B^{2}FH: What they did, and didn't.

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Verbal Remarks for PPt: [Slide in BLACK; verbal comments COLOR]

Good Morning!

Today I will address issues that you may not expect. Instead of adulation of B^{2}FH, I will cast the cold eye of the historian on what it achieved scientifically.

I will advance some sociological reasons for it's becoming an icon.

Slide 1:

B^{2}FH: What they did, and didn't

1. B^{2}FH was a paper of destiny. Widespread research did not exist in 1957, but it was ready to break out.

I mean "destiny" in the sense that Harry Truman was a president of destiny. (FDR, WWII, Iron Curtain, etc).

B^{2}FH was timed fortunately, at the onset of an outbreak in nucleosynthesis. (When I say "nucleosynthesis" I mean synthesis of new heavy nuclei in stars, not stellar power, which had been active for years.)

2. Hoyle created the theory (1946,1954)

Hoyle introduced *Nucleosynthesis in Stars* with these two papers.

Hoyle went directly to increased numbers of heavy nuclei—primary Nucleosynthesis. (Only triple-alpha and NSE did that from H and He). He addressed the processes that increase metallicity.

(Reminder: CN cycle, s process, *p* process only change 1 heavy nucleus into another-secondary—no metallicity increase)

3. Kellogg Lab was engaged in stellar reaction rates in stars: the goal was to understand stellar power (which Bethe had pioneered).

But Nucleosynthesis per se was not really active in Kellogg.

In 1956-58 I heard no discussion of Nucleosynthesis (except of 3α) at Caltech. It was not yet a hot topic, even at Caltech.

4. B^{2}FH became the standard reference for a worldwide eruption of nucleosynthesis

Most papers in Nucleosynthesis for next 20 years cited it, many symbolically. But many did not.
Many did not cite Hoyle or Cameron

Many cited B^{2}FH rather than original improvements of nucleosynthesis. This is unprecedented in my experience—that citations of a review paper take precedence over those of subsequent discovery papers (specific examples of this follow).

A personal Mini-survey:

I selected 30 significant reprints during 1960-73. (From my personal archive). I judged these to be *important for nucleosynthesis.*

12 of 30 did not cite B^{2}FH. None could have been unaware of it. Probably reflected their policy to cite only papers that technically advanced their research;

15 made *pro forma* citations, to the overarching idea of Nucleosynthesis in Stars;

3 cited B^{2}FH for their formulation of heavy-element nucleosynthesis. These were its only three technical citations.

Hoyle got 1 citation.

Astronomers were enthusiastic (following some initial resistance) because secondary nucleosynthesis in stars was visible at telescopes.

The adulation of B^{2}FH that we see today seemed to increase later.

First a word about my relationship to WAF and to FH.
This might seem in poor taste, but bear with me for relevance.

Slide 2:

I entered Caltech in 1956 while Fowler was on leave.
This photo shows Fowler at age 46 shortly after the publication of B^{2}FH.

August Occasion: Niels Bohr's last CIT visit. Thursday physics colloquium.
Two beyond Bohr sits youthful looking Richard Feynman, looking into the camera as Dick was so good at.
I am here too; I sit four rows directly above WAF.
I had just solved (1959) the time-dependent mathematical formulation of the *s* process. (Clayton PhD thesis) It reoriented *s*-process thinking.

Because I had begun that research in fall 1957, I am this year celebrating also my own 50th anniversary of nucleosynthesis in stars.

Slide 3:

I was Fowler's first grad student in nucleosynthesis.
Prior WAF students' studies were of experimental nuclear physics, often related to question of solar power.

Amusingly today, Willy was unsure if *s*-process was sufficiently scholarly for a PhD thesis! How times change. At this time Fowler was still learning nucleosynthesis, continuing his intense Cambridge experience. His style was to ask me questions about what he did not understand; and I in turn did the same. We were a two-man study group. These questions pointed to the need of a "time-dependent formulation".

(We formulated a time-dependent s-process). More on this later.
Pictured (1963):
G. Goldring (measured mass of ^{56}Ni), DDC (second), Peter Parker (far right) –all leaving Kellogg
We represented a first wave of Kellogg seeding the world with nuclear physicists attuned to nucleosynthesis for research motivation.

I had at this time just completed 7 years at Caltech, the last 2 as Postdoctoral years within the first NSF support of Nucleosynthesis in Kellogg . These two years (1961-63) saw Kellogg branch out from nuclear physics lab to nucleosynthesis factory. Fowler's three other hires in that first NSF program were John Bahcall, Icko Iben and Richard Sears. Bahcall was to work on weak interactions in stars (electron capture); Iben's goal was construction of an automated computer program for stellar evolution (needed for nucleosynthesis in Fowler's view); and Sears was to compute models of the sun (with

Willy's special interest in its neutrino emission). I was the nucleosynthesist.

