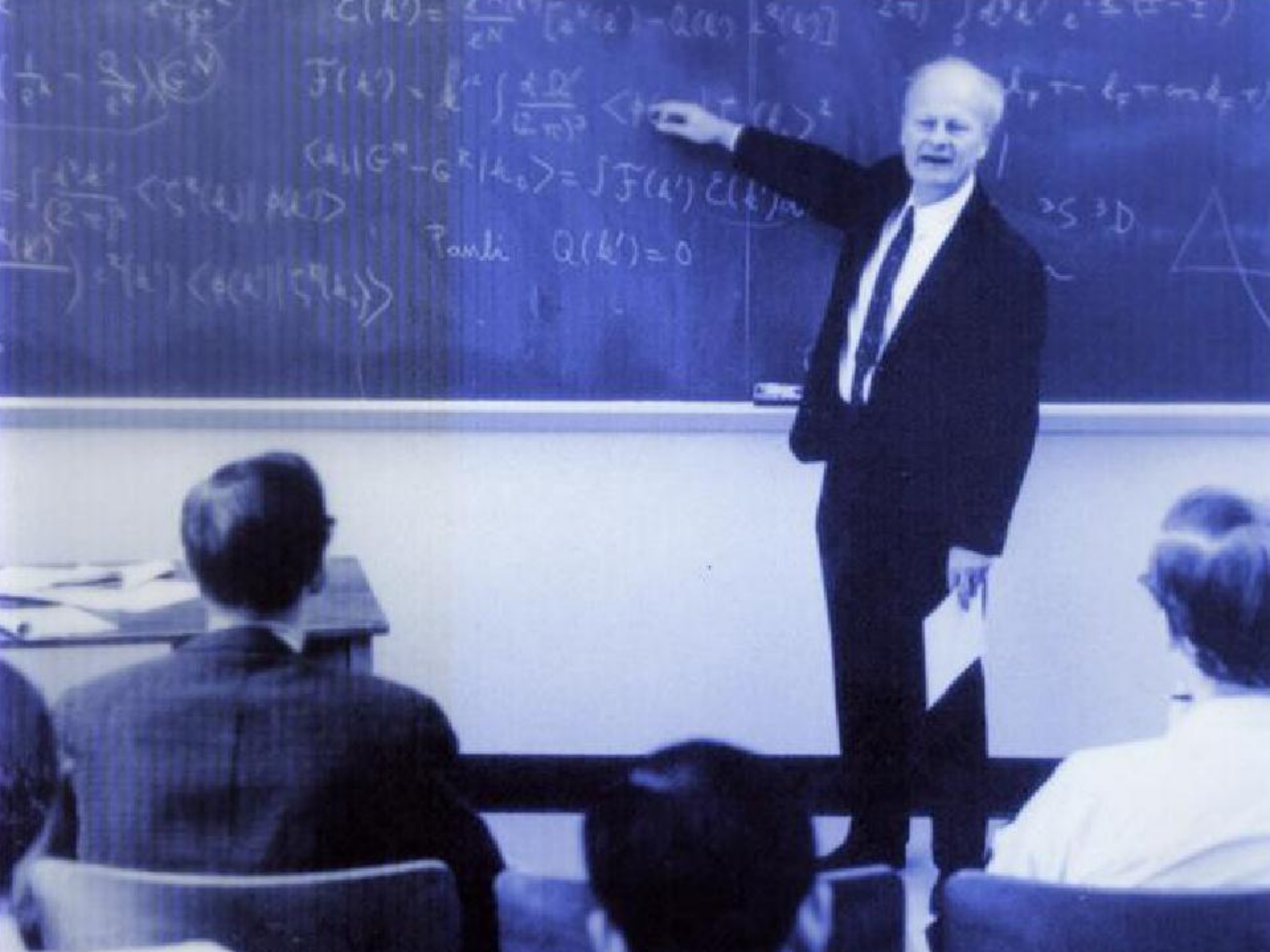
Hans A. Bethe

A giant in physics and a statesman in nuclear disarmament

Vital Statistics

- Hans Albrecht Bethe was born in 1906 in Strassburg and died on March 6th 2005 at Ithaca, the town that housed his beloved Cornell University.
- He got his doctorate in 1928 from the University of Munich. During 1929-33 he moved around different universities, at Frankfurt, Stuttgart, Munich, Rome (with Enrico Fermi) and Tubingen.
- He emigrated to England (Manchester) in 1933 and from there to Cornell University, USA , in 1935 where he spent the rest of his working life.


Pauli Q(k') = 0

Elder Statesman par excellence

- **Decades before his death he had already become the most revered physicist alive in the world .**
- **This was not just because he had physically outlasted fellow greats of his generation and confounded scientists half his age by remaining a working physicist well into his mid-nineties.**
- **But he had attained his awesome reputation long before that, through the all pervasive breadth of his research, his contributions to public policy in science, and the statesmanlike role on both these fronts that naturally fell upon his shoulders.**

The Second Generation

- He was not part of the first generation of giants in 20th century physics—Einstein, Bohr, Heisenberg, Schrodinger Dirac Pauli… – who brought about a profound conceptual revolution in physics through Relativity and Quantum Mechanics.
- Bethe belonged to the next generation, on which fell the task of constructing, based on the principles of quantum mechanics and relativity, individual theories of widely different domains of physics.
- As the worlds of atomic, nuclear, condensed-matter, sub-nuclear and astro-physics were unveiled through the ingenuity of experimental physicists, Hans Bethe had made seminal contributions to each of these areas in his amazingly long career.

