LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

83550

conf. 650 301-2

MASTER

Transition States at the Fission Barrier*

by

James J. Griffin

University of California
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

ABSTRACT

The current knowledge of the transition states which a nucleus traverses en route to fission is reviewed, together with the relevant theory of fission fragment anisotropy. Theoretical progress in understanding this kind of data in terms of nuclear superfluidity is summarized. The evidence indicates that nuclear pairing effects play an important role in determining the transition state spectrum. Recent (d,pf) experimental data are noted, and their statistical analysis in terms of a pairing Hamiltonian considered in the fixed-energy ensemble appropriate for finite nuclei is presented. The results indicate that such pairing effects lead in Pu^{240} to an energy gap in the transition spectrum nearly twice that which occurs at the ground state shape of the same nucleus. Such a result is quite significant from the point of view of nuclear many body physics, suggesting that the nuclear surface plays an important role in the pairing of nucleons in the finite nuclei. The significance for nuclear fission is also broad. Such a large energy gap forces reassessment of certain detailed conjectures which have been put forward concerning fission widths and mass asymmetry associated with capture resonances of specific spin and parity. The new situation suggests that the (even-even) and (odd-odd) (spin-parity) correlation which rules in the low energy spectra of deformed even-even nuclei does not prevail in the transition state spectrum. A possible explanation in terms of low energy mass-asymmetric and bending vibrations of the fissioning nucleus is discussed. Possible experimental studies which could support or negate the validity of this viewpoint are mentioned.

*Work done under the auspices of the U. S. Atomic Energy Commission

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

1. The Development of the Transition State Concept

A. Bohr [1] first suggested that a nucleus with only slightly more excitation energy than its fission threshold must pass over the fission potential energy barrier in an almost "cold" state of internal excitation, and that at the fission barrier the spectrum of "transition states" of the highly deformed nucleus ought to resemble the spectra near the ground states of stably deformed nuclei. Such a picture is exhibited in Figure 1. This proposal led immediately to a qualitative understanding of the photon-induced and neutron induced fission fragment anisotropy. Later, it provided the basis for a detailed explanation of the $(\text{Th}^{232} + n)$ fragment angular distribution, [2], and for the statistical treatment which explained the detailed energy dependence of the neutron-induced fission angular distributions, [3] to [5], and the tendency in high energy fission for symmetric mass fragments associated with early-chance fissions from highly excited nuclei to be more isotropic than the mass asymmetric events [6]. During this evolution improved data supported the assumption that the fission threshold energy, and not, for example, the energy of the scission configuration was the relevant zero of excitation energy for the transition state spectrum.

For slow neutron fission, the transition state concept explained the fact, established from fission width fluctuations [7], that at most a few channels were determining the statistical properties of fission width distributions. It led also to certain conjectures [8] concerning possible correlations between the spin of a slow neutron fission resonance, its fission width, and the mass asymmetry of the resonance fission.

Under the stimulus of a successful theory, data concerning the fission transition states improved qualitatively and quantitatively [9]. During this period the relevance of the superfluid model of Bardeen, Cooper and Schrieffer [10] to nuclei was first suggested [11] and established by a variety of theoretical successes.¹ The fission fragment angular distribution data had meanwhile become sufficiently detailed to substantiate clear-cut deviation from the behavior of a Fermi gas or independent particle model of the heavy nucleus. It is this matter, and the new implications for fission which the experimental data obtained in studying it, which are the concern of this talk.

¹E.g. The resolution of the problem of nuclear moments of inertia and various detailed features of nuclear spectra. See references [12] through [18].

2. Fission Fragment Angular Distributions and the Transition States at the Fission Barrier

A few qualitative notions about fission fragment anisotropy will be helpful in the following discussion. We digress to present them here.² The basic elements of the theoretical description are (a) the assumption that orientation of the highly deformed nucleus passing over the fission barrier is described by the wave functions of the symmetric top, Φ_{MK}^I , which form the basis for the rotational model of deformed nuclei, and (b) that fission occurs rapidly enough thereafter that the fragments are emitted along the direction of the nuclear axis. For a nucleus with angular momentum (I, M) passing through a transition state with projection K of angular momentum on the nuclear axis the angular distribution of the fragments is then given by