We named that group *SINS*, for "stellar evolution and nucleosynthesis". Willy loved that name and bragged often about his "sins seminar" (our weekly meeting and presentation).

Slide 4:

I became a close friend both of Fowler and of Hoyle. That remained true for 35 years

Not boasting! The relevance is my closeness to their ideas. Closeness gave me valuable insight into their opinions.

left: Willy and I (1967) at "the hut" on Madingley Road (age 53 and 32). This was our office in 1967 before *IOTA* was built.

right: Fred and I in his office in 1968 after completion of *IOTA* building. I call attention to two things:

(a) Nuclide chart on wall behind Hoyle desk. But this was actually the end of Fred's overriding interest in the theory that he had created. He turned his attention to cosmology, his favorite subject.

(b) Paper held by Hoyle is Chap. 1 of book we discussed coauthoring. More on this in a moment. It was Chapter 1 "Abundances of Chemical Elements", and it had been drafted by Fred. Our idea was using new astronomical data and new data from space physics to improve Suess & Urey table. But….

Cameron (1968) had beaten us to this punch with his very influential table.

Slide 5:

***B^2FH*-- a review paper suddenly came to represent an entire field of science**

- **1. Subsequent citations were often to *B^2FH* rather than to the primary literature, an exceptional phenomenon.**

Before B^2FH: Citations of Hoyle were rare—but also *after!*

After B^{2}FH: **My time-dependent formulation of s-process was published in 1961; but citations were rare.**

This sounds like sour grapes—but bear with me. My point is that in a sense B^{2}FH was overcited relative to later original formulations. Just a month ago a SCIENCE paper decomposing Ba into s/r components cited B^{2}FH! This despite B^{2}FH not having done this quantitatively. The first quantitative decomposition was Clayton & Fowler (1961), a paper I have never seen cited.

Nor am I the only researcher whose work was hidden by this practice. Many original works, including Fred Hoyle's, were hidden. This accounts for Fowler's needing after his 1983 Nobel Prize to stress publicly that the theory of nucleosynthesis is Hoyle's theory.

Overcitation of B^{2}FH was not altogether healthy for orderly development of nucleosynthesis science. It gave the impression that not much happened in nucleosynthesis after B^{2}FH. Indeed, some in this room have heard astronomers make that statement. In fact, the decade following B^{2}FH was one of intense and original reformulations.

- **2. Imagine some other possible reviews that did not happen.**
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- **3. Bethe, Fowler, Lauritsen and Salpeter "Nuclear Reactions in Stars"** ***BFLS***

This could have happened in 1950s. It would have been sensational. But it would not have captured the attention of astronomers like B^{2}FH did. I will explain why later.

- **4. Clayton, Fowler & Hoyle "Nucleosynthesis of Chemical Elements"** ***CFH***

A monograph on nucleosynthesis in stars. Why such an apparently self-serving example?

5. I was invited (1965) to do this because B^{2}FH needed much extension and correction. I declined to instead publish my 1968 textbook

Official letters from Caltech even promised the author order CFH if I would agree to do it. Correspondence documenting this is being transmitted to AIP *Center for the History Physics*.

I did immediately (1966-67) take the proffered 1-year leave of absence from Rice U at Caltech's invitation (and Caltech's expense) to

help formulate improvements to B^2FH. The quasiequilibrium understanding of Si burning (the alpha process!) took the entire year. Even Willy agreed that "the book" would have to wait.

This is significant in showing the degree to which both Fowler and Hoyle agreed that B^2FH formulations were already seriously out of date. This was precisely why I wrote my textbook rather than urging students to read B^2FH.

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So what did ***B^2FH*** do to become so legendary?

I have given <u>5 decades of thought to this question while working on its forefront</u>, and will suggest some reasons on subsequent slides

Firstly,

Slide 7: **1. *B^2FH* spoke to astronomers**

It spoke of a rich astronomical interplay between spectroscopic observations and nucleosynthesis. This was actually the <u>most important consequence of B^2FH</u>, and accounts for later adulation by astronomers.

