

Lawrence Berkeley National Laboratory

Recent Work

Title

ON THE SPONTANEOUS FISSION OF NUCLEI WITH Z NEAR 114 AND N NEAR 184

Permalink

<https://escholarship.org/uc/item/59h9f0kv>

Authors

Nilsson, S.G.

Nix, J.R.

Sobiczewski, A.

et al.

Publication Date

1968-02-01

g. 2

University of California

Ernest O. Lawrence
Radiation Laboratory

TWO-WEEK LOAN COPY

*This is a Library Circulating Copy
which may be borrowed for two weeks.
For a personal retention copy, call
Tech. Info. Division, Ext. 5545*

**ON THE SPONTANEOUS FISSION OF NUCLEI WITH Z NEAR
114 AND N NEAR 184**

**S. G. Nilsson, J. R. Nix, A. Sobczewski, Z. Szymański,
S. Wycech, C. Gustafson and P. Möller**

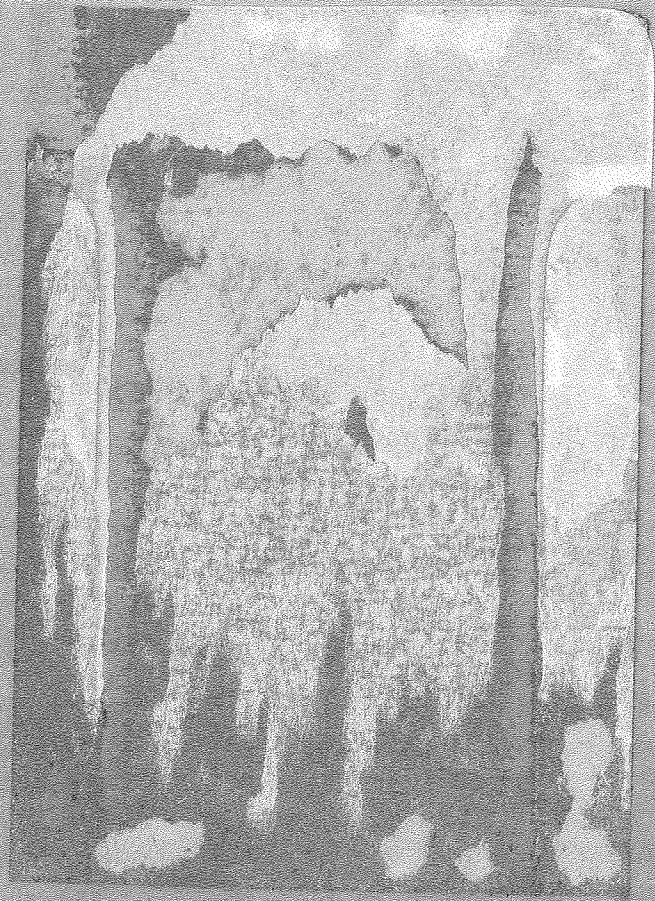
February 1968

RECEIVED
LAWRENCE
RADIATION LABORATORY

Berkeley, California

LIBRARY AND
DOCUMENTS SECTION

*UCRL-18068
g. 2*



LRL
to be submitted to Nucl. Phys.

UCRL-18068
Preprint

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

ON THE SPONTANEOUS FISSION OF NUCLEI WITH Z NEAR
114 AND N NEAR 184

S. G. Nilsson and J. R. Nix
and
A. Sobiczewski, Z. Szymański, and S. Wycech
and
C. Gustafson and P. Möller

February 1968

ON THE SPONTANEOUS FISSION OF NUCLEI WITH Z NEAR 114 AND N NEAR 184

S. G. Nilsson^{*†} and J. R. Nix^{*‡}

Lawrence Radiation Laboratory
University of California
Berkeley, California

and

A. Sobiczewski, Z. Szymański, and S. Wycech
University of Warsaw, Poland

and

C. Gustafson and P. Möller
Lund Institute of Technology
Lund, Sweden

February 1968

ABSTRACT

Theoretical calculations of the potential energy surface as a function of quadrupole and hexadecapole distortion parameters are reported for super-heavy nuclei with Z near 114 and N near 184. Estimates of spontaneous fission half lives indicate a sizable island of relative stability in the vicinity of these closed-shell nucleon numbers.

* This work was performed under the auspices of the U.S. Atomic Energy Commission.

† On leave from Lund Institute of Technology, Lund, Sweden

‡ Present address: Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

We have attempted to predict spontaneous-fission half lives of a series of isotopes with Z values near the closed shell proton number $Z = 114$ ^{1,2,3)} and neutron number N near 184. The calculations lend some support to speculations that an island of relatively long lived elements may be expected for nuclei with Z near 114 and N near 184.