$$W_{MK}^I(\theta) \propto |\Phi_{MK}^I|^2 \quad (1)$$

If $M \ll I$, then these wave functions are peaked forward and backward for small K and sideward for $K \approx I$. If all K values were equally available in the transition state spectrum then the sum over various terms (1) would yield an isotropic distribution of fragments. It is in fact the preponderance of low K values in the transition spectrum just above threshold which causes the forward-backward peaking of fragments from fission induced by energetic projectiles. Also, the increase in the average K-value of the transition states as more excitation energy becomes available explains the decrease in anisotropy with increasing energy above threshold. When many different transition states are available one assumes a statistical distribution of K-values and takes an angular distribution of the form [3]

$$W_M^I(\theta) \propto \sum_{K=-I}^{+I} |\Phi_{MK}^I(\theta)|^2 \exp - \frac{K^2}{2K_0^2} \quad (2)$$

for each (I, M) value of the compound nucleus. It is then possible to extract from adequate data the dependence of K_0^2 on the excitation energy, $E^* - E_f$. In this way the transition state spectrum can be studied and subjected to comparison with theoretical expectations.

²References [1] through [4] and [23] supply more technical detail than time allows in this talk.

3. Conflict Between the Data and the Independent Particle Model

The Gaussian weighting in equation (2) is essentially a statistical Boltzmann factor. From this point of view one expects that $\hbar^2 K_0^2 = J_{\text{eff}} \cdot T$. Then, if the nucleus were composed of independent particles in a potential well exhibiting a uniform single particle spacing, J_{eff} could be estimated from the rigid body moments of the nucleus, and T would be proportional to $(E^* - E_f)^{\frac{1}{2}}$. Such a dependence is shown by the dotted curve of Figure 2. A careful experimental study of $\text{Pu}^{239} + n$ angular distributions was carried out to check this dependence [19]. The results indicated that K_0^2 increases very nearly as $(E^* - E_f)$ and not as $(E^* - E_f)^{\frac{1}{2}}$. The BCS model of nuclear pairing gives just such a dependence³ for K_0^2 (solid line, Figure 2). It predicts also that above some critical excitation energy E_c^* , the pairing effects should disappear and the nucleus should behave according to the independent particle model. Moreover, the value of E_c^* is, according to BCS, related quite simply to the magnitude of the ground state energy gap, $2\Delta_0$.

By utilizing the high energy data of Vandenbosch et al [21] and choosing E_c^* and $(K_0^2)_c$ to fit both those and the low energy data optimally [22], it was possible to estimate that $2\Delta_0$ for the Pu^{240} transition state spectrum is about 2.3 Mev, nearly twice the value appropriate for the low energy spectrum of stable Pu^{240} [14].

³This qualitative feature was first pointed out by Yu. T. Grin [20].

4. Verification in (d, pf) Data

More recently, the large pairing gap in the transition state spectrum of Pu^{240} has been observed directly by measuring the fragment angular distributions from (d, pf) on Pu^{239} [23]. This reaction allows one to explore excitation energies below the neutron binding energy all the way down to the threshold, and provides enough angular momentum to guarantee strong anisotropies.

Figure 3 shows a summary of these results. One sees that $K_0^2 = 0$ is observed near threshold and that K_0^2 jumps from ~ 8 to ~ 16 at $E^* - E_c = 2.6$ Mev. $K_0^2 = 16$ is consistent with the expectation for two quasi-particle-states in a heavy nucleus, whereas $K_0^2 = 8$ is rather too small for this average. This experiment therefore corroborates directly the estimate based on the smooth BCS dependence.

5. Statistical Description of Discontinuities in K_0^2

The smooth BCS description of K_0^2 in Figure 2 is an inevitable result of the use of the macro-ensemble, $\exp - \mathcal{H}/T$, to describe the statistical mechanical system. It is possible, however, to treat the BCS Hamiltonian in a (approximately) fixed energy ensemble [25], $\delta(E - \mathcal{H})$. Then the minimization of the Free Energy, $(U - TS)$, is replaced by the maximization of the entropy as the condition for the optimal pairing solution. In such a treatment the discontinuities associated with the two (and four) quasi-particle excitations become evident, and the BCS formulas are seen as averages in which such discontinuities are smoothed out.