- **104 specific stars or phases that reveal evidence of nucleosynthesis were described by B^2FH.**
- **Specific star (HD112869) ; Type of star (WN enriched by CN) ;**
- **mixing of H with CN in Red Giants to provide free neutrons; *etc*.**
- **One must go back to 1957 setting to grasp that nucleosynthesis interpretations were rare. But after B^2FH they became common! One sees the hand of B^2 here.**
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- **111 citations of observational papers 111 teams of astronomers who were assigned roles confirming or negating nucleosynthesis in stars! Astronomers became heavily invested in the theory.**
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- **<u>Immense scholarship</u> shown by these references suggested new realms of astronomical observations. This energized astronomy!**
- **Astronomers loved B^2FH! After an initial resistance, they soon became the champions of that paper. It had brought nucleosynthesis to life by suggesting a host of astronomical observations.**

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- <u>**Immense scope:**</u> **Many astronomical arguments off the main line of nucleosynthesis in stars can be found: cosmological D—Stellar evolution (Hoyle was the world's most complete thinker on that problem at this time)—SN mechanism and light curves (radioactive light curve)---galactic chemical evolution—radioactive chronology (age of elements)**

Slide 8:

2. B^2FH gave *NAMES* to processes (more significant than you might at first think)

- not events so much as ***correlations between nuclear properties and nuclide abundances***— but venues were described (**astronomical settings in stars)**
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- Venues are mixed later! This had powerful astronomy impact. (**astronomers leaped to provide evidence from their own work. Highly constructive interplay.)**
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- Names are significant—**strangeness, quarks, eight-fold way, charm, color. (One need not have been a Caltech grad student to see lasting connotations of Murray Gell-Mann and of Caltech in these poetic names. B^2FH's names were similar attachments of the theory to them)**
- The names were:
- <u>***Alpha process--***</u>**(today** <u>O,Ne,Si burn</u>); **(more on next view) This name has been dropped owing to ill formulated ideas.**
- <u>**e Process (Fe);**</u> **Took a wrong formulation which sought explanation of the abundances of the iron peak in terms of the** <u>**nuclear properties of Fe**</u>**. But it was the nuclear properties of Ni that were the key to radiogenic iron. I brought many reprints of** <u>**my historical essay "Radiogenic Iron"**</u> **for those of you who wish one.**
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- <u>***s process*** (slow capture of neutrons)</u>; **Creative analysis. From that time on we could make statements such as the "main *s* process occurs in AGB stars; weak *s* process is in massive cores", etc.** ***Cameron by contrast did not*** **give this process a name, but he**

presented a creative study of it including the first computer computations. Needless to say, one does not today see citations of Cameron for "neutron capture on a slow time scale", when one can instead say "*s* process".

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- ***r process*** (rapid capture of n); **B^{2}FH setting was wrong, and they viewed it as a secondary process, deriving from initial Fe nuclei; but its mechanism was right and extremely creative.**
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- ***p process*** (rapid proton capture) **B^{2}FH (p,γ) mechanism was wrong emphasis, but still….it has remained a useful name that remains in use.**
- **One also speaks forever now of "s nuclei", "r nuclei" or "p nuclei". This name association with B^{2}FH is strong.**

Slide 9: **Hoyle (1954 ApJ) *vs.* B^{2}FH "α"**
to contrast Hoyle's 1954 picture with the B^{2}FH "α process"

- **Hoyle (1954) stressed massive stars yield**:
- **Carbon burning**: ^{20}Ne, ^{23}Na, ^{24}Mg, ^{16}O **(Salpeter had suggested this in 1952 in his triple-alpha paper)**
- **Ne burning**:^{24}Mg,^{16}O from ^{20}Ne**(conserves α nuclei number)**
- **Oxygen burning** gives ^{28}Si, ^{32}S **(creates new nuclei >A=24)**
- **32S(γ,α):** ^{32}S, ^{36}Ar, ^{40}Ca **(A good new idea!)**
- ***Very modern primary* nucleosynthesis*!*** **B^{2}FH had lumped all of Hoyle's processes into alpha-process. Their paper did surpisingly little for primary nucleosynthesis. This contrast suggests that B^{2}FH may not to have been thoroughly proofread by Hoyle before submission.**
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- ***Cameron57 adopted H54 but improved it*.**

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Slide 10: **3. B^{2}FH presented Decomposition of the elements**

"Main line" of neutron-capture nuclei and "bypassed nuclei" by those processes are designated s, r, p—with rough estimated fractions. This Slide 10 sums up the greatest technical achievement of B^{2}FH.

Aside on themes: Clayton & Fowler (1961) published the first quantitative decomposition of s/r/p. I have never seen it cited despite the large astronomical importance for early GCE. Just last month SCIENCE paper cited B^2FH for s/r decomposition of Ba! (without citing any of many subsequent quantitative papers. (overcitation example)

Slide 11: **dN/dt = 0? σN_s=constant (B^{2}FH had no calculation. They stressed the assumption of "steady flow"). I quote:**

"The slow and rapid neutron-capture processes operated under conditions of steady streaming,….so that σN_s products are remarkably constant from isotope to isotope".

