holes. Thus, assuming a simple mass cut below which stars leave neutron stars and above which they become black holes, the lower mass limit expected for black holes rose with time to > 50 $M_{\odot}$. Such massive stars are rare, and their number is two to three orders of magnitude too low to make the number of black hole binaries in our Galaxy. This was a paradox, which I resolved.

The way to evolve a sufficient number of black hole binaries was first suggested by Brown, Weingartner, & Wijers [34]. They pointed out that in the usual evolution of binaries, when the more massive star evolved, it transferred its hydrogen envelope, while either in main sequence stage or in red giant, to the companion star; leaving a naked helium star. The latter burns hot, exerting a lot of thermal pressure on its outer parts, so that the helium star blows away to the extent that there is too little remaining core to form a black hole, rather ending up as a neutron star. This paper contradicted the "accepted wisdom" that the way a helium core burned did not depend upon whether it was naked or covered by a hydrogen envelope. Our paper was not generally believed because we used wind loss rates that were later shown to be a factor of 2 to 3 too high.

Nonetheless, the idea that the helium core burning must be completed before the hydrogen envelope was removed was pursued because it explained observations. Stars of all zero age main sequence (ZAMS) masses were evolved, with the best available physics, and lower, more correct wind losses were employed. The result confirmed our earlier idea [35]. Enough of the star in order to make a black hole remained only if the helium core burning took place while the star was still clothed by a hydrogen envelope. By this time the hydrogen envelope of the giant star will have expanded to about 5 times the distance from earth to the sun, so the binding energy of its envelope, which goes inversely with the radius as 1/R, is very small. The envelope expands out to the binary companion after it has completed helium core burning. The companion star in the binary then couples to the envelope hydrodynamically, and removes it by common envelope evolution, the removal energy being furnished by the drop in gravitational binding energy of the companion as it spirals in. In this way a relatively low mass companion; e.g., a G-star of about the mass of our sun, can end up just outside the helium core of the giant after furnishing the energy to remove the hydrogen envelope of the giant; the low-mass star ending up sufficiently close to the giant to donate matter to it (so that we can observe the system). This gives an explanation of why in all of the black hole binaries with main sequence companions, the latter has a low mass of ~ 1 $M_{\odot}$ even though the mass of the giant black hole progenitor was ~ 25 $M_{\odot}$.

Suppose the companion is more massive, say of several solar masses. Then it can furnish the required energy to remove the envelope of the expanding giant by a smaller decrease in orbital separation; e.g., a 2 $M_{\odot}$ companion has to spiral only half of the way in to deliver the same binding energy as a 1 $M_{\odot}$ star that spirals all of the way in. But then the companion lies too far away from the black hole which results from the giant. We call these companions "silent partners" [36]. These binaries will be seen only late in the life of the companion, when it evolves and expands.

In fact, we observe about as many black hole binaries with evolved companions as main sequence. But the time of evolution is only a few percent of the main sequence time. Thus, there must be between one and two orders of magnitude more binaries with silent partners than those observed in the Galaxy. Our population syntheses give a total of about 100,000.

The black hole progenitors are stars of ZAMS masses 20-30 $M_\odot$. Once they have finished the helium core burning, they all have a radius of 1,000 $R_\odot$ (~ 5 AU where 1 AU is the distance between earth and sun) within 10%. Thus, we find that following common envelope evolution, the binary separation of the core and the donor companion star is

$$a_f \approx 2.8\ M_{donor}$$

with M_{donor} in units of solar mass, and a_f in solar radii. The explosion of the He star comes essentially immediately, on the time scale of the giant black hole progenitor, so this relation tells us the pre-explosion period of the binary. In the explosion, matter is ejected from the part of the He core that remains after the center goes into a black hole. Part of this matter is intercepted by the companion star. In the cases of the explosion we have reconstructed this took place about one billion years ago, sufficient time for the accreted matter to be homogenized throughout the companion. From the relative abundances of the elements we can reconstruct the energy of the explosion, about ten times that of a supernova explosion. Hence, we name it a "hypernova".

Hypernovae seem to be associated with gamma ray bursts. In the next section we shall see that both are powered by the rotational energy of the black hole.

XII. Theory of Gamma Ray Bursters

Woosley [37] was on the right track when he suggested the failed supernova, later renamed collapsar, as model for GRBs. In this model a rapidly rotating Wolf-Rayet (large star without hydrogen envelope) collapses in the center into a black hole, the outer part of the star – which is supported by centrifugal force – falling into an accretion disk from which matter is transferred into the black hole. This is a model for the longer term GRBs in which the central engine runs more than ~ 2 sec. There are two problems with this model: (1) Viscosity, arising mostly from the twisting of magnetic field lines, is sufficiently strong in order to bring the entire star into a common (rigid-body-like) rotation, so that when it collapses it will simply fall inwards and disappear. (2) Even if this does not happen, the centrifugal force can only support the outer part of the star for a viscous time, the time it takes to change angular momentum into energy (advecting enough material with angular momentum from the outer part of the He star to satisfy the conservation of it.) This time is

$$\tau_{viscous} \sim 100 \text{ seconds},$$

relatively long because of the thin, neutrino cooled, accretion disk.

