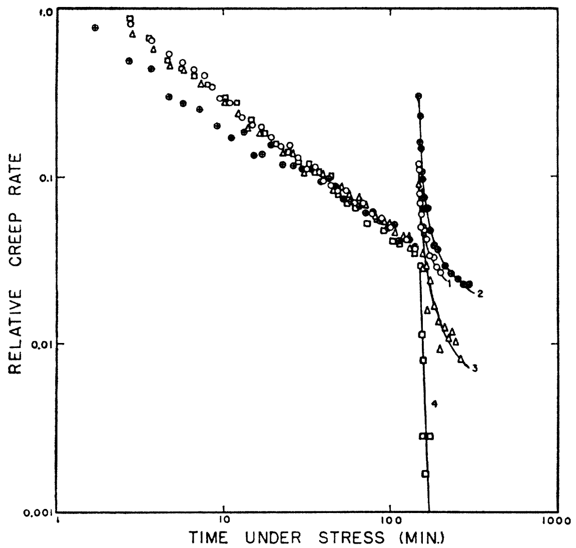

FIG. 1. Creep rate of zinc crystal with rests of various durations interposed after 150 min. of creep. The points denoted by ○, ⊕, Δ, and □ represent runs in which the rest periods were 1 min., 100 min., 25 hr., and 70 hr., respectively. The curves were displaced vertically to make them coincide at 150 min. The actual creep rates (in units of 10^{-5}/min.) are given by these relative rates multiplied by 1.0, 2.0, 0.89, and 0.88, respectively.

and longer time required for the rate to fall to the linear extrapolation.

If the crystals were allowed to rest for a very long time at 35°C, complete recovery would presumably take place; therefore, the effects of still longer rest periods (up to 70 hr.) were studied. A totally unexpected result was obtained. With rests of about 24 hr., the rate immediately after re-application of stress was approximately the same as, or somewhat larger than, that before resting, but it soon fell below the extrapolation of the original log rate-log time curve (curve 3 in Fig. 1). With rests of about 43 and 70 hr., even the initial rate after resting was below the value just before removing the load, and it cornnued to decrease sharply with time (curve 4 in Fig. 1). It thus appears that the crystal, after softening somewhat upon resting, hardens again upon further resting. This behavior was observed eight times with all of the three crystals tested. It shows some similarity to Orowan's thermal hardening effect[6,7] found in investigating stress-strain curves of zinc and cadmium. There are, however, important differences such as the absence here of softening upon further deformation.

Further investigations of this effect are in progress.

[1] This zinc was a gift from the New Jersey Zinc Company.
[2] Other crystals gave slopes even more nearly equal to $-\frac{2}{3}$ than the data in Fig. 1 indicate.
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[4] E. Orowan, J. West Scot. Iron Steel Inst., 45 (1947).
[5] A. H. Cottrell and V. Aytekin, Nature **160**, 328 (1947).
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Fast Neutron Cross Sections and Nuclear Shells

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IN a previous paper[1] a method for measuring fast neutron activation cross sections was described. The neutron source is a plate of uranium enriched in U^{235} which, when placed in a beam of thermal neutrons from the pile, emits fission neutrons of effective energy 1 Mev for the radiative capture process. The flux of unmoderated fission neutrons is calibrated in terms of the known thermal flux and is high enough so that activation cross sections as low as 10^{-4} barn can be measured. The isotopic activation cross sections reported in reference 1 showed a rapid increase with atomic weight up to 100 and approximate constancy for heavier nuclei, with several striking exceptions. The exceptions were Ba^{138}, Pb^{208}, and Bi^{209}, all of which showed cross sections about a 100-fold lower than neighboring isotopes. The unexpectedly low results were soon explained[2] however, by the nuclear shell hypothesis, as Ba^{138} contains 82 neutrons, and Pb and Bi, 126 neutrons, both "magic numbers." A nucleus containing a complete shell of neutrons (20, 50, 82, or 126 neutrons) would be expected to show a low binding energy for an additional neutron, a low excitation energy after neutron capture, a small level density, and hence a low capture cross section.

In order to investigate further the relationship between cross sections and shell structure, additional isotopes with neutron numbers in the 50 and 82 regions have been measured. Most of the elements which were activated were used in solid form in exactly the same manner as was previously described[1] and no additional details are necessary. However, several noble gases were measured and the activation and counting of these proved somewhat difficult, especially Xe with its inconvenient 3.5 min. period. The gases were irradiated in a flat glass cylinder, cadmium covered for fast neutrons and bare for thermals (see reference 1), which was filled to two atmospheres pressure. The cylinder was carried from the pile after irradiation to a system where the gas could be transferred rapidly to a space around a thin-walled G-m tube by freezing and evaporation.