But this is NOT TRUE for the process itself! Astrophysics with the s process requires time dependence in stellar settings to understand the large overabundances in stars.

Flyin 1. Clayton (1961) did time dependent calculation
Flyin 2. CFHZ figure (from my PhD thesis)

Solar N_A looks like none of these! I described how some portion of Fe nuclei were exposed to fluence τ, some to greater τ, *etc*..
I defined $\rho(\tau)d\tau$= #Fe exposed to fluence τ in interval $d\tau$
Fe grows as galaxy evolves; so secondary yield increases

This was not a detail, but what Al Cameron later called "the essential complexity " of the s process".

Cameron (1957) had done a calculation of overabundances vs. τ of the solar abundances; but he agreed (1959 conversation) that my formulation (based on fractions of solar Fe exposed to fluence τ) addressed the salient astrophysical point.

Slide 12: **dN/dt = 0? $\Lambda_\beta N_Z$=constant (B^{2}FH had no calculation) Our first real *r*-process calculation became the prototype for subsequent studies**
Flyin: Seeger, Fowler, Clayton figure for increasing fluence

Just as for the *s* process, time-dependent reformulation installed "<u>an analogous essential complexity</u> "into the *r* process". This remains today and has in fact grown with time and astronomical data.

Fowler was very proud of coauthoring these two time-dependent formulations, which he regarded as fundamental.____

- <u>Slide 13</u>: **4. "*B^2FH*"** calls "***Caltech"*** to Mind (**this is significant because it endowed B^2FH with the aura of Caltech!)**
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- **Not St Johns College, where Hoyle lived and worked, and where *B^2FH* was conceived by three Englishmen and Fowler**
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- **not La Jolla, where Hans Suess lived and worked** following a decade of his research on correlations between nuclide abundances and nuclear properties and nucleosynthesis processes**, and where Harold Urey coauthored Suess&Urey's abundance table,**
- **and where two coauthors (*B^2*) of *B^2FH* became professors**
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- **not Chalk River Lab, where Al Cameron lived and worked and published his independent treatment of Nucl in stars**
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- **not Yale where Al Cameron produced a school of nucleosynthesis**
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- **Kellogg Lab was already famous for stellar nuclear rates** (This helped the association along. **Kellogg became provider of experimental nuclear rates in stars) Caltech now became training ground for postdoctoral terms by young researchers**
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- Kellogg sent nucleosynthesis researchers out into the world—beginning with me
- As the first Caltech PhD thesis in nucleosynthesis theory (as opposed to *nuclear reactions in stars).*
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- Nuclear astrophysicists took sabbaticals in Kellogg Lab **(Audouze, Bodansky, Goldring, Hebbard, and many others)—and they**

returned <u>from Caltech</u> with this new sense of nuclear physics in astronomy.

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- B^2FH merged nucleosynthesis with Kellogg Lab-- a goal of Fowler's as a Caltech man-- in science consciousness (**by 1965 Caltech seemed the center of the world of nucleosynthesis)**
- Caltech is a juggernaut (**This conference occurs at Caltech, for example)**

<u>Slide 14</u>: B^2FH was a paper of destiny. I have suggested reasons that may differ from what most of you have in your thoughts

- It energized astronomers as theory could not

It was not astronomers style to read nucleosynthesis theory. B^2FH addressed tangible connections to stars that they observe.

- Astronomers enshrined that paper

It brought astronomy and nucleosynthesis to life as a symbiotic science.

- I emphasized events when its ink was barely dry, because I have spent this 50 years with it
- I celebrate not only 50 years since B^2FH and Cameron, but also my own 50th anniversary of research in nucleosynthesis
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- I have cast a cold historical eye **on some aspects of its nucleosynthesis**, finding some sociological reasons along with the scientific ones for its iconic status
- Except for their descriptions of heavy-element nucleosynthesis (all of which they viewed as *secondary*), B^2FH made little contribution to nucleosynthesis theory.
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- But it created enormous vitality in **the astronomy of nucleosynthesis**
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- Whatever one's view of the B^2FH paper, we all agree that
- We celebrate here the semicentennial of B^2FH placing "nucleosynthesis in stars" on the cultural front page of astronomy

As we celebrate 50 years of B^2FH, I am suggesting that we should augment the celebration of Fred Hoyle, who created the theory, and also that of Al Cameron, who made forceful, original formulations.

Thank you for your attention.