The first of these problems is cured by starting from binaries, because in both the common envelope evolution and the later He star, donor binary, the tidal interactions will work to isochronize only the outer part of the He star with the orbital period of the binary. This results in the necessary centrifugal force to support the outer part of the He star. We will return to the expulsion of the supported matter below.

The center of the He star burns first to an Fe core, which later falls into a neutron star. Accretion from the inner disk adds matter to the neutron star and brings it into corotation with the inner disk. Once the maximum neutron star mass (~ 1.5 $M_\odot$) is surpassed the neutron star falls into a black hole. The latter is much smaller than the neutron star, but must carry the same angular momentum, so it must rotate much faster; in fact, with nearly the speed of light.

In general there will be strong magnetic fields of ~ 10^{14} Gauss present. Some of these fields thread the black hole, the open field lines going in the direction of the rotation axis, the closed ones ending up at the other end frozen in the accretion disk. Such a rapidly rotating black hole in a strong magnetic field is a good generator of electrical current, ~ 10^{24} amperes under the given conditions [38]. The black hole surface ("event horizon") is a good conductor of electricity with resistance $R = 4\pi/c$, just the impedance of a wave guide ending in a vacuum. Thus, if one thinks of a wire loop attached to the black hole, with one piece of the wire along the surface of the black hole from north pole (in the direction of rotation) to equator, and the rest of the loop opening out into the region about the black hole (including some of the accretion disk), then as the black hole rotates such a rigidly attached wire will cut magnetic field lines. From Faraday's law it will drive electrical currents.

Such a current will go along field lines in the region where the magnetic field is strong, up the north pole, driving the jets which result in the gamma ray bursts.

The black hole is formed rotating several times faster than the accretion disk. Through the closed field lines which thread the black hole and are frozen in the matter of the disk, it torques the disk up. Angular momentum is delivered to the inner disk, the energy being transformed into heat over a viscous time scale. This heat energy then powers the hypernova explosion, which takes some days to develop. The gamma ray burst is highly beamed, to an opening angle of a degree or two, whereas the hypernova explosion, although aspherical, is not beamed in this way.

Our scenario explains the nearly equal energies in GRBs, once beaming is taken into account, as well as those in the hypernovae explosions, since the black hole rotational energies are always roughly the same. The rate at which energy is delivered, the power, will, however, vary from GRB to GRB, since it depends on B^2 , the square of the magnetic field.

We presently observe 15 black hole binaries in the Galaxy which we identify as fossil remnants of GRBs. The most famous one, Nova Scorpii, went off about one billion years ago. From the factor of ~ 10 enhancement in the metals found on the companion we can construct in some detail what the separation of the He star core of the giant and the companion was at the time of explosion and the energy of that explosion.

Our scenario has been developed in [39,40].

XIII. The QCD Phase Transition as Studied at RHIC

To the surprise of many, the Au + Au collisions at RHIC appear completely different from what would result from the folding of 197 nucleon-nucleus collisions, the way in which many heavy ion phenomena at lower energies are "explained." Clearly there is a collective phenomenon which overwhelms the single part of the collisions. We (Brown/Rho) describe this collective phenomenon in terms of chiral restoration as detailed in Brown/Rho scaling.

When the Lorentz-contracted Au nuclei are on top of each other, the baryon number density per unit of rapidity is about 20 n_o , where n_o is nuclear matter density, clearly enough for chiral restoration (3-5 n_o).

So the RHIC collision begins with a chiral restoration wave sweeping over each nucleus, bringing the hadron masses to zero (in the chiral limit) and also the coupling constants to zero, as shown by Harada and Yamawaki [33] and as deduced from lattice gauge couplings of the quark number susceptibility by Brown and Rho [31].

With the piling of positive energy constituent quarks on top of the negative energy sea, which produces the breaking of chiral symmetry and gives the quarks their masses, chiral restoration is restored in the time that it takes the constituent quarks to exchange a scalar σ particle

$$\tau_{xr} \approx \hbar / E_\sigma c \sim 0.2 \text{ fm} / c.$$

By this time the plate-like nuclei, which travel with the velocity of light, are ~ 0.52 fm apart. Since the gauge couplings go to zero with chiral restoration, the gluons in the gluon cloud about the constituent quarks are set free. There are enough of them to form a Bose condensate, the color glass of McLerran and collaborators … to be continued.

Recently Brown and Rho (in preparation) have shown that the vector meson mass m_ρ* scales with the square root of the quark in medium quark condensate <qq>* for low densities n_o, up to nuclear matter density, and linearly with this condensate for higher densities and temperatures. The <qq>* is easily calculable from the Nambu-Jona Lasinio effective theory. Thus, we now have a quantitative theory of how masses drop with either density or temperature or both. Thus, Brown/Rho scaling is now a quantitative theory (for which Mannque Rho received the 2002 Hoam Prize of ~ $100,000 in Korea).

Chiral restoration with density occurs at $n = 5\ n_o$, where n_o is nuclear matter density, but can be brought down to ~ 3 n_o with the help of the Rapp/Wambach configuration mixing provided that their matrix elements are correct.

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