Short list of seminal contributions

- The Bethe Ansatz (1931)
- Theory of Metals (with Sommerfeld, Handbuch 1933)
- The Bethe Bible for Nuclear theory (3 long reviews in Rev Mod Phys.1936-37)
- The empirical mass Formula, Shell Model O^{16} and Ca ^{40}, Effective length (1930’s)
- The Lamb Shift (1947; Resurrection of QED)
- The Bethe-Salpeter equation
- Theory of Nuclear Matter (1956-67)

Astrophysics

- Energy production in Stars
- Nuclear Matter and Structure of neutron stars
- Solar Neutrinos
- Merging of neutron star–black hole binaries; Accretion, Supernova dynamics
- Shock Waves and other classified work
- John Bahcall : It was as if “several people (were) engaged in a conspiracy to sign their work with the same name”
- I will describe briefly the first two topics (Bhaskar Dutta)

Energy Production in the Sun and Main Sequence stars

- The energy the Sun gives is crucial not only for us humans but for all life and so much else on earth.
- Not surprisingly the source of this energy has intrigued scientists, philosophers and lay persons alike for centuries.
- Leaving out mystical and religious depictions of the sun, let us focus on what modern science tells us.
- Two of the simplest and most natural candidates that 19th century physics would naturally think of as the source of the sun’s energy don’t fit the bill
- Let us give quick estimates for why they are ruled out, before going on to the correct explanation

Is the Sun just an ordinary Fireball ?

- The most natural way of heat and light get generated on earth is thorough burning– of coal, wood, hydro carbons.
- Can this explain solar energy? Is some material (Carbon ? Hydrogen?) just burning there in the sun, in our day to day sense of burning?
- Burning is release of chemical energy stored in atomic and molecular bonds. Typically such energies are in the range of electron volts or less. Let us assume that all the atoms in the sun contribute through burning a few eV each. Can that explain solar energy? Even a rough order of magnitude estimate will rule it out.

- The mass of the sun is 2 x 10 ^{33} g. At approximately an Avagadro number (6x 10 ^{23}) of atoms per gm this corresponds to 10 ^{57} atoms. At 1 eV each(10 $^{-19}$ Joules), these can give altogether 10 ^{38} Joules.
- Meanwhile the solar luminosity is 3.8 x 10 ^{26} J/sec. At that rate the 10 ^{38} Joules will last for only 3 x10 ^{11} seconds or 10,000 years.
- But the life of the sun is known to be about 4.5 billion years.
- So ordinary chemical combustion cannot be the source of solar energy.

Gravitational energy

- The other obvious candidate is gravitation.
- Could the Sun and other stars be releasing some of their massive gravitational potential energy by gradually shrinking.
- Such calculations were done already by mid 19th century (Helmholtz)

$$P.E./g = {}^{-GM}\!\Big/_{R}$$

$$M \approx 2.10^{33}\, g,\quad R \approx 7.10^{10}\ cm,\quad G \approx 6.7.10^{-8}$$

$$PE/g \approx 2.10^{15}\, ergs$$

Solar radiation $\approx 1.96\ erg/g/\sec$

Grav energy can last for $10^{15}\sec$

≈ 30 million years

Sun's actual age ≈ 4.56 billion yrs

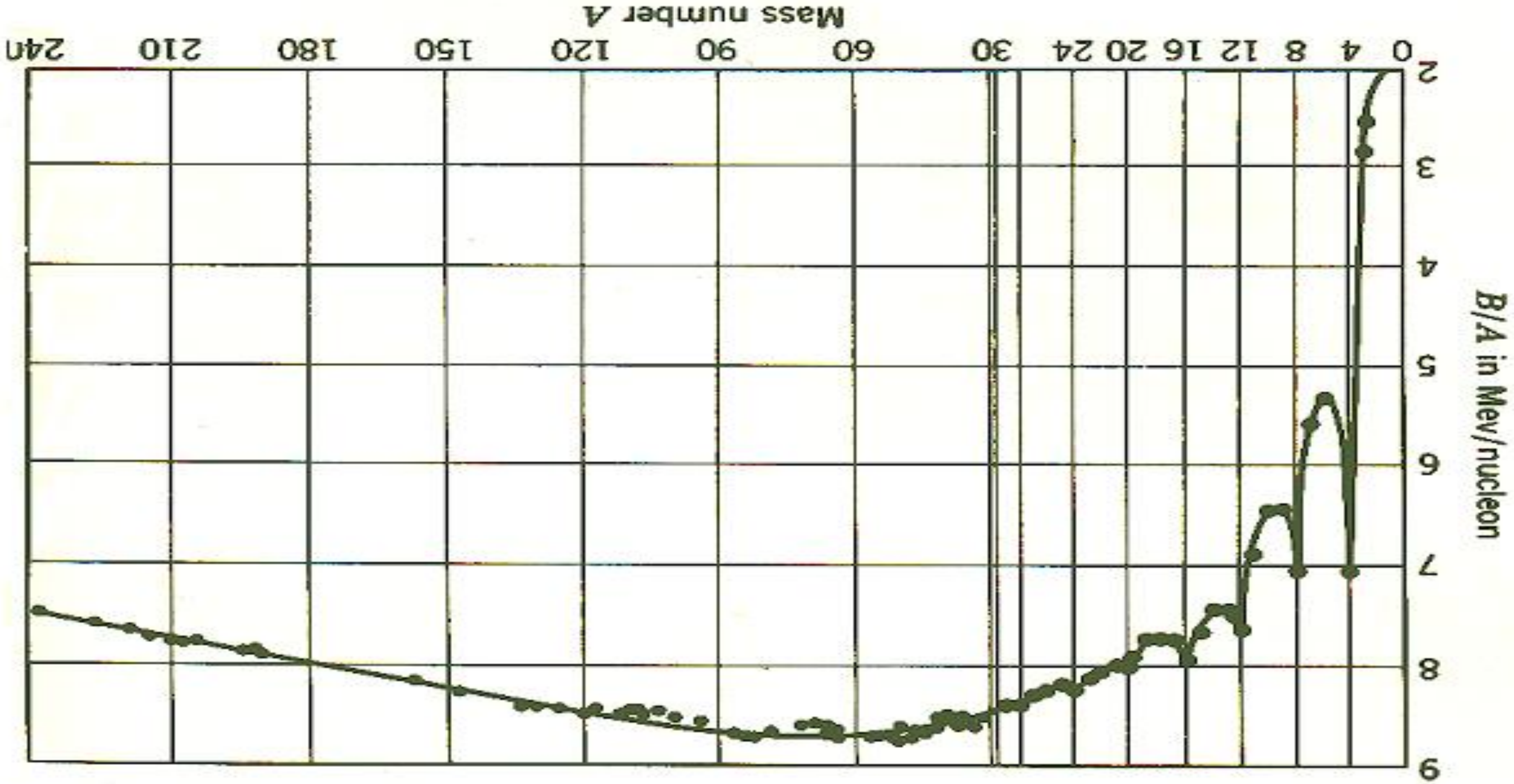
Gravity cant be the main energy source.

