dependence of gamma-transition lifetime on nucleon configuration. The data presented in Fig. 1 show that there is, in fact, some evidence to this effect.

In Fig. 1, the values of the matrix elements $|M|^2$ for all the evaluable $E3$ transitions of the $7/2+\rightleftarrows p_{\frac{1}{2}}$ type are plotted against a number n, representing the complexity of the nucleon configuration. For odd-proton nuclei (open circle points), n is the number of protons coupling to form the $7/2+$state, and for odd-neutron nuclei (full circle points) n is the number of neutron holes in the configuration forming the $7/2+$state. Reasonable estimates of n can be arrived at in the case of $g_{9/2}$ proton and neutron configurations by consideration of the energy systematics of the 7/2 +levels.[4] For the cases of Os^{191}, W^{183}, and W^{185}, however, the n-values for the $i_{13/2}$ holes can be regarded as no more than judicious shell-theory guesses. It is apparent from the plot that $|M|^2$ increases steeply with n and at approximately the same rate for odd protons of the $g_{9/2}$ shell, and for odd neutrons of both the $g_{9/2}$ and $i_{13/2}$ sub-shells. To indicate the odd-proton variation, the Rh^{105} and Ag^{107} points have been joined by a line because these isomers have equal neutron numbers. There appears to be some evidence from the plot that there is a systematic effect of adding pairs of neutrons and protons. The departure of Kr^{79} from the general trend may be due to experimental inaccuracy.

Since the factors involved in the estimates[2] of transition probabilities are the same for both odd-proton and odd-neutron transitions and since the single nucleon $p_{\frac{1}{2}}$ states are common to all transitions, the differences of $|M|^2$ should be attributed to the differences of nucleon electric moment of the $7/2+$states. It is not surprising that the electric moment of the odd-proton 7/2 states should increase with increasing numbers of protons in the outer-shell configurations. It is also reasonable to expect that an increasing number of neutrons in the outer shell configurations should tend to crowd protons into the core, thus affecting the electric moment in an inverse manner to the odd-proton states. This is equivalent to saying that for odd-neutron states the electric moment should increase with the number of neutron holes in the configuration.

If the argument for the variation of $|M|^2$ with configuration complexity be accepted for the $E3$ transitions, it may be conversely argued that the constancy of $|M|^2$ for the $M4$ transitions also indicates relatively pure configurations. Analysis of the $M4$ cases makes this indeed appear so, for there are only two cases (Ag^{110} and In^{110}) which have $|M|^2$ values departing significantly from the mean, and these configurations are, in fact, the only ones which are not describable in terms of a single nucleon. It may well be, therefore, that large departures of $|M|^2$ values from the mean value for a particular multipole transition are associated either with departures of one or both of the states from single nucleon configurations or alternatively with actual mixing of multipole radiations as, for example, in the case of $M1$ and $E2$ transitions.

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The Inherent Half-Width of *K*-Conversion Lines

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IN 1951, one of us[1] found that the well-known F line (which is a K-conversion line) in the beta-spectrum of ThB was broader than the I line (L_I line). The half-widths in momentum were 0.14 and 0.10 percent. respectively. The observation was made in the semicircular beta-spectrometer constructed by Lindström and confirmed with the double focusing spectrometer.

Later, one of us measured the broadening effect in his permanent magnet beta-ray spectrometer of high resolving power[2]

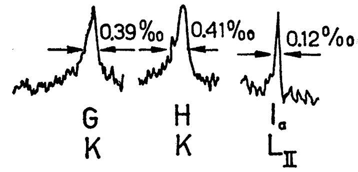

FIG. 1. Broadening effect of the K lines in the beta-spectrum of ThB. The relative half-widths are given in parts per thousand.