The recent cross-section measurements are listed in Table I and are plotted against neutron number in Fig. 1 along with the results of reference 1. Most of the fast cross sections were measured relative to the known thermal values listed by Way and Haines.[3] For a few cases, such as the Ce isotopes, for which no recent results were available, thermal cross sections were measured also by irradiating and counting thin foils on a calibrated end window G-M tube. It is clear from Fig. 1 that the nuclei with 50 and 82 neutrons have extremely small cross sections, in agreement with the early results for Ba, Pb, and Bi, and in support of the idea that the level density is unusually low in the compound nuclei formed by neutron capture in these isotopes. It follows that the neutron binding energy in these cases must be lower than that of neighboring nuclei by enough to cause a discontinuity in level density by a factor of 50 to 100. If the concept of neutron shells is taken literally, it would be expected that a nucleus with 84 neutrons (two more than a closed shell) would have a cross section lower than normal, but one of 80 neutrons would have a high cross section. The few nuclei of this type measured so far do not seem to fit this simple picture because, while Ce with 84 neutrons has a very small cross section, Rb and

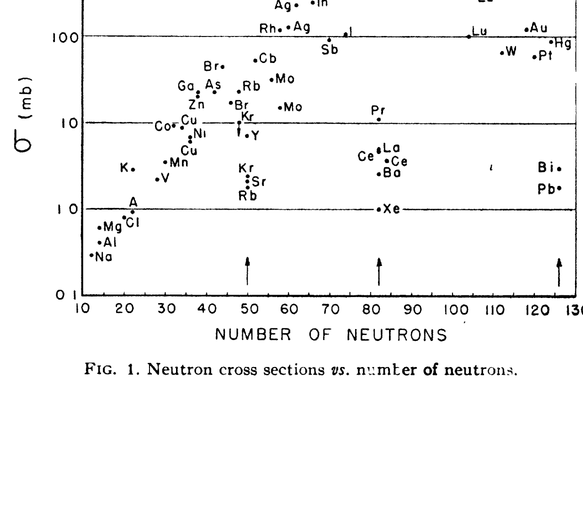

FIG. 1. Neutron cross sections *vs.* number of neutrons.

TABLE I. Isotopic activation cross sections at 1 Mev.

Isotope	No. of neutrons	Activity	Cross sections	Remarks
A^{40}	22	110 min.	0.93 mb	
Kr^{84}	48	(4.5 hr.)	1.9	
		(9.4 yr.)	<8	Activity not detected in thermal or fast irradiation; upper limit estimated from fast flux and counter geometry.
Rb^{85}	48	19.5 day	23.1	
Kr^{86}	50	74 min.	2.4	
Rb^{87}	50	17.5 min.	1.8	
Y^{89}	50	62 hr.	7.0	
Sr^{88}	50	53 day	2.1	
Xe^{136}	82	3.8 min.	1.0	
La^{139}	82	40.4 hr.	5.0	
Ce^{140}	82	28 day	4.8	Thermal $\sigma = 0.24$ b measured also
Pr^{141}	82	19.3 hr.	11.0	
Ce^{142}	84	33 hr.	3.6	Thermal $\sigma = 0.72$ b measured also
Lu^{175}	104	(3.7 hr.)	101	This value (101 mb) plotted on Fig. 1 for Lu^{175} is a lower limit because the fraction of neutron captures forming the 10^{10} yr. activity is unknown.
		(10^{10} yr.)	—	
Lu^{176}	105	6.8 day	296	

Kr, with 48 neutrons, instead of being higher than normal, are actually somewhat lower.

All of the nuclei discussed so far have an even number of neutrons, measurement of capture cross sections of odd neutron number nuclei being difficult because stable nuclei are formed. The neutron binding energy for an odd neutron nucleus would be about 1 to 2 Mev (twice δ_A of Bohr and Wheeler[4]) higher than for an even neutron number, and the cross section would be correspondingly higher. The change in level density corresponding to this difference in excitation energy was investigated with Lu^{175} (104 neutrons, stable) and Lu^{176} (105 neutrons, radioactive). Table I shows that the cross section of Lu^{175} is normal and that of Lu^{176} larger by a factor of at most 3. Thus a change of 1.2 Mev ($2\delta_A$ for $A = 175$) in excitation energy produces a change in level density small compared to that produced at the completion of a shell, indicating that the latter discontinuity must be of the order of several Mev. In fact, the usual statistical nuclear model,[5,6] gives a level density variation with excitation energy which would require a 4-Mev change in binding energy to produce a factor of 50 in level density at $A = 140$, and 3 Mev at $A = 200$. From Way's[7] analysis of the binding energies in the lead region, however, it is seen that the binding of the 127th neutron in Pb and Bi is only about 2 Mev lower than the average for other odd neutrons in the same region. Thus, the change in level density at the shells, as shown by the fast neutron capture cross sections, is quite marked, and in fact larger than would be expected from other evidence based on binding energy and the statistical model.