The results of such a calculation for the gap parameter, Δ , and the average number of quasi-particles excited are shown in Figure 4. It could also be noted that the decrease in the gap in such a treatment is fully analogous to the phenomenon of "blocking" which has been considered in some detail for the low-lying spectra of stable nuclei [26].

6. Implications of the Large Gap for Nuclear Many Body Theory

The problem of nuclear pairing has been studied for infinite nuclear matter [27]. The results indicate that nuclear matter should exhibit a gap of nearly zero energy. This result arises from the repulsive nuclear core which nearly cancels out the nuclear attraction for particles near the top of the Fermi sea in heavy nuclei.

It has been suggested, therefore, that the pairing effects observed in nuclei are essentially connected with the finite size of nuclei, and in particular, with the influence of the nuclear surface. Calculations [28] based on a slab model, finite in one of three dimensions show a gap which is very sensitive to the thickness of the slab, diminishing towards zero as the slab becomes thicker.

The relevance of the present result that the gap in highly deformed Pu²⁴⁰ is rather larger than the gap in the same nucleus at its stable shape is obvious. In the process of deformation, the surface area of the nucleus is increased noticeably, so that one should expect a surface-sensitive gap also to be affected. In analogy to W. Swiatecki's proposal that nuclei deformed to the fission barrier ought to fit into an adequate semi-empirical mass formula, one can suggest that such highly deformed nuclei also warrant consideration in theories designed to describe nuclear many-body phenomena.

7. Implications of the Large Pairing Gap for Nuclear Fission

Conjectures⁴ concerning the correlation between the spin of a resonance and its fission properties have been mentioned above. We discuss here in particular the suggestion that the regular (e-e or o-o) spin-parity resonances ought to have greater average fission widths than the irregular combinations. This idea followed quite simply from the assumption that for even-even nuclei the transition state spectrum would exhibit in its low-lying states the correlation between spin and parity which dominates the spectra of stable deformed nuclei, and that odd-even or even-odd spin-parity combinations could arise only from two quasi-particle excitations. It has survived for several years because (a) of the difficulty in determining certainly the spins of given resonances and (b) of the fact that thermal neutrons commonly provide excitation energies about 1 Mev above the fission threshold, an amount not very different from the lowest two-quasi-particle energy in stable spectra.

With the new information from (d, pf) about the transition state pairing gap, the possibility that any two particle transition state is available at thermal neutron energies appears to be excludable, at least for $\text{Pu}^{239} + n$. On the other hand, measurements of spins for eight resonances [31], reveals five of spin 1+ and three of spin 0+ states, precluding thereby the possibility that all the observed resonances have the same spin, 0+. Moreover, the average fission widths among these measured-spin resonances show no significant tendency for 0+ states to fission more easily than 1+ states.

One is therefore forced to take seriously the possibility that irregular spin-parity combinations lie low in the transition state spectrum. Although the lowest lying collective states are all expected to exhibit regular spin-parity, one could build irregular spin parity states by combinations of collective states. These would occur at energies no less than the sum of the two component energies. Thus for example a gamma vibration, $K = 2^+$, $I = 2, 3, 4, \dots$, plus a mass asymmetry vibration, $K = 0^-$, $I = 1^-, 3^-, \dots$, could provide states $K = 2^-$, $I = 2^-, 3^-, \dots$, beginning at an energy $E_{2-} \approx \hbar\omega_Y + \hbar\omega_{MA}$.

Pu is a somewhat fortunate choice for detailed study in this respect, since its irregular combination is 1+, - the least easily constructed from the well known collective states. No 1+ state, for example, could be constructed in the manner noted above. In fact, the simplest 1+ combination of collective

⁴For a summary of these conjectures and their confrontation with the data available at the time, see reference [29]. Earlier discussions occur in references [9] and [30].

states is that formed from the mass-assymetry and bending vibrations.⁵ It would provide a transition state at energy $E_{1+} \approx h\nu_{MA} + h\nu_B$, which might be less than the 1.6 MeV available from thermal neutron capture, if only these odd parity vibrations in the transition state spectrum have low enough excitation energy.