- You might say that electricity is another familiar source by which we generate heat. But remember that most of our electrical currents are also created by converting gravity (hydroelectric) or coal/diesel burning.
- So there was no candidate for the sun’s energy till, fortunately, the much stronger nuclear forces were discovered in early 20th century . Coupled with radioactive decay and Einstein’s $E = mc^2$ they offered a possible candidate

By the 1930s it was felt that solar energy must come from FUSION of very light nuclei.

Potential energy per nucleon in different nuclei

(Bethe -Weizsacher formula)



Nuclear Fusion

- Before fusing, the two nuclei must overcome coulomb repulsion to get close enough to each other. Requires low Z nuclei and high temp (available in the sun)
- The simplest candidate (Weizsacher , Bethe-Critchfield) is
- $\mathrm{H} + \mathrm{H} \rightarrow \mathrm{D} + e^{+} + \mathrm{v}$ υ
- Once deuterium was formed, it would fuse further to ultimately produce the very stable nucleus of He.
- $\mathrm{H} + \mathrm{D} \rightarrow \mathrm{He}^{3} + \gamma$, $\mathrm{He}^{3} + \mathrm{He}^{3} \rightarrow \mathrm{He}^{4} + p + p$
- B-C (1938) calculated energy produced from this sequence of reactions in detail and found it could explain the energy production in the sun provided the central temperature was appropriate.

- Around this time, in 1938 Gamow gathered together a small select group of physicists and astrophysicists, to discuss energy production in stars. Bethe, then busy with QED, was persuaded by Teller to attend this conference and that turned out to be a great boon.
- For one thing, Stromgren informed them that the latest estimate of the solar central temperature was closer to 15 x 10^6 than Eddington’s earlier estimate of 40 x10^6.
- This lowered temperature, when inserted into the Bethe -Critchfield calculations correctly predicted the solar luminosity. The sun’s energy had been understood!
- That was good, but it was also clear that this H+H reaction does not work well for heavier stars in the main sequence, which have a much higher luminosity.

Heavier stars

- They do have a higher internal temperature making the reactions go faster as it is easier to overcome the coulomb repulsion. Indeed Bethe’s calculations showed that the energy produced by the H+H sequence grows as T^4
- Now, T varies from19 to 33 x10^6 as you go from the Sun to 10 solar masses. So T^4 increases by about 9.
- But that is nowhere nearly enough.
- Observations showed that when the star’s mass increases by10, the luminosity increases by about 3000. Hence the energy production per gram has to be about 300 times larger. Some other theory had to be found for the bigger stars.
- Bethe returned home with this challenge

- (This pattern of running into a theoretical challenge on a trip, and subsequently solving it in a seminal paper has happened to Bethe more than once. In two famous instances he had in fact solved the problem in the train ride back from the visit.
- One was the theory of the photo disintegration of the deuteron, which he constructed with Rudolph Peierls, on the train ride back from Cambridge where Chadwick had just told them about the experimental discovery of this reaction ($\gamma + d \rightarrow n + p$)
- The other was the 1947 calculation of the lamb Shift on his train journey back from the Shelter island meeting on QED.

