BF

SOLAR FLARES AND ‘LOW-ENERGY NUCLEAR REACTIONS’;

COULD THERE BE A CAUSAL CONNECTION?

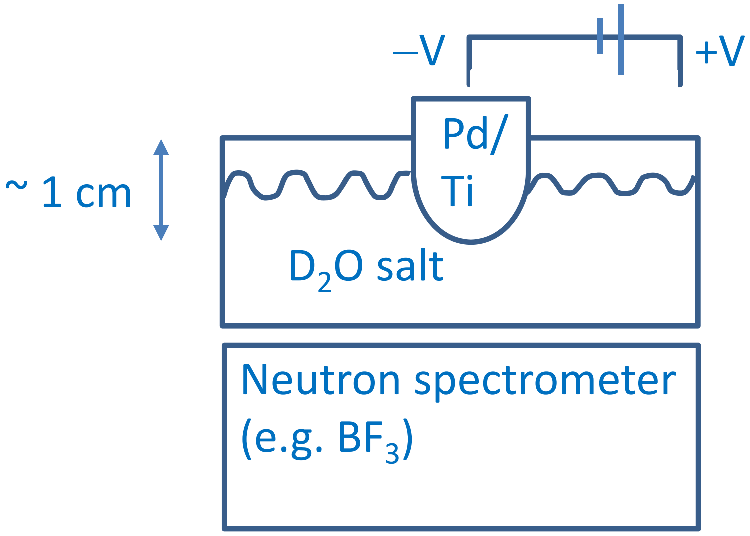
A. J. Leggett
University of Illinois at Urbana-Champaign

Quantum Fluids from nK to TeV
80th Birthday Symposium in Honor of Gordon Baym
16 October 2015

STOP May be flogging very dead horse!

Apart from apparent irreproducibility (etc.) a major generic difficulty plaguing reports of “cold fusion” is that, typically, experiments claiming anomalous heat (e.g. Pons & Fleischmann) require for their explanation a $\sim 10^9$-10^{12} higher fusion rate than those claiming anomalous neutron production (e.g. Jones et al.). Hence, for present purposes concentrate on neutron experiments.

Typical “cold fusion” setup for neutron detection (schematic):



BF_3: $(n, {}^{10}B) \rightarrow ({}^{7}Li, \alpha)$

PdD is f.c.c. with $a \cong 4$Å

TiD_2 " " "

In both cases, deuterons sit in interstitial sites between (111) planes.

From observed count rate in neutron spectrometer, Jones et al. infer D-D reaction rate of $\sim 10^{-23}$ sec^{-1} (pair$)^{-1}$, i.e.

$\sim 0.6\ cm^{-3}\ sec^{-1}$ (in Pd)

and I will take this (“Jones rate”) as a figure to shoot at.

Some early events involving apparent anomalous generation of neutrons by PdH/TiD_2.

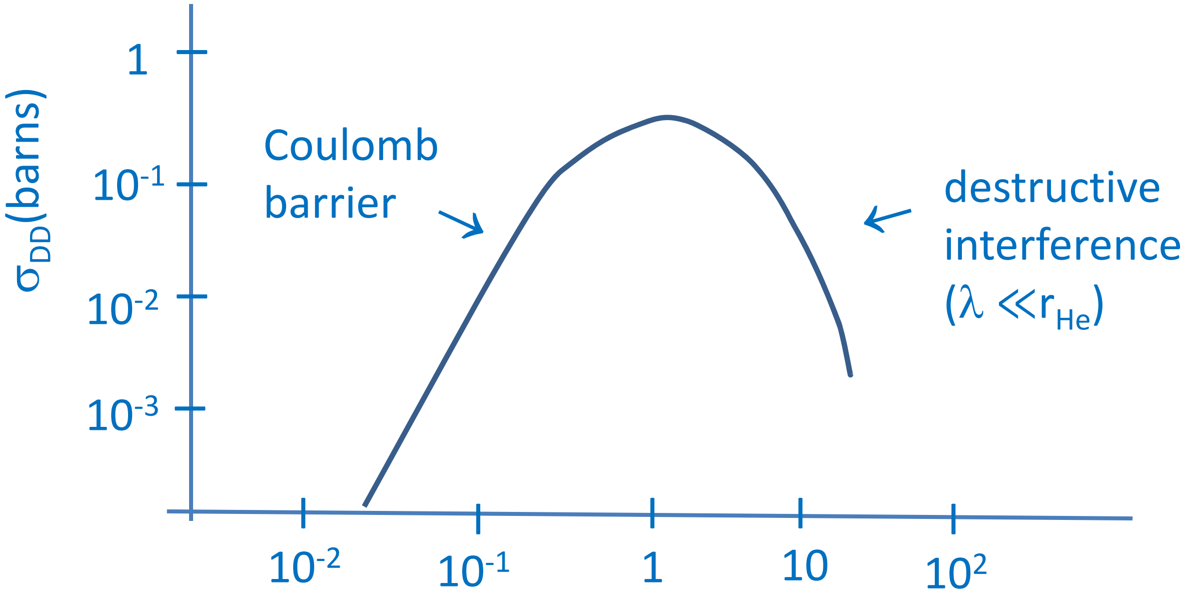
Authors	Date of experiment	Date of submission	Location of lab	Altitude (m)
Pons & Fleischmann	?	13/22 March 89	Salt Lake City	1,288
Jones et al.	1 Jan – 6 March 89	24 March 89	Provo, UT	1,387
Scaramuzzi et al.	7-10 April 89	24 April 89	Frascati	320
[Madrid event]	8 June 89	_	Madrid	667