To check this possibility, we have investigated the trend of these modes' frequencies as a function of the nuclear elongation in a pure liquid drop model.⁶ The calculation is outlined in the Appendix and the results are given in Figure 5. The results indicate that as deformation increases the energy of these modes decreases. These calculations are by no means a complete treatment, even within the liquid drop model, since only relatively simple shapes are included. Still, they offer qualitative support to the conjecture that these excitations will be found to lie low in the transition state spectrum, and provide thereby a reasonable basis for understanding the various features of Pu^{239} fission now evident in the experimental data.

Another implication of the large gap at the fission barrier is that spontaneous fission will be retarded in odd nuclei by an increase in their fission barrier in an amount $\Delta E_f = \Delta_{\text{barrier}} - \Delta_{\text{stable}}$. This difference is about 0.600 MeV in the case at hand, and may be adequate⁷ to explain the entire retardation ($\sim 4 \times 10^4$) factor from Pu^{240} to Pu^{239} , without recourse to the assumption that K remains a good quantum number enroute to the fission barrier [35].

⁵The mass assymetry mode corresponds to a Y_3^0 deformation of the deformed nucleus, the bending mode to a Y_3^1 . In classical terms, the mass assymetry mode is the oscillation of a pear shape into its mirror image, or the running of a bulb about the greatest perimeter of the deformed nucleus. Bending (Y_3^1) corresponds to a wave running about the surface at an angle, $\theta = \cos^{-1} 1/(3.4)^{1/2}$, with the symmetry axis. Higher excitations of order three can exist with $K = \pm 2, \pm 3$, but presumably, at higher excitation energies than the motions considered here. Cf reference [32].

⁶Note that in reference [33], similar calculations are made for saddle point shapes in the two-spheroid model. However in that model, the mass assymetry mode exhibits infinite inertia, and therefore, zero frequency.

⁷This statement is based on the assumption that each one MeV increase in the barrier energy corresponds to a factor 10^{-8} in lifetime [34].

8. Avenues of Further Experimental Study

In order to study further the "spectroscopy" of highly deformed nuclei, more certain information on resonance spins is essential. Fragment anisotropy measurements for specific fission resonances [36], which require aligned or polarized targets, could provide a solid basis for such spin assignments, and provide as well an indication of the K-values relevant to the different spin states.

(D, pf) evidence of the kind now available for Pu is required for other nuclides to preclude the possibility that the large pairing gap there is a quirk of Pu alone, and not to be extrapolated to neighboring isotopes. The $(\alpha, \alpha'f)$ reaction also promises to be useful in such studies [37] [38].

Angular studies of photon-induced fission of even-even isotopes also offer a possible tool for studying the transition states, especially if the precision of the process could be increased. The picture discussed above implies that a $K = 1, 1^-$ state lies not too far above the lowest ($K = 0$) 1^- state. The observed rate of decrease in an isotropy from photon induced fission [39], which has been interpreted to imply a $K = 1$ state at ≈ 0.230 MeV above the $K = 0, 1^-$ state is not inconsistent with this picture.⁸ Sufficient precision to specify or to put bounds on the energy difference between the lowest 1^- transition state and the fission threshold ($0+$) energy would be a valuable advance. Quadrupole transition states might also be studied in detail by this process [40].

Properties associated with specific neutron resonances other than the angular distributions will also be useful in constructing a solidly interlocked picture of the transition state spectrum. Studies, for example, of fragment mass asymmetry [41], of the probabilities of α - emission in fission [42], and, indeed, of the basic partial widths for each resonance, will hopefully find a place in such a picture. Regarding the latter, due cognizance must be taken of the recent work of Lynn [43], which suggests firmly for U^{233} and U^{235} , and less definitely for Pu^{239} that resonances come within a width of one another often enough to deceive the naive one-level student into accepting a warped picture of the underlying resonance properties.

In summary, one can observe that the transition state spectra have grown in recent years into a fruitful object for study, and that there appears every promise that the range and interest of such studies will continue to grow.

⁸ This estimate would be decreased by at least a factor of two if the assumed barrier curvature were chosen as small as the data of reference [23] requires.