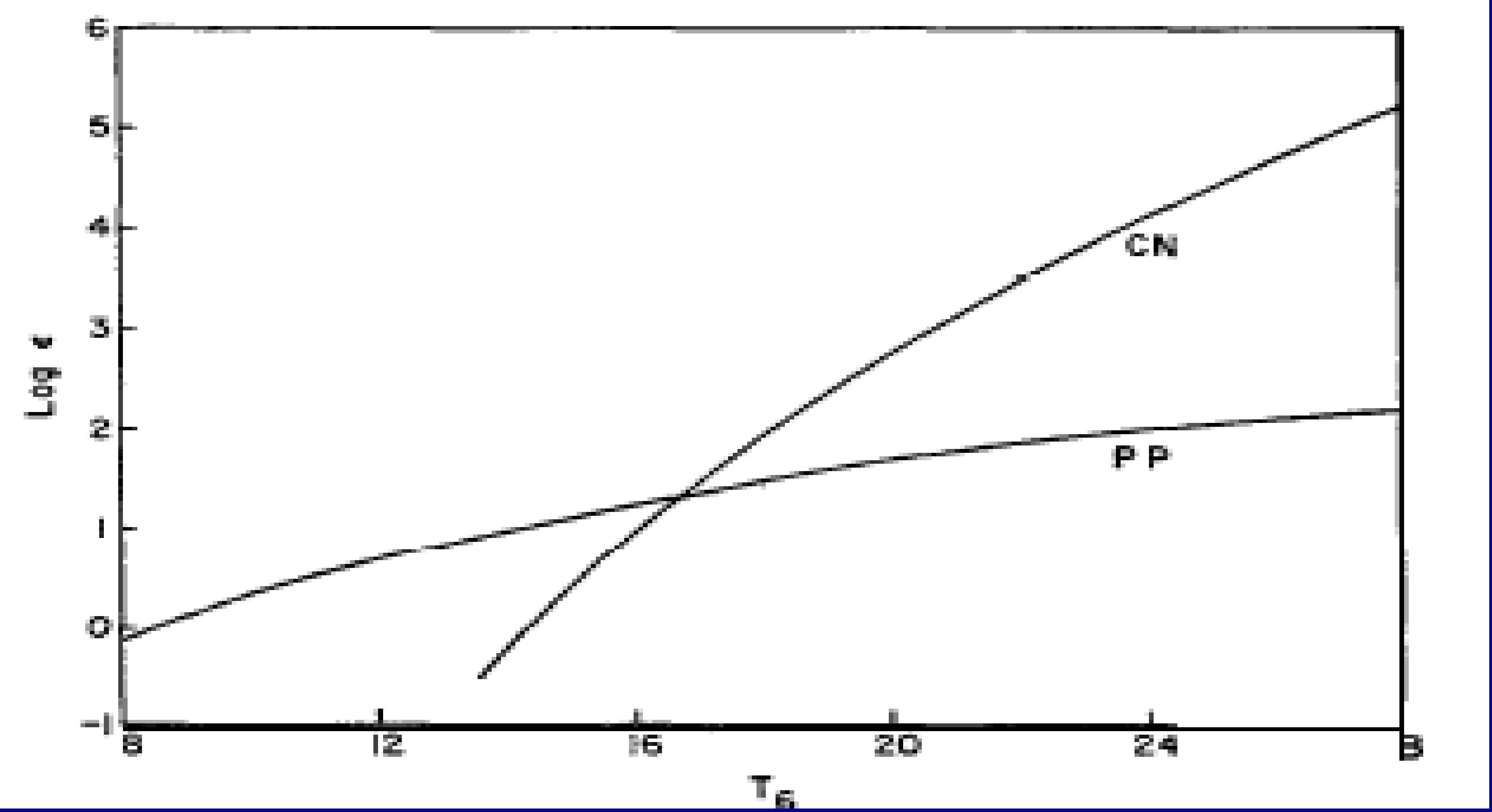
- The Stellar energy problem took more than a train ride to solve, but Bethe did publish it within a year. His 1939 paper was a tour de force of theoretical prowess.
- He systematically looked for reactions involving heavier nuclei where the increased Coulomb interaction brings stronger temperature dependence.
- Fusing H with He^4 is not possible since there is no stable nucleus of mass 5.
- Reactions of H with Li, Be and B do happen , but at stellar temperatures of 20 million degrees are so fast that the supply of the latter nuclei is very quickly consumed in the process. These cannot provide sustained energy over stellar lifetimes.
- That took Bethe to the next element C, where he found an ingenious answer

THE C-N-O Cycle

H.A. Bethe, Phys. Rev., 55 (1939) 436.

- $C^{12} + H \rightarrow N^{13} + \gamma + 1.95$ MeV
- $N^{13} \rightarrow C^{13} + e^{+} + \nu + 2.22$ MeV
- $C^{13} + H \rightarrow N^{14} + \gamma + 7.54$ MeV
- $N^{14} + H \rightarrow O^{15} + \gamma + 7.35$ MeV
- $O^{15} \rightarrow N^{15} + e^{+} + \nu + 2.75$ MeV
- $N^{15} + H \rightarrow C^{12} + He^{4} + 4.96$ MeV
- The carbon is essentially a catalyst and is recovered and available for the reaction again
- In effect, $4\,H \rightarrow He^{4}$ + energetic leptons, photons

- This carbon-nitrogen-oxygen cycle has a strong temperature dependence $T^{18\text{-}24}$.
- While the basic H + H→ D fits the smaller stars , the CNO cycle picks up speed for the heavier stars.
- (The basic H+H reaction and the CNO cycle were independently considered by Weizsacher; but he did not calculate either their energy production or T dependence)



The energy production, in erg/g sec as a function of the temperature in millions

As T grows by a factor of 1.5, (which in turn would correspond to M growing by a factor of 10), the luminosity increases by 3 orders of magnitude. Thus the model also fits the high luminosity of heavier stars.