(half-width of the I_a line, which is an L_{II} line, only 1.2 parts in 10,000). The difference in half-width between the K and L lines was now found to be 3 parts in 10,000. In addition, the G and H lines, which also are K lines, were found to be 3 parts in 10,000 broader than the I_a line (Fig. 1). This broadening effect in momentum corresponds to about 80 ev in energy, and seems to be the same for all observed K-conversion lines in the β-spectrum of ThB.

Professor Kai Siegbahn has suggested the following explanation of the observed inherent line width of conversion lines: The fact that all the K-conversion lines investigated so far in the ThB spectrum have the same width indicates that the line broadening is essentially independent of the particular nuclear configuration of the states between which the transition takes place. The refilling of the empty place in the K shell, which occurs within a time which is very short compared to the life-time of the nuclear state, is accompanied mainly by the emission of $K\alpha$-radiation. The width of this radiation must, therefore, be expected to show up also in the width of the emitted K-electron line. An inspection of existing data[3] on $K\alpha$-line widths gives quantitative support to this view. For $Z=20$ to 40 the $K\alpha$-line widths increase from 1.7 to 6.8 ev. At $Z=74$ (W) the $K\alpha$-line width is already 42.5 ev, and a reasonable extrapolation to $Z=83$ yields here a line width of 70 ± 5 ev, in remarkably good agreement with the widths of the K-conversion lines reported above. The widths of the L-conversion lines should be expected to be about 10 ev, which is just too small to be observed at present.

The authors are indebted to Professor K. Siegbahn and Professor L. Hulthén for valuable discussions.

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Activation Energy for Fission*

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THE rate of spontaneous fission for even-even nuclides has a simple exponential dependence [1–3] on Z^2/A, and a plot of the logarithm of the "half-life" for this process *vs* Z^2/A (Fig. 1 of references 1 and 3) yields the relationship

$$T=10^{-21}\times10^{178-3.75Z^2/A}\text{ sec.} \qquad (1)$$

It is the purpose of this note to point out how this information can be related to the activation energy for fission and, hence, be correlated with the known information on slow neutron and photofission of heavy nuclides.

The barrier penetration probability for spontaneous fission has been shown to have the general form $10^{-k\Delta E}$, where ΔE is the energy deficit at the saddle point.[4,5] In particular Frankel and Metropolis[5] have derived for the liquid drop model the relationship

$$T=10^{-21}\times10^{7.85\Delta E}\text{ sec,} \qquad (2)$$

where ΔE is in Mev. On the assumption that their treatment for the rate process is essentially correct so that the general form of (2) is valid, even though the calculation of ΔE is not, as evidenced from the failure to account for experimental spontaneous fission

TABLE I. Correlation of slow neutron fissionability with potential barrier to fission and corresponding neutron binding energy.

Nuclide	ΔE (Mev)	NBE[a] (Mev)	$NBE-\Delta E$ (Mev)	SNF[b]
Ra^{226}	6.7	4.9	−1.8	−
Ra^{228}	6.8	4.6	−2.2	−
Ac^{227}	6.5	5.1	−1.4	−
Th^{227}	6.2	7.0	0.8	+
Th^{228}	6.3	5.4	−0.9	−
Th^{229}	6.3	6.7	0.4	+
Th^{230}	6.4	4.6	−1.8	−
Th^{232}	6.5	4.8	−1.7	−
Th^{234}	6.6	4.7	−1.9	−
Pa^{230}	6.1	6.9	0.8	+
Pa^{231}	6.1	5.4	−0.7	−
Pa^{232}	6.2	6.7	0.5	+
Pa^{233}	6.3	5.1	−1.2	−
U^{232}	5.9	5.9	0.0	+
U^{233}	6.0	6.7	0.7	+
U^{234}	6.0	5.4	−0.6	−
U^{235}	6.1	6.5	0.4	+
U^{238}	6.2	4.8	−1.4	−
Np^{234}	5.7	7.1	1.4	+
Np^{237}	5.9	5.2	−0.7	−
Np^{238}	6.0	6.4	0.4	+
Np^{239}	6.0	5.0	−1.0	−
Pu^{238}	5.7	5.7	0.0	+
Pu^{239}	5.8	6.5	0.7	+
Pu^{241}	5.9	6.2	0.3	+
Am^{241}	5.5	5.3	−0.2	−
Am^{242m}	5.6	6.5	0.9	+
Am^{242}	5.6	6.5	0.9	+
Am^{243}	5.7	5.2	−0.5	?
Cm^{242}	5.4	5.9	0.5	?