March – June 1989: Several negative reports, including some checking possibility of muon-catalyzed fusion (MIT, KEK)

many theoretical papers claiming to use solid-state screening, etc., to allow fusion at “Jones rate” (or higher)

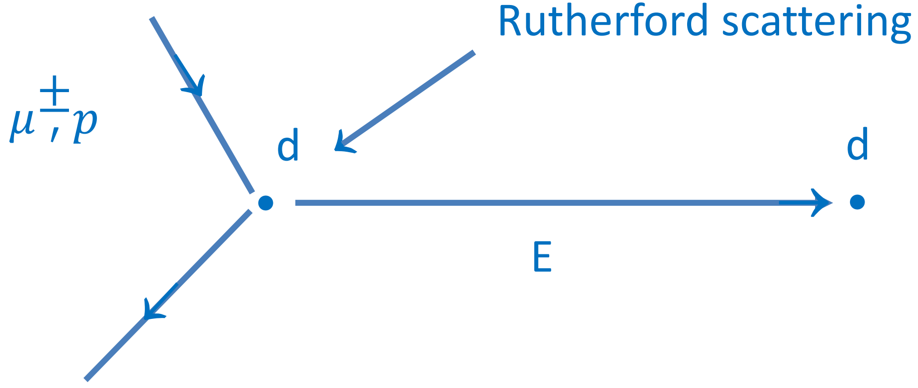
AJL & GB, April – May 1989:
for deuterons in equilibrium in Pd/Ti, upper bound on fusion rate is 27 orders of magnitude below Jones rate.

Energy dependence of cross-section for d+d $\rightarrow \left\{ \begin{array}{l} t+p \\ {}^{3}He+n \end{array} \right.$: (after Torrisi et al., Applied Surface Science 272, **42** (2013))

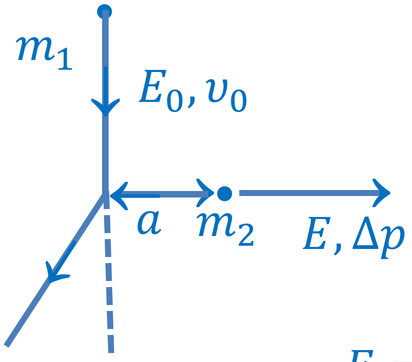


Max. is $\cong 0 \cdot 2$ barn, at 3 MeV.

Scenario:



Does this work quantitatively?



Small-angle Rutherford scattering: use impulse approximation in lab. frame

$$E = \frac{1}{2m_2}(\Delta p)^2, \quad \Delta p = \int_{-\infty}^{\infty} F_\perp dt = 2e^2/av_0$$

$$\Longrightarrow E = \frac{e^2}{a_2}\left(\frac{m_1}{m_2}\right)\frac{1}{E_0}$$

Convenient to express resulting differential cross-section $d\sigma/dE$ in form

$$\frac{d\sigma}{dE} = \pi\left(\frac{m_1}{m_2}\right)\frac{a_d^2}{E_0}\left(\frac{E_d}{E}\right)^2 \qquad (*)$$

a_d ≡ deuteron Bohr radius (~1 · 4 x 10^{-12} cm)

E_d ≡ deuteron Hartree (~100 keV)

