TALK FOR SUN VALLEY

We are interested in a quantitative understanding of the phenomena ? involved when neutron lifetimes are sufficiently short that thermal equilibrium between neutrons and moderator is incompletely established. This understanding is necessary primarily in order that the effects of moderator temperature on reactivity can be adequately estimated. The absolute magnitude of the thermal cross sections is also desired, but this is not usually an uncertainty in design calculations.

ask Nelkin if he means Σ_a large or that neutrons slow down fast

The most fundamental approach to this problem is to go back to the differential cross sections $\sigma(\theta, \epsilon)$, and use these to determine the reactor situation by machine calculation. This has two disadvantages. First, although a general understanding of the $\sigma(\theta, \epsilon)$ is important and necessary, its determination in complete detail is exceedingly difficult, and is more properly in the domain of learning about matter with neutrons. Secondly, it is far beyond our present techniques to solve anything but trivial geometries once $\sigma(\theta, \epsilon)$ is known.

The most useful approach from a reactor point of view seems to me to be

1. To get a feeling for the cross sections by measurements of $\sigma(\theta, \epsilon)$ such as those of McReynolds, Brigger, Brockhouse.
2. To do measurements in clean situations more directly related to the thermalization process.
3. To develop theoretical models through study of (1) and (2) which will enable predictions of more realistic reactor geometries at least insofar as general features are concerned.

I think the emphasis at present should be on (2) using the pulsed neutron techniques which have shown great promise in this field, but which have yielded only a tantalizingly small amount of good data. Even this data does not seem self-consistent in the case of water. Also no information at all is available concerning spatially dependent neutron spectra which will frequently be of importance, and the pulsed method is the most promising for such investigations.

The basic information available from the pulsed experiments $n(E, \bar{r}, T)$ (for steady state distribution is just $\int$ N (E, r, t) dt). Only a very small part of this has so far been obtained. Consider first the experiments with a low intensity source in which no time of flight analysis is feasible in order to directly determine energy distributions. An imaginative analysis of what can be done with these experiments was given in Von Dardel's thesis, and a careful experimental job along these lines has been done by Beckurts and collaborators at Gottingen. There are two interesting experiments that can be done with this method.

1. The intensity vs. time of neutrons escaping from sample can be measured with and without absorbing foils. The transmission of various foils as a function of time can then be used to infer a time dependent "neutron temperature" which is observed to approach one moderator temperature in an essentially exponential way. The results of Beckurts are shown in Slide I for graphite.

The ratio of the "thermalization time" thus measured to the thermal neutron lifetime should be directly relevant to the degree of thermalization in a reactor.

2. The second measurement is the thermal neutron lifetime vs. size of (buckling) of moderating sample. It can be shown that the most important correction to equilibrium diffusion theory is the "diffusion

cooling" effect discussed by Von Dardel due to preferential leakage of high energy neutrons. The cooling effect depends on competition between the preferential leakage and the tendency of the moderator to restore thermal equilibrium. A variational formulation gives

$$\lambda = (\sigma_a N)^{-1} + D_0 B^2 (1 - cB^2 + O(B'')$$

where $\lambda_{tr}(E) \doteq E^{\alpha}$ $\qquad c = \dfrac{(\alpha + 1/2)^2 \sqrt{\pi}\, D_0}{v_0 M_2}$

$v_0 = \sqrt{2kT/m}$

$M_2 = \left\langle \sigma_s \dfrac{\Delta E^2}{(kT)^2} \right\rangle$

If a Maxwellian spectrum during slowing down is assumed, one gets

$$\gamma = \frac{2}{3\sqrt{\pi}} v_0 M_2$$

so that $$C = \frac{2}{3} (\alpha + 1/2)^2 \frac{D_0}{\gamma}$$

Comparison with expt:

Graphite: Beckurts measured D_0 c and γ and finds that $C \approx \dfrac{D_0}{6\gamma}$ in agreement with $\alpha = 0$ as one would expect. The value of M_2 is about 0.3 times the free atom value which is reasonable on the basis of Debye model calculations that I have done.