Nuclear Matter:

- **Next, let me talk about the theory of Nuclear Matter, and its applications to astrophysics, on which Bethe worked for a long period, starting from about 1955.**
- **This was the area on which I worked with him ; so I can talk with some first and knowledge.**
- **All nuclear structure theory till then had started with some intermediate “phenomenological” models: Liquid Drop Model, Shell Model, Collective Models, ...**
- **These models, although successful in predictions, could not be derived from the basic Schrodinger equation. What is the source of the Shell Model’s central force which makes the shells form?.**

Theory of large nuclei from First Principles

Ideally one would like to solve

$$\left(\sum_i^A -\frac{\hbar^2}{2m_i} \nabla_i^2 + V(1,2,.....A) \right) \Psi(1,2,....A) = E\, \Psi(1,2,....A)$$

where Ψ is the wave function in terms of the A nucleon coordinates, E the total energy and V(1,2, A) is the interaction given by

$$V(1,2,....) = \sum_{i,j} v_{ij}$$

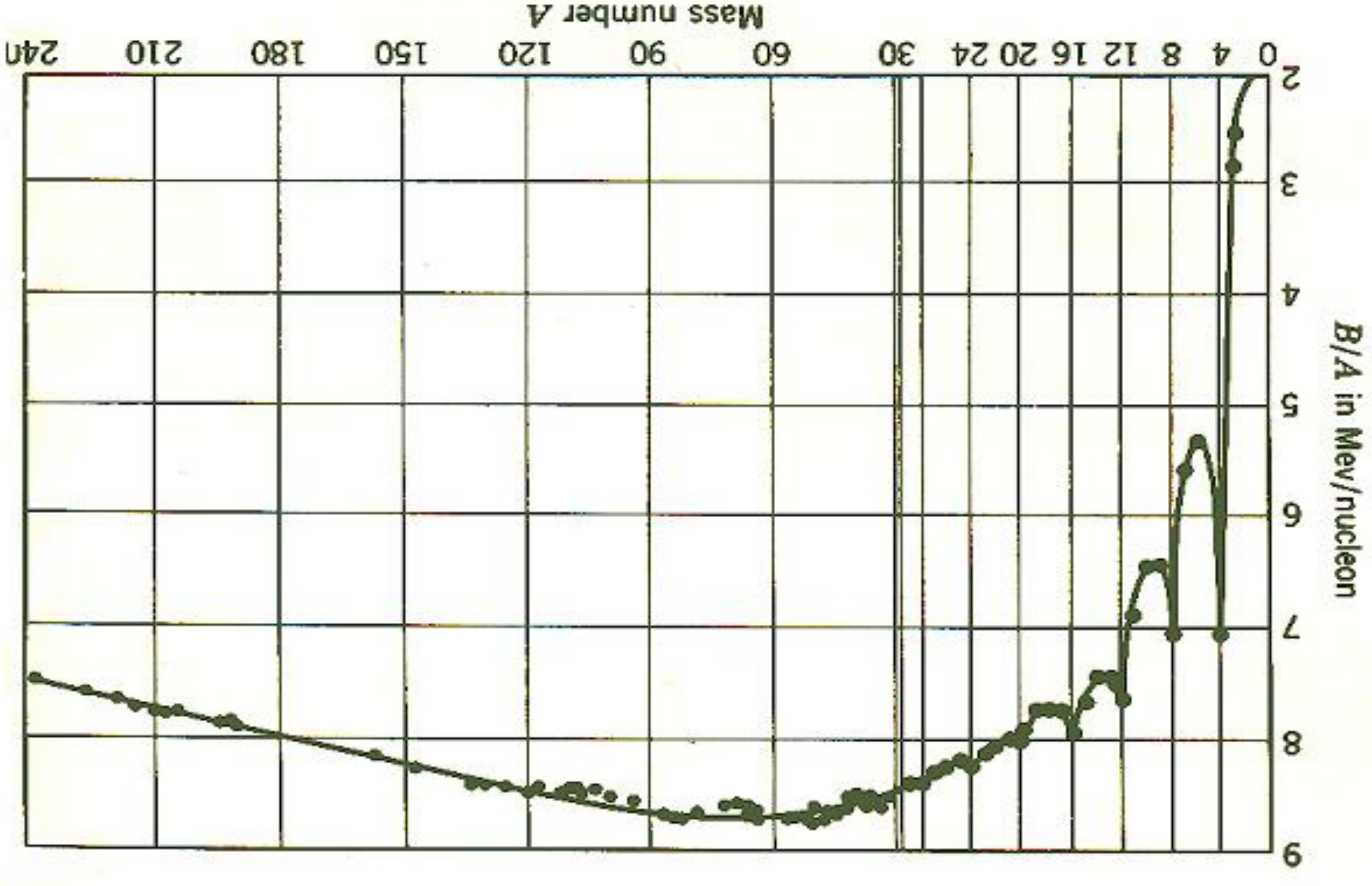
where v_{ij} is the normal two-body interaction between the ith and the jth nucleon (including both the strong nuclear as well as the Coulomb interaction),

- But this is a very hard to do, even in classical mechanics for n>2. Thus the Sun-Earth problem can be tackled analytically, but add on the moon or a few other planets , calculations become very difficult requiring cumbersome numerical work.
- In quantum mechanics difficulties can only get worse! Thus the H atom can be attacked analytically, but Helium already requires approximations, and something like Copper is impossible to do exactly.
- Similarly in nuclear physics. People could do the deuteron problem easily, given some n-p interaction. But triton onwards, calculations become hairy.
- Two things make the nuclear situation even more difficult compared to Atomic theory:
- 1.There is no strong and heavy central nucleus, which provides a central force in Atomic physics
- 2. The N-N potential is much more complicated than Coulomb.