For large-angle scattering, (*) is multiplied by $\theta(E_c - E)$ where E_c is cutoff energy

$$E_c = \frac{4m_1m_2}{(m_1+m_2)^2}E_0 \qquad \left(\cong \frac{7}{16}E_o \text{ for } \mu^\pm, \frac{8}{9}E_0 \sim E_0 \text{for } p\right)$$

Thus, on traversing a length d of PdD/TiD_2 the incident particle will produce (neglecting energy degradation for $E_o \gtrsim 1 \text{ GeV}$)

$$n(E)dE = n_0(E_d/E)^2 dE/E_0$$

deuterons in range $dE(E < E_c)$, where

$$n_0 \equiv (m_1/m_2)\left(\pi a_d^2 n_d d\right) \qquad n_d \equiv \text{density of deuterons}$$

For $1 = \mu^\pm, d = 1$ cm in PdD, factor n_0 is ~0 · 05

Efficiency of secondary deuterons in inducing fusion: Since relevant energies are now in the MeV rather than GeV range, it is essential to take into account degradation by the standard Bethe-Bloch (ionization) process. If we write

$$\ell(E) = (E/E_d)^2 \ell(E_d)$$

range at energy E_d

and the fusion cross-section as

$$\sigma_f(E) \equiv f(E)\sigma_0 \qquad (f(E)\leqslant 1)$$

maximum cross-section, $\sim 0{\cdot}2$ barn

then the probability of a secondary with initial energy E inducing fusion is (to an order of magnitude only)

$$p(E) \sim (E/E_d)^2 f(E)\ell(E_d)\sigma_0 n_d$$

Thus, finally, the probability per incident particle 1 of inducing a fusion reaction is as a junction of incident energy E_0.

$$\boxed{\begin{gathered} P(E_0) \sim P_0 \int_0^{E_c} d\,\frac{Ef}{E_0} f(E) \\ P_0 \equiv (m_1/m_2)\left(\pi a_d^2\right) \cdot \left(d\ell(E_d)\right) \cdot \left(\sigma_0 n_d^2\right) \end{gathered}}$$

For (pure) P_d, $\ell(E_d)$ is ~ 300Å, and $n_d \sim 0{\cdot}06$ Å^{-3} so if we take $d = 1cm$ and $1 = \mu$ (so $m_1/m_2 \sim 1/7$)

we find

$$P_0 \sim 1 \cdot 5 \times 10^{-9} \qquad (PdD)$$

For $TiD_2 n_d$ is larger by a factor of 2 and $\ell(E_d)$ by a factor of ~3, so

$$P_0 \sim 1 \cdot 8 \times 10^{-8} \qquad (TiD_2)$$

Since background rate of incidence of cosmic rays (mainly muons) on 1 cm^2 surface is ~2 · 4 x 10^{-2}.

rate of fusion induced by background cosmic rays ~ 9 orders of magnitude below Jones rate.

So ... end of story?

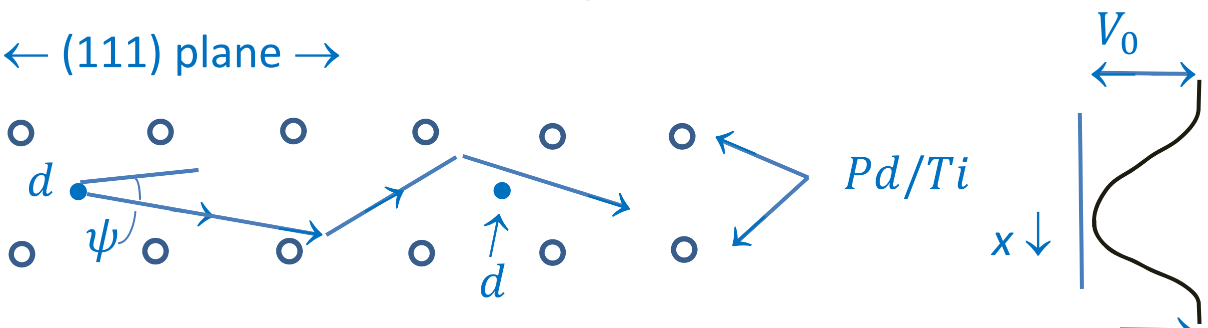
Well, maybe not quite...