[a] Neutron binding energy for nuclide with mass number $A+1$, from reference 6.
[b] Slow neutron fissionability: + denotes σ_f greater than about 1 barn; − denotes σ_f less than about 1 barn.

rates,[1] we can relate (1) and (2) and obtain

$$T=10^{-21}\times 10^{7.85(22.7-0.477Z^2/A)}\text{ sec,} \tag{3}$$

where

$$\Delta E=(22.7-0.477Z^2/A)\text{ Mev.} \tag{4}$$

However, (2) actually applies only to U^{238} ($Z^2/A=35.56$) of different degrees of excitation, and extension to different values of Z^2/A leads to a somewhat more complicated expression. When this is related to (1), we find that ΔE can be approximately represented over a limited range of Z^2/A by

$$\Delta E=(19.0-0.36Z^2/A)\text{ Mev.} \tag{5}$$

When ΔE is calculated using (5) and compared with the binding energy (NBE) of the added neutron[6] for each of the nuclides whose slow neutron fission cross sections[7] or upper limits are known, remarkable agreement is observed as shown in the last two columns of Table I. Something approaching a quantitative correlation is attained if the individual values of $NBE-\Delta E$ are compared with the corresponding values of σ_f/σ_r (σ_f=fission, $\sigma_r=n,\gamma$ cross section for slow neutrons) for each nuclide; since the probability for gamma-emission might be approximately the same for all these nuclides, the ratio σ_f/σ_r may give a good measure of the relative probability for fission[8] and, hence, can be used to better advantage for comparative purposes than σ_f alone. Such a plot is shown in Fig. 1 where the available points, perhaps fortuitously, are rather well represented by a straight line with some exceptions discussed below.

Perhaps all of the presently available data on three types of fission (spontaneous, slow neutron, photo) are consistent with the view that an odd nucleon has the effect of slowing the fission process (possibly due to larger radii than corresponding even-even nuclides, giving smaller values of Z^2/r^3 which Z^2/A is meant to represent). In the spontaneous fission case, nuclides with odd nucleons have rates up to some 10^3 times slower than corresponding even-even nuclides (Fig. 1 in reference 1). In the case of photofission,[9] odd nucleon nuclides like U^{233}, U^{235}, and Pu^{239} have thresholds 0.4–0.5 Mev nearer the top of the barrier than U^{238} and Th^{232} corresponding to rates some 10^2–10^3 times slower than those of U^{238} or Th^{232}, indicating that the slowing effect of an odd nucleon is operative even at excitation to near the top of the barrier. However, the probability for gamma re-emission may be less for the even-even nuclides, because of a larger level spacing, which means that fission is relatively favored and would occur at lower excitation relative to the barrier height; thus, the odd nucleon may slow the photofission process, (1) in a manner analogous to the effect in spontaneous fission or (2) relative to gamma-emission owing to its effect on level spacing and, therefore, on the probability for competitive gamma-emission. If we apply these considerations to slow neutron fission, we must think in terms of the intermediate fissioning nucleus which is formed upon capture of the neutron. Thus, it would be interesting to see if even-odd nuclides (even protons, odd neutrons), where the intermediate fissioning nuclei are of the even-even type, undergo slow neutron induced fission with greater probability than other nuclear types at comparable excitation energy. Unfortunately, there are no presently known cases of the ratio σ_f/σ_r for nuclides with $NBE-\Delta E<0$ but only for nuclides which are apparently excited above the barrier in the slow neutron fission process; those that form intermediates with an odd nucleon (see especially Cm^{242}) seem to be slower in undergoing this process; again either of the two mechanisms for the slowing effect of an odd nucleon may be operative. The variation in the positions of the points for the even-odd nuclides in the region above the barrier ($NBE-\Delta E>0$) may perhaps be explained by a small nonuniform variation in the probability for gamma-emission.