References

- [1] BOHR, A., Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva 1955 (United Nations, New York, 1956), Vol. 2, p. 151.
- [2] WILETS, L. and CHASE, D., Phys. Rev. 103, 1296 (1956).
- [3] HALPERN, I. and STRUTINSKII, V., Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva (1958), Vol. 15.
- [4] GRIFFIN, J., Proceedings of the International Conference on Nuclear Structure, Paris, 1958; Phys. Rev. 116, 107 (1959); Phys. Rev. 127, 1248 (1962); with GIBBS, W. R., Phys. Rev. in Press.
- [5] BROLLEY, J., DICKINSON, W., and HENKEL, R., Phys. Rev. 99, 193 (1955); Phys. Rev. 103, 1292 (1956).
- [6] COHEN, B. L. et al, Phys. Rev. 94, 625 (1954); 98, 685 (1955); FAIRHALL, A. et al, Phys. Rev. 94, 733 (1954).
- [7] PORTER, C. E. and THOMAS, R. G., Phys. Rev. 104, 483 (1956).
- [8] WHEELER, J. A., International Conference on Nuclear Reactions, Amsterdam, Physica XXII, 1103 (1956).
- [9] SIMMONS, J. and HENKEL, R., Phys. Rev. 120, 198 (1960); BLUMBERG, L. and LEACHMAN, R., Phys. Rev. 116, 102 (1959).
- [10] BARDEEN, J., COOPER, L., SCHREIFFER, J., Phys. Rev. 108, 1175 (1957), referred to as BCS.
- [11] BOHR, A., MOTTELSON, B., and PINES, D., Phys. Rev. 110, 936 (1958).
- [12] BELYAEV, S. T., Mat.-Fys. Medd. (Kgle. Danske Vid. Selsk.) 31, No. 11 (1959).
- [13] GRIFFIN, J. and RICH, M., Phys. Rev. Letters 3, B516, (1959); Phys. Rev. 118, 850 (1960).
- [14] NILSSON, S. G., and PRIOR, O., Mat. Fys. Medd. (Kgle. Danske Vid. Selsk.) 32, No. 16 (1960).
- [15] KISSLINGER, L. and SORENSEN, R., Mat.-Fys. Skr. (Kgle. Danske Vid. Selsk.) 32, No. 9 (1960).
- [16] SOLOVIEV, V., Mat.-Fys. Skr. (Kgle. Danske Vid. Selsk.) 1, No. 11 (1961).
- [17] BES, D. R. and SZYMANSKI, Z., Nucl. Phys. 28, 42 (1961).

- [18] GALLAGHER, C., and SOLOVIEV, V., Mat.-Fys. Medd. (Kgle. Danske Vid. Selsk.) 32 No. 16 (1960).
- [19] SIMMONS, J. E., Unpublished. See reference [22], however, for the results of this experiment.
- [20] GRIN, YU. T., Zh. eksper. teor. Fiz. (USSR) 43, 1880 (1962).
- [21] VANDENBOSCH, R., WARHANECK, H. and HUIZENGA, J., Phys. Rev. 124, 846 (1961).
- [22] GRIFFIN, J., Phys. Rev. 132, 2204 (1963).
- [23] BRITT, H. C., STOKES, R., GIBBS, W., and GRIFFIN, J., Phys. Rev. Letters, 11, R502 (1963), and to be published.
- [24] GRIFFIN, J. and RICH, M., Bulletin of Amer. Phys. Soc. II, 18, 526 (1963).
- [25] RICH, M. and GRIFFIN, J., Phys. Rev. Letters, 11, L518, (1963) and to be published.
- [26] WAHLBORN, S., Nuclear Physics, 37, 554 (1962).
- [27] EMORY, V. and SESSLER, A., Phys. Rev. 119, 248 (1960).
- [28] HENLEY, E. and WILETS, L., Phys. Rev. Letters 11, 326 (1963); KENNEDY, R., WILETS, L., and HENLEY, E., Phys. Rev. Letters, 12, 36 (1964).
- [29] GRIFFIN, J., International Conference on Nuclear Structure, Kingston, Ontario, Canada (1960) (U. of Toronto Press).
- [30] WILETS, L., Proc. International Conf. on Nuclear Structure, Rehovota, Israel, 1957. (North Holland Publishers, Amsterdam)
- [31] FRASER, J. and SCHWARTZ, R., Nuclear Physics 30, 269 (1962).
- [32] WHEELER, J. A., in Fast Neutron Physics, Part II. Edited by J. Marion and J. Fowler (Interscience-New York, 1963).
- [33] NIX, J. R., Lawrence Radiation Laboratory Report - UCRL 11338 (1964), unpublished.
- [34] SWIATECKI, W. J., private communication.
- [35] WHEELER, J. A., Proc. International Conf. on the Peaceful Uses of Atomic Energy, Geneva, 1955 (United Nations, New York, 1956) Vol. 2, p. 155.
- [36] Such experiments are in progress at the Oak Ridge National Laboratories (private communication from J. Dabbs).
- [37] WILKINS, B. D., et al, Physics Letters, 12, 243 (1964).