Nuclear Matter

- **Although n-body dynamics is exceedingly difficult for any finite n > 2, it becomes in some ways simpler for n → ∞ if we can exploit the thermodynamic limit.**
- **Consider an infinite number of nucleons, occupying infinite volume, distributed at some uniform density. *This is the hypothetical system called Nuclear Matter*. It is similar to ordinary matter, like a big chunk of iron with 10^{23} closely packed iron atoms. Nuclear matter is similarly close packed with nucleons instead of atoms.**
- **To simplify further, assume it has an equal number of protons and neutrons, with the Coulomb interaction turned off . This is called "symmetric nuclear matter". Since we have a good understanding of the Coulomb force, we can add it in later.**
- **BUT even assuming that these assumptions simplify the theory, where can we get a sample of such matter to check the predictions of the theory? Real nuclei are far from infinite or Coulomb free.**
- **An obvious candidate today is a neutron star, but remember that Pulsars were discovered only in 1967.**

But theorists cleverly found a way of extrapolating the properties of real nuclei to get properties of such infinite symmetrical nuclear matter



Bethe - Weiszacker Mass Formula.

- This energy curve can be fitted well by the Bethe-Weiszacker Semi-emperical Mass Formula.

$$E(A) = -a_v A + a_s A^{2/3} + \frac{a_c Z^2}{A^{1/3}} + \frac{a_a D^2}{4A} .$$

where *A* is the nucleon number, Z is the atomic number, D=A-2Z. Let us apply this to our nuclear matter.

The second term vanishes as compared to the first as A → ∞.

The third term is zero since the coulomb interaction is, by hypothesis absent. Finally since symmetric nuclear matter has equal no. of protons and neutrons, the last term is zero.

So the entire energy comes from the first (volume) term alone and we know from fitting the B.E curve that it has a value of $a_v \approx 15.8$ MeV per nucleon. So this is the experimental value of the energy of our hypothetical nuclear matter.

Another feature of nuclear matter is also deducible from finite nuclei. The density profile of nuclei can be measured by scattering electrons. One can take the density of infinite nuclear matter to be the interior density of large nuclei, after correcting for the absence of Coulomb interaction. It is $\rho_0 \approx 0.17$ nucleons per F^3 .

So our task is to solve from first principles the Schrodinger equation , in the limit $A \rightarrow \infty$, and the volume $\Omega \rightarrow \infty$ at some fixed density $\rho = A/\Omega$.

Then calculate the ground state energy E as a function of ρ and show that it minimizes at $\rho_0 = 0.17$ F-3 at a value of E/A = -15.8 MeV.

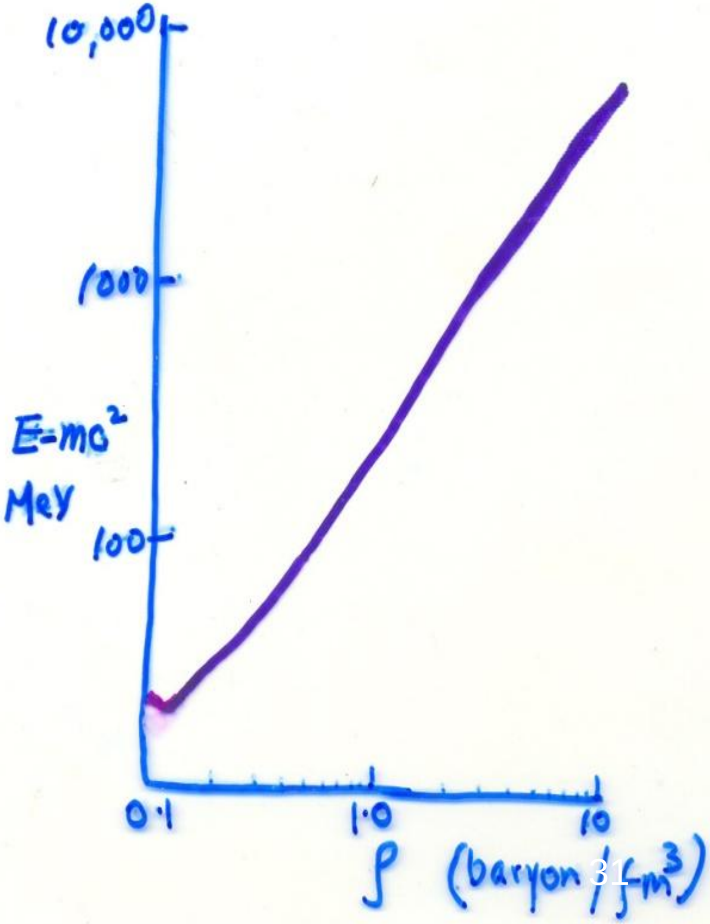
- **After years of effort and much development of many-body techniques, we managed to do calculate E(ρ) by the mid sixties and found the correct energy and density of nuclear matter from first principles.**
- **But I wont go into the details since that was of interest primarily to nuclear physicists, whereas our primary interest in this talk is in Astrophysics.**
- **However, by that time Pulsar was discovered and it became accepted that except for a thin surface crust, the bulk of the pulsar was a liquid of neutrons.**
- **This was then an actual realization of the hypothesized nuclear matter. It was essentially infinite, had mostly neutrons (no Coulomb) and essentially in the ground state (Temp $\approx 10^{8}$ K, whereas 1Mev $\approx 10^{10}$ K), at a density varying from ρ_0 to $10\rho_0$**
- **Bethe and M. Johnson did extensive calculations of the equation of state $P = \rho^2 dE/d\rho$ of pulsar interiors with E(ρ)calculated using nuclear matter techniques.**