The empirical relationship (1) depends, of course, upon how the line is drawn through the points representing the measured spontaneous fission rates of the even-even nuclides. In order to examine this point further, other possibilities were examined; for example, a line drawn somewhat higher with a steeper slope gives more weight to the point[3] for U^{234} and passes somewhat above such points as those for Cm^{244}, U^{238}, and Th^{232} as it might do if these latter nuclides have slightly shrunken radii because of proximity to closed subshells. Such considerations lead to somewhat different constants in relation (5) but do not change per-

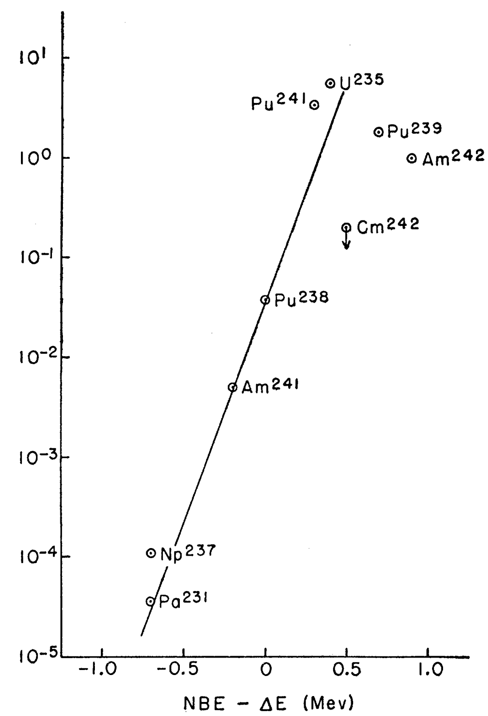

FIG. 1. Plot of comparative slow neutron fissionability. σ_f/σ_r denotes ratio of slow neutron fission to n,γ-cross section (♀ signifies upper limit), $NBE-\Delta E$ denotes difference between neutron binding energy and potential barrier.

ceptibly the results in the correlations presented in Table I and Fig. 1.

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The Vapor Pressure of He^3-He^4 Mixtures*

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THE saturated vapor pressure of helium isotopes and mixtures of the helium isotopes can be discussed on the basis of the clustering avalanche theory of condensation applied to quantum degenerate gases.[1] The saturated vapor pressure is expressed in this theory in terms of the surface energy of small clusters. We calculated the surface energy per atom in clusters in pure He^4 and in pure He^3 to fit the theory to observed vapor pressures of the pure isotopes.[2,3] We then tentatively adopted an interpolation formula in an attempt to predict the vapor pressure of mixtures of the two isotopes. This formula was linear in the concentration; in other words, it assumed the same average concentration of He^3 in the surface of the clusters as in the vapor.