Rewrite expression for rate of fusion reactions:

$$R = \underbrace{\overset{\text{incidence rate}}{R_0}(m_1/m_2)}_{\text{properties of incident particle}} \cdot \underbrace{\sigma_0(\pi a_d^2)d}_{\text{not adjustable}} \cdot \underbrace{\ell(E_d)n_d^2}_{\text{properties of } PdD/TiD_2}$$

(1) Is there scope for modifying (effective value of) n_d and/or $\ell(E_d)$?

Yes! Phenomenon of channelling*



$$E_{tot} = E_\parallel + E_\perp \; ; \text{ if } E_\perp = E_{tot} \sin^2 < V_0.$$

even fast particle may be trapped between planes. This both (a) reduces Bloch-Bethe energy degradation, (i.e. increases $\ell(E_d)$) and (b) increases probability of hitting target deuteron. (i.e. increases effective n_d). Note second effect may occur both for secondary and for incident particle.

Alas, in general, while effects of channeling on processes associated with “forbidden” region (e.g. nuclear reactions on Pd) can be large, those associated with “allowed” region are relatively small (e.g. ℓ increases only by factor ~ 3). Also, only a small fraction of “incident” (or in our case secondary) particles are expected to be channeled.

And yet...

---

*see e.g. M.W. Thompson, Contemp. Phys. **4**, 375 (1968)

Three apparent experimental anomalies concering H/D in fcc metals:

1. R. J. Buehler et al., PRL **63**, 1292 (1989):
   fire $(D_2O)_n$ clusters at TiD target, observe strongly energy-dependent fusion rate, interpret in terms of "cluster-impact fusion" (thermonuclear) effect. Unclear how far exclusion of ballistic effect depends on assumption of "standard Bloch-Bethe degradation (if so, might be remedied by effective increase of $\ell(E)$ by channelling).

2. K. Czerski et al., Nucl. Mater. Methods B **193**, 183 (2002):
   investigate $d-d$ fusion reactions in Ta (etc.) in range 5-60 keV, observe very strong increase over expected (vacuum) value of $\sigma_f(E)$, interpret in terms of a channelling concentration factor (equivalent to effective increase of n_d) of 19 · 3. If we believe this,

$$n_d \rightarrow n_d^{(eff)} \sim 20n_d \qquad (\Rightarrow 2 \cdot 5 \text{ orders of magnitude in } P_0)$$

3. Z. Chylinski et al., Nucl. Instrum. Meth. **B 71**, 255 (1992):
   try to explain experimental data of Quillico et al., Phys. Rev. B 11 (1975) on dechanneling of α's by (dilute) H and C atoms in Pd. For C they get good agreement with experiment, but for p's they under-estimate the dechanneling cross-section by a factor of up to ~10. However, it seems that in the calculation they have ignored reduced-mass effects, which for α on p would reduce the theoretical value by a factor of 5. Hence, if this is right, it would imply

$$n_d \rightarrow n_d^{(eff)} \sim 50n_d \qquad (\Rightarrow 3 \cdot 5 \text{ orders of magnitude in } P_0!)$$

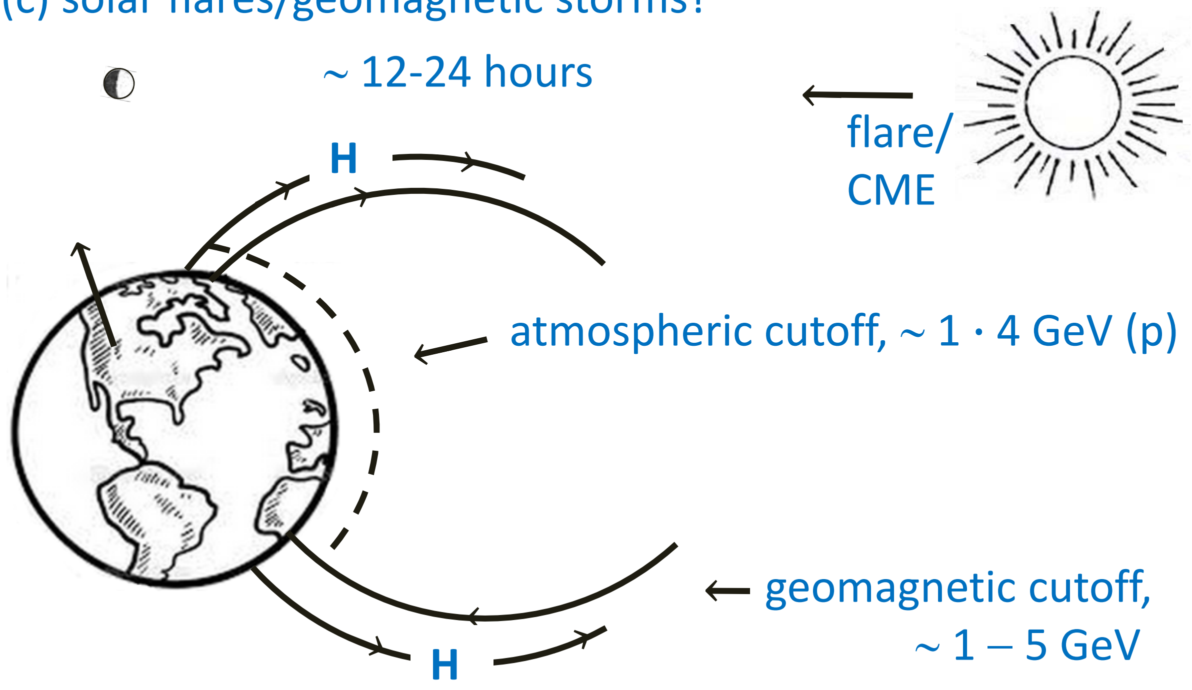
Even more speculative: could an array of D's lead to further concentration?