- [38] BRITT, H. C., private communication.
- [39] BAERG, A. P., et al, Can. Journal of Physics, 37, 1418 (1959).
- [40] FORKMAN, B. and JOHANSSON, S. A. E., Nuclear Physics, 20, 136 (1960).
- [41] FALER, K. T. and TROMP, R. L., Phys. Rev. 131, 1746 (1963); and references cited therein; COWAN, G. A., et al, Phys. Rev. 130 2380 (1963); and references cited therein.
- [42] MELKONIAN, E., Columbia University Progress Report, CU (PNPL) 212 - 1961, unpublished.
- [43] LYNN, J. E., Phys. Rev. Letters 13, 412 (1964).

James J. Griffin; SM 60/4
Transition States at the Fission Barrier

Figure 1. The transition states at the fission barrier are compared with the low-lying spectrum of a heavy deformed nucleus. Various energies indicated are specifically appropriate to Pu^{240} . The gamma and double gamma vibrations in the transition spectrum have been suggested [24] by the data of reference [23]. The mass-asymmetry and bending modes are hypothesized here in order to place a 1^+ state low in the transition spectrum, as present (fragmentary) data seems to require.

James J. Griffin; SM 60/4
Transition States at the Fission Barrier

Figure 2. The implications for K_0^2 of the independent particle model (parabola) and the superfluid model of nuclear pairing (linear at low energy, parabolic above E^*) are compared with the data. The energy difference between zero excitation energy and the energy where the parabola goes to zero is the energy gain due to nuclear pairing. From the best fit (solid line) to the data the gap is estimated to be $2\Delta_0 \approx 2.3 \text{ MeV}$.

James J. Griffin; SM 60/4
Transition States at the Fission Barrier

Figure 3. The (d, pf) experimental results for K_0^2 vs. $E^* - E_f$ in Pu^{240} and (of lower statistical quality) U^{234} are presented. Near threshold $K_0^2 \approx 0$, as is expected for an even-even nucleus. At $\sim 2.6 \text{ MeV}$, K_0^2 jumps to a value appropriate for an average over two quasi-particle states. The smaller jumps at 0.7 MeV and 1.5 MeV may correspond to low lying collective excitations in the transition state spectrum [24]. At higher excitation energies, the results agree well with comparable results from neutron work [10], indicated by triangles.

James. J. Griffin; SM 60/4
Transition States at the Fission Barrier

Figure 4. The results of optimizing the choice of independent quasi-particles for a BCS (pairing) Hamiltonian are compared for (a) the fixed temperature ensemble and (b) the fixed energy ensemble. The latter replaces the smooth dependence on energy by one which exhibits appropriate discontinuities in the various energy dependent functions of the system. The energy gap and the average number of quasi-particles are shown here as examples.

TRANSITION STATE SPECTRUM vs SPECTRUM NEAR GROUND STATE

LOS ALAMOS
PHOTO LABORATORY

NEG. NO. 649495

PLEASE RE-ORDER
BY ABOVE NUMBER

LOS ALAMOS
PHOTO LABORATORY

NEG
NO. 64113

PLEASE RE-ORDER
BY ABOVE NUMBER

LOS ALAMOS
PHOTO LABORATORY

NEG.
NO. 635521

PLEASE RE-ORDER
BY ABOVE NUMBER

LOS ALAMOS
PHOTO LABORATORY

NEG.
NO. 64114

PLEASE RE-ORDER
BY ABOVE NUMBER