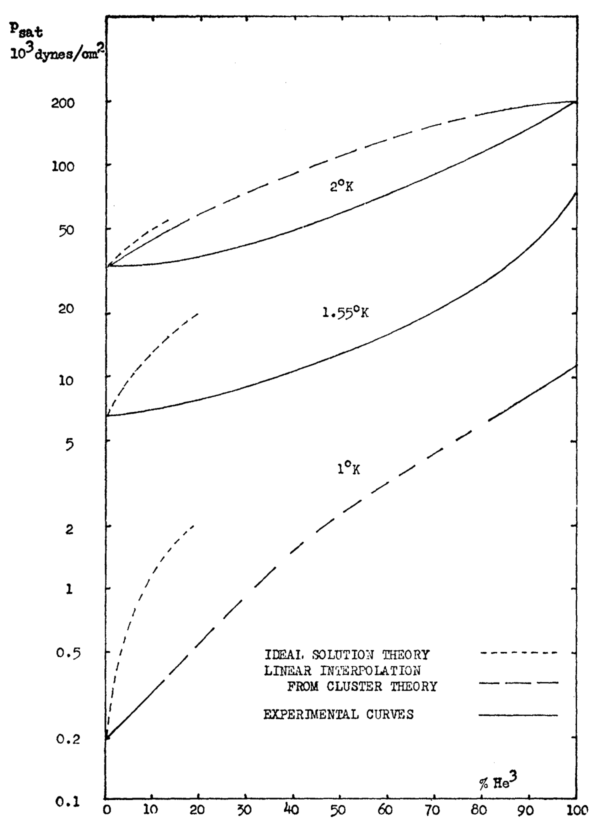

FIG. 1. Saturated vapor pressure as a function of He^3 concentration.

The results of these calculations were given in detail in a technical report to the Office of Naval Research dated June 16th, 1952. Since then the experimental data of Sommers[4] have become available. Figure 1 shows the theoretical curves we found at 2°K and 1°K compared with the ideal solution theory curves and smoothed curves for 2° and 1.55°K taken from Sommers' data. Clearly, although the theoretical curves lie appreciably lower than those of an ideal solution, the experimental curves are very considerably lower still.

This can be accounted for in theory if we use another interpolation formula that is nonlinear in the concentration, and is such as to decrease the average concentration of He^3 in the surface of clusters compared with that in the vapor. A long and tedious computation, however, is needed to find the best formula, and we plan to complete this before publishing a full report.

Sommers analyzed the relation between his saturated vapor pressures and the relative concentrations in the liquid phase, and noted that it was quite doubtful whether there was any significant effect resulting from the lambda-transition in the liquid. Our point of view coincides with this in that the liquid phase does not enter our analysis as such: saturation is an effect of clustering in the vapor. However, we do find that an anomalous decrease of He^3 in the surfaces of clusters is required to explain the data at 2°K. Whether this anomaly is connected with the similar anomaly that exists in the liquid phase below the lambda-point is an open question. It can perhaps be decided after we find whether or not the same anomaly in the clusters is required to explain the vapor pressure curves above as below the lambda-transition.

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Multiple Coulomb Scattering of High Energy Pions in Photographic Emulsions*

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THE small angle scattering in photographic plates of negative pions from the Chicago cyclotron[1] has been measured by the saggitta method. The measurements were undertaken in order to provide information on the multiple scattering of high energy pions over very long cell lengths which is of great importance in numerous cosmic-ray studies.

This investigation was made by methods similar to those initiated by Goldschmidt-Clermont *et al.*[2] and Fowler[2] which were worked out in considerable detail by others.[3,4] Negative pions of 226±7 Mev energy were allowed to pass through two Ilford G5 plates 200 microns in thickness with surfaces nearly parallel to the pion beam. The microscope and techniques were identical to those described by Berger *et al.*[4] The lateral displacement of the tracks y_i were measured at equal distances t (cell length) along a straight line defined by the rectilinear motion of the precision microscope stage.[4] The set of second differences of these lateral displacements $\Delta^2 y_i = y_{i+2} - 2y_{i+1} + y_i$ obtained from the tracks provides a measure of the multiple scattering of the pions. The 89 tracks which were measured were selected along a line 2 cm from the edge of the plate. Then only tracks nearly parallel to the surface were selected and measurements made until they were 5 microns from the surface. The energy of the pion beam before entering the plates was 227±7 Mev from previous calibrations.[1] When corrections were made for energy loss in the plates and wrapping material, the average energy of the pions used in this experiment was 218±11 Mev. The average measured length of the tracks in this investigation was 8000 microns and only 10 percent were shorter than 5600 microns. No measured length of track shorter than 3500 microns was found by the above selection