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Binding Energy of the Triton

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CALCULATIONS have been carried out to investigate the sensitivity of the binding energy of the triton to assumptions about the shape and range of the nucleonic interaction, assuming tensor forces. Assuming a tensor interaction the ground state of

TABLE I. Binding energy of the triron.[a]

Well shape	r_C in 10^{-13} cm	$\frac{r_N}{r_C}$	Exchange nature	$E(H^3)$ in Mev	$E(He^3)$ in Mev	Terms included in trial wave function
Y	1.36[b]	1	Ex.	7.0	—	Including first-order terms for $^2P'$, $^2\bar{P}$, ^4P and second-order terms for $^2S'$, $^2\bar{S}$, $^4D(r_{12})$, $^4D(r_{31}) \pm {}^4D(r_{23})$.
Y	1.36	1	Ord.	6.7	—	
Y	1.36	1	Ex.	5.28	4.26	Including first-order terms for all eight spin and angular functions.
Y	1.36	1	Ord.	4.52	3.50	
Y	1.74[c]	1	Ord.	6.5	—	
Y	2.18[c]	1	Ord.	6.4	—	
Y	3.05[c]	1	Ord.	5.4	—	
Y	1.36	∞	Ord.	12.16	—	Including first-order terms for ^2S waves.
Y	1.74	∞	Ord.	9.00	—	
Y	2.18	∞	Ord.	7.43	—	
Y	3.05	∞	Ord.	5.44	—	
Y	0.80[d]	2	Ord.	10.2	—	Including zero-order terms in $^2S'$ and first-order terms in $^4D(r_{31}) \pm {}^3D(r_{23})$.
S.W.	2.80[e]	1	Ord.	4.0	—	Including zero-order terms in $^2S'$ and $^4D(r_{31}) - {}^4D(r_{23})$ and first-order terms in $^4D(r_{31}) + {}^4D(r_{23})$

[a] Y = Yukawa; S.W. = spherical well; Ex. = exchange; Ord. = ordinary.
[b] K. N. Hsu (unpublished).
[c] T. M. Hu and H. S. W. Massey, Proc. Roy. Soc. **A196**, 135 (1949).
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the triton will be a mixture of eight angular and spin functions, *viz.*,† $^2S'$, $^2\bar{S}$, $^2P'$, ^4P, $^4D(r_{12})$, $^4D(r_{31}) + {}^4D(r_{23})$, $^4D(r_{31}) - {}^4D(r_{23})$, where

$$^4D(r_{12}) = [3(\sigma_1 \cdot r_{12})(\sigma_3 \cdot r_{12}) - r_{12}^2(\sigma_1 \cdot \sigma_3)]\chi$$

and

$$\chi = 2^{-\frac{1}{2}}(\alpha_1\beta_2 - \alpha_2\beta_1)\alpha_3.$$

Previous investigations[1,2] have considered only the contribution from the $^2S'$ and $^4D(r_{31}) - {}^4D(r_{23})$ components. However, if the problem is regarded in an iteration scheme both $^4D(r_{31}) + {}^4D(r_{23})$ and $^4D(r_{31}) - {}^4D(r_{23})$ appear as first-order terms, considering the $^2S'$ wave as primary.[3] In the present work a combination of all the components was taken as trial function.

The effect of range of interaction on triton binding energy has been investigated for a Yukawa interaction with interaction constants adjusted to give correctly the binding energy and quadrupole moment of the deuteron, and the incoherent low energy $n-p$ scattering cross section. Calculations have also been carried out for a Yukawa interaction which gives the correct deuteron binding energy, but assumes central forces only. This is equivalent to making the ratio of the ranges r_N/r_C of the tensor force to the central force infinite. Any other value for this ratio intermediate between 1 and ∞ should lie between the two curves giving triton binding energy as a function of r_C for these two extreme cases. This is in fact found for calculations made using $r_N/r_C = 2$ and $r_C = 0.80 \times 10^{-13}$ cm.

The results are summarized in Table I.

It is seen from the table that the difference produced by assuming different exchange properties is comparatively small, so that most of the calculations were carried out assuming ordinary forces.

It is also clear that the convergence is much better for the long range than for the short range cases. This is a characteristic feature of the variation method. For the case $r_C = r_N = 1.36 \times 10^{-13}$ cm the convergence limit cannot be precisely extrapolated. It may attain a value as high as 8 Mev, but the possibility of determining the range from the triton problem is made difficult by the poor convergence at short ranges. For the long range case $r_C = r_N = 3.05 \times 10^{-13}$ cm the convergence is at least as good as for the pure central force.

The binding energy of He^3 has also been calculated assuming exchange forces and Yukawa interaction of range $r_C = r_N = 1.36 \times 10^{-13}$ cm. In this case the ground state is a mixture of charge doublet and charge quartet, but the effect of the latter is very small and the binding energy obtained was the same as that