Some sample results :

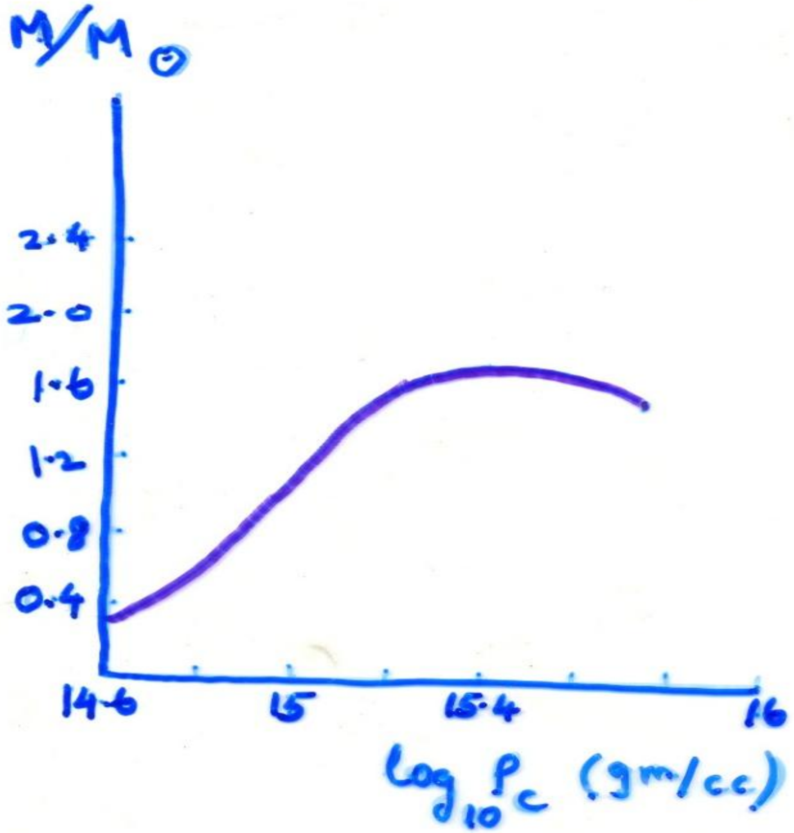
Energy vs density of dense baryon matter

Notice:

1. The energy has a minimum around the normal nuclear density $\rho_0 = 0.17$ baryons/fm ^{3}
2. At higher densities the energy becomes large and positive. Nuclear matter becomes unbound in terms of nuclear forces alone. Gravity is what holds the star together.

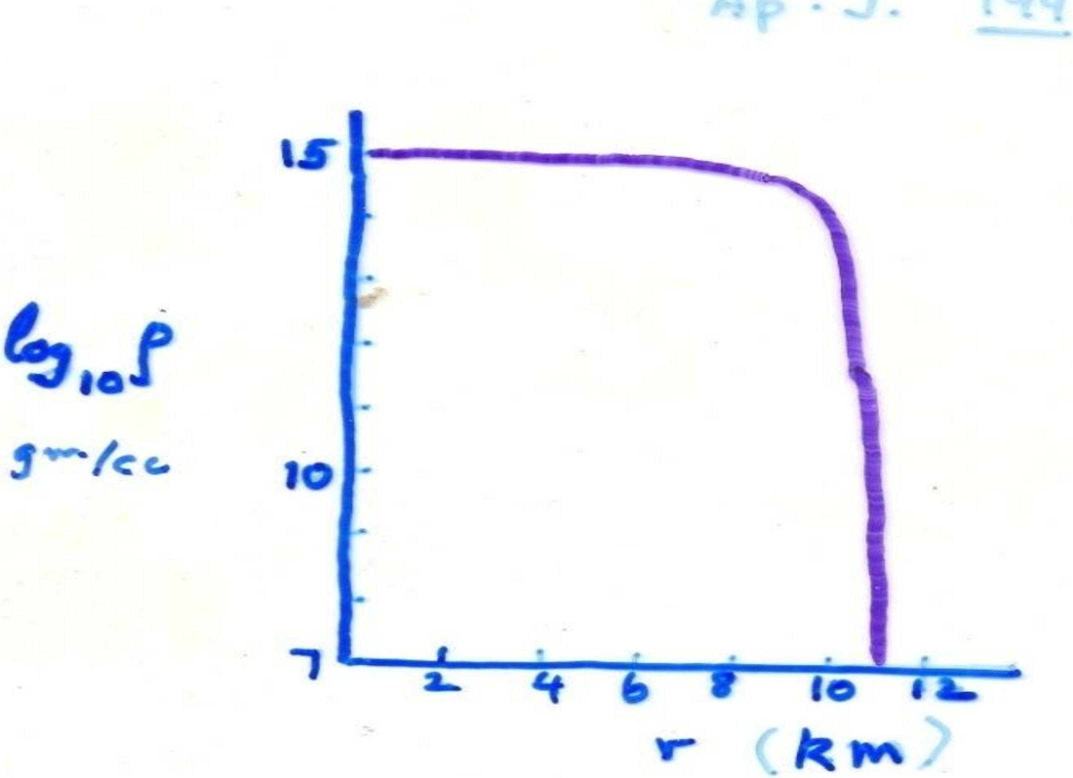


Mass of the neutron star as a function of central density



Taken from Malone, Johnson and Bethe
Ap. J. <u>199</u>, 741 (1975)