(2) Can we improve factors m_1/m_2 or R_0?

(a) $\mu^{\pm} \to p \Longrightarrow$(effect of (m_1/m_2)) $\times \sim 8$. (but p only ~0 · 3% of CR background)

(b) altitude effect: ~6 at Provo/SLC.

(c) solar flares/geomagnetic storms?



~ 12-24 hours

flare/
CME

atmospheric cutoff, ~ 1 · 4 GeV (p)

← geomagnetic cutoff,
~ 1 – 5 GeV

What is rate of arrival during major geomagnetic storm?

Autran & Munteanu: "an evident lack of data characterizes the low-energy domain, typically around and below a few MeV"

↑ [for proton flux under normal conditions]

Problem: <u>total</u> proton flux incident on upper atmosphere in geomagnetic storm can easily be ~10^5 cm^{-2} sec^{-1}, giving enhancement ~10^7. But most are in MeV range and don't get through. Primary flux at $E > 1 \cdot 4$ GeV ~ 20% of normal CM background: most protons in MeV range arriving at sea level probably secondaries.

Coincidences: known solar flares

Obvious question:

Was idea already tested and refuted in 1989 (or since)?

Chen et al. (MIT) J. Fusion Energy **9**, 155 (1990):

explicitly, test of hypothesis of muon-catalyzed fusion.

μ^- energy on entering Pd/Ti : ~6 MeV; most muons decelerated to rest inside sample

⇒maximum secondary energy $< 2 \cdot 8$ MeV, rapidly decreasing.

⇒ if (present) hypothesis correct, expected rate of fusion per (eventually) stopped $\mu^- < 10^{-7}\left(n_d^{eff}/n_d\right)^2$

experimental upper bound $0 \cdot 25$! ⇒ no evidence against hypothesis provided rate enhancement over standard CR background $\gtrsim 400$.

March 1989 geomagnetic storm - Wikipedia article

Geomagnetic storm and auroras

The geomagnetic storm causing this event was itself the result of a coronal mass ejection on March 9, 1989. A few days before, on March 6, a very large X15-class solar flare also occurred. Three and a half days later, at 2:44 am EST on March 13, a severe geomagnetic storm struck Earth. The storm began on Earth with extremely intense auroras at the poles. The aurora could be seen as far south as Texas and Florida. As this occurred during the Cold War, an unknown number of people worried that a nuclear first-strike might be in progress. Others considered the intense auroras to be associated with the Space Shuttle mission STS-29, which had been launched on March 13 at 9:57:00 AM. The burst caused short-wave radio interference, including the disruption of radio signals from Radio Free Europe into Russia. It was initially believed that the signals had been jammed by the Soviet government.

As midnight came and went, a river of charged particles and electrons in the ionosphere flowed from west to east, inducing powerful electrical currents in the ground that surged into many natural nooks and crannies.

Some satellites in polar orbits lost control for several hours. GOES weather satellite communications were interrupted, causing weather images to be lost. NASA's TDRS-1 communication satellite recorded over 250 anomalies caused by the increased particles flowing into its sensitive electronics. The Space Shuttle Discovery was having its own problems: a sensor on one of the tanks supplying hydrogen to a fuel cell was showing unusually high pressure readings on March 13. The problem went away after the solar storm subsided.