Water: Here the situation is somewhat more confusing. If we assume $\alpha = 1/2$ in agreement with $\frac{d}{dT} \langle \lambda_{tr} \rangle$, then both C and γ are in fairly good agreement with M_2 given by

$$M_2 = \underset{\substack{\uparrow \\ \sigma_{sc}(H_2O)}}{\langle \sigma_s \rangle} \underset{\substack{\uparrow \\ \approx \text{Mass 18 gas}}}{\left\langle \left(\frac{\Delta E}{kT}\right)^2 \right\rangle}$$

in good agreement with Brockhouse who sees M = 18 curves for thermal neutrons with strongly hindered rotations. The quantitative way in which the hindered rotations come in to the thermalization process is very complicated and not well understood.

Let us now go on to the high intensity time of flight measurements done by Poole. Good results for boric acid solutions (show slides) note that only the ∞ homog. medium with $1/v$ absorber has been studied so far. This was found to agree well with free M = 1 calc. by Amster. This is very hard to understand since distortion of Maxwellian
OK should be $\sim \frac{\gamma^{-1}}{\tau_{th}}$ and γ^{-1} was measured by Von Dardel to be characteristic of M = 18 and therefore to be $\sim 3 \times \gamma^{-1}$ for free M = 1
It is strongly suggested that one or the other measurement is wrong although our lack of quantitative knowledge about the hindered rotations leaves open the possibility of an accidental cancellation of effects (SM ← $\Sigma\sigma_s$ for rigid molecule $>$ $\Sigma\sigma_s$ free atom)

Possible Future Expts.

Poole intends to continue his expts. with new linac, and we (Beyster) are planning to do similar work at G.A. We see that even the ∞ med. experimental situation is confusing. How would we clear this up?

A. ∞ med.

1. Non $1/v$ absorbers (e.g. Cd sol.). This is closely related to diffusion cooling, and should be sensitive to binding. Discuss.
2. Perhaps phase linac with chopper and watch N (E, t) vs. t.
3. Other moderators - particularly D_2O, ZrH and C; in solids it is hard to dissolve absorber, but ZrH is interesting even with no absorber. C is of interest primarily if phased chopper is used

since effective time is too long for other method. D_2O can be done with absorber dissolved.

B. Geometry Effects

Here we don't even have a qualitative understanding can only mention expts; understanding too poor to more than stab. in dark.

1. Plane boundary

a. $H_2O \,//\, H_2O$ + Boran
$D_2O \,//\, D_2O$ + Boran
Mod A // Mod B
Hot Mod A // Cold Mod A

2. Lattices - This is more empirical. Won't discuss exptl problems of dist. source, etc.

Finally it is interesting to mention a reactor design situation in which the effects of chemical binding on neutron thermalization are such as to qualitatively alter the reactor properties. The work I will discuss is not mine, but that of Rosenbluth and Stern. The reactor is the homogeneous research reactor in which a sizable amount of Zr H moderator is hom. mixed with the fuel. A leading feature of this design is the ability to get a large prompt negative temperature coeff. from the neutrons following the moderator temperature. This will come mostly from an increase in thermal leakage with temp. as the thermal utilization in a homogeneous system is $\simeq$ temp. ind. If, however, water and solid moderator are heterogeneous then an increase in solid mod. temp will also yield an increase in the fraction of captures in the water. Consider first the simplest case of bare homogeneous reactor. There the leakage $\simeq L^2$

$$L^2 \simeq \frac{\tau \langle \lambda_{tr} v \rangle}{3} \quad \text{for } 1/v \text{ abs}$$

$$= \frac{\int \lambda_{tr}(E)\, v\, n(E)\, dE}{\int n(E)\, dE}$$

In Zr H, the binding makes λ_{tr} a strongly increasing function of E. The quantization of the energy transfer has a very strong effect on the temp-dep. of L^2. To see this, Rosenbluth and Stren worked out $\langle \lambda_{tr} v \rangle$ vs T for an Einstein model. The neuts are first assumed to slow down to an equil. dist. given by either H_2O temp or uniform N (E) below $h\nu$ that would occur for oscillator at zero temp. Then fraction are speeded up to $E+h\nu$ determined by detailed balance.

$$\frac{n(E+h\nu)}{n(E)} \approx \left(\frac{E+h\nu}{E}\right)^{1/2} = e^{-h\nu/kT}$$

This is for small H_2O fraction. Show slide.