Density profile of the star



Work In the public realm

- In addition to the massive amount of work he did in pure physics Bethe had a major role to play in the unfolding of the nuclear era, both its technology and its public policy.
- This part of the story is harder to tell than describing his purely scientific achievements.
- It requires touching on the moral and ethical issues he grappled with, in first helping make the first nuclear bomb, and then in subsequent decades working very hard for nuclear arms control.
- This side of his life also gives us some glimpses of Bethe the man.

Refuge from Nazi Germany

- He was deeply devoted to the US and its security. To appreciate this let us recall how he moved to the US.
- In the early thirties, dark Nazi clouds were gathering ominously in Germany. Bethe was half Jewish and was dismissed from his job in Tubingen for that. Clearly it was getting unsafe to stay on and Bethe had to leave Germany .
- The US gave him a home and a permanent job In 1935 at Cornell University, USA , where he spent the remaining 60 years of his life.

Manhattan Project

- That whole experience left him with deep gratitude to his new homeland and a commitment to its defense.
- He was also personally familiar with the Nazi menace and realized the imperative to stop them from winning WW II
- Rumors were emanating from Germany that they were building a nuclear bomb.
- So when the Manhattan Project was started in the US (to design and build a nuclear weapon) and Bethe asked to head its theory division, he readily agreed.
- Some of the world's greatest theoretical physicists of time worked under his command and together they designed the Bomb.

Disarmament work

- He does not seem to have regretted his participation in creating that horrible weapon either then, or later. He was not by nature the guilt ridden type, and I think he took the view that the dangers and compulsions of the time required him to do what he did then.
- But as the arms race developed between the US and the USSR during the fifties and the sixties, he became an advocate of nuclear moderation and disarmament.
- In his own un-dramatic way he made several contributions to reducing nuclear dangers.

- He opposed the development of the H bomb and had a long and well known dispute with Teller over that.
- But President Truman decided to go ahead with the H bomb in 1950, largely because of the advances the USSR was making in developing weapons and the famous Klaus Fuchs spy case.
- By the mid-fifties Bethe had become a highly respected and influential advisor to the US government.
- He was a member of the President's Science Advisory Committee (1956-64)
- [That is what I knew about him when I went to Cornell in 1958– not his physics!]

- In 1957, after the Russians launched the world’s first satellite Sputnik , with all that it implied about the Soviet Union’s ability to make missiles, a “worried President Eisenhower” summoned Bethe to discuss what should be America’s response.
- Bethe took the opportunity to suggest a negotiated nuclear test ban. Ike was sympathetic to the idea and made Bethe the Head of Presidential Study of Disarmament in 1958.
- When the Russians exploded the 60 megaton bomb, in 1961, I was directly working under him. President Kennedy would call upon his advice more than once. Bethe was viewed as a dove, and to offset him Kennedy would also consult Teller !
- Bethe strongly opposed atmospheric testing of nuclear weapons, and helped to have such tests banned in 1963.

- And so it went on, for decades. He wrote numerous articles, and gave talks around the world preaching disarmament.
- He was an active public advocate for arms control and a test ban treaty.
- He strongly opposed the Anti-Ballistic Missile System (ABM) proposal of the 1960s and the Star Wars of the 1980s, both of which he perceived to be destabilizing.

- But he did all this without ever carrying a placard or joining a protest march. That was not his style.
- He was a pragmatist, not an idealist -- a reserved person, not given to public displays.
- But he was very fair minded, not afraid to come out publicly in defense of what he believed in.
- His support of Professor Oppenheimer and Professor Philip Morrisson harassed by the “Commie hunters “ of that MaCarthy period are well known.
- He made his contributions to public issues in the same calm, measured, mature and unspectacular way that he did all his physics.
- He was not a prima donna but became a towering elder statesman, respected by those who agreed with him as well as those who didn’t.

My Personal Homage

- For the 7 years I spent in close contact with him, four as his student and another three as a junior colleague at Cornell, he was extremely kind and patient with me.
- I learned from him many things about real science, especially the importance of concrete calculations and hard results as compared to just pretty ideas.
- I was only 20 when I started work with him. So he was very much also a father figure.
- So much so that he “gave away the bridegroom” at my wedding held in Ithaca!

His last day
(as recollected by Gerry Brown)

- " Hans and I, with Chang-Hwan Lee, prepared a manuscript, The Evolution and Merging of Binaries with Compact Objects for Hans' Centennial Physics Report.....
- I discussed this manuscript with him the morning of his death. His mind was clear and his voice was strong.
- I also told him that C.N. Yang was writing a review of the Bethe Ansatz-- Yang gave it that name Ansatz-- for the Bethe Biographical volume Hans was also very happy about that. He wanted his physics, not his philosophy, explained."

- Bethe passed away a few hours after that, missing his centennial by just a little over a year.

THE END