The shell model field on which this study is based is effectively that suggested by Gustafson et al. in ref. ³⁾, and given here in eq. (5). The corresponding level scheme in the spherical case is exhibited in figs. 1a and 1b. A careful determination of the parameters of the potential in the rare earth deformed region and in the actinide region exists, and from these regions a brave and linear extrapolation of the potential parameters is made to $A \approx 290$. In the figures mentioned we show the levels corresponding to a Woods-Saxon potential fitted by Rost⁴⁾ to reproduce the experimental single-particle properties of ^{207}Pb , ^{209}Pb , ^{207}Tl , and ^{209}Bi and extrapolated to $A = 298$ in accordance with a prescription outlined in ref. ⁴⁾. For both potentials mentioned[§] moderately large single-particle level gaps are suggested for $Z = 114$ and $N = 184$ respectively. The level order is in other respects relatively different, underlining the general uncertainty of an extrapolation procedure. Note in particular the different variation with A of the position of the $(N=l, j=l+\frac{1}{2})$ subshells. As important results,

[§]In the present case, in contrast to ref. ⁴⁾, no separation of the potential is made into an isoscalar and an isovector part. As achievable isotopes of $Z = 114$ lie along the direction of the stability line in the actinide region, such a separation might not be necessary. However, in order to describe nuclei far off the stability line, such a separation definitely appears desirable.

on which there is good agreement, one may note the low level density between $Z = 114$ and $Z = 124$ (126) in the proton level diagram and generally a region of low density of levels extending more than $0.5 \hbar\omega_0$ above $N = 178$ in the neutron diagram. Thus, for $Z = 114$ or $Z = 124$ (126) and $N = 184$ we expect a probable location of a region of spherical nuclei, according to either of the level schemes. Predictions of fission half lives require a more detailed study of a large portion of the potential energy surface, and this is carried out here.

It has been found earlier that a summation of single-particle energies based on the potential (5), or its predecessor, subject to the condition of conservation of equipotential volumes and with appropriate correction for Coulomb and pairing effects, gives good predictions for the relatively small equilibrium distortions.^{5,6)} However, the same procedure fails at large distortions. Thus the $\frac{1}{l^2}$ term, or the ρ^4 term, treated within only one N shell, is found to simulate a surface-energy term only at small distortions.⁷⁾

To overcome this deficiency of the nuclear potential a normalization procedure due to Strutinsky⁸⁾ has been applied. The renormalized energy obtained by this method represents a shell and pairing correction (see fig. 2) to a smooth background energy provided by the liquid drop model. The present line of approach thus represents a further development of the work of Myers and Swiatecki⁹⁾ and that of Johansson.¹⁰⁾ At equilibrium deformations the normalization effects are relatively insignificant. Indeed the difference in equilibrium quadrupole and hexadecapole deformations between the cases when the normalization is and is not applied amounts to a magnitude of 0.01 or less.

According to Strutinsky's prescription one first defines a smoothed reference level density $g(e)$ by averaging the calculated single-particle levels

e_ν over a range γ , where γ is an energy of the order of the shell spacing,

$$g(e) = \frac{1}{\gamma\sqrt{\pi}} \sum_{\nu} (1 + t_{\text{corr}}) \exp \left[- \left(\frac{e - e_{\nu}}{\gamma} \right)^2 \right], \quad (1)$$

and where

$$t_{\text{corr}} = \frac{1}{2} - \left(\frac{e - e_{\nu}}{\gamma} \right)^2. \quad (2)$$

We have used the value $\gamma = 0.8 \hbar\omega_0(\epsilon, \epsilon_4)$. The term (2) is inserted to correct for errors introduced by the folding procedure.^{8,11)} Based on this smoothed level density a corresponding average energy is calculated as

$$E(g) = \int_{\bar{\lambda}} 2eg(e) de, \quad (3)$$

where $\bar{\lambda}$ is determined separately for neutrons and protons so as to meet the requirement of given neutron and proton numbers.

This background energy, given by eq. (3), is later to be replaced by the liquid drop energy. Shell and pairing corrections, to be added later to the liquid drop energy, are calculated with reference to this background energy as[§]

$$E_{\text{shell}} + E_{\text{pair}} = \sum_{\nu} e_{\nu} 2V_{\nu}^2 - G \left(\sum_{\nu} V_{\nu} \right)^2 - G \left(\sum_{\nu} V_{\nu}^4 - \sum 1 \right) - E(g). \quad (4)$$

[§]For a more detailed discussion see ref. 7) (forthcoming).

This sum is to be evaluated separately for neutrons and protons. In eq. (4) the quantities e_ν are the single-particle energies, and V_ν^2 and U_ν^2 are the corresponding pairing theory population factors. The strength G in eq. (4) of the pairing interaction is taken to be $(19.6/A)$ MeV and $(14/A)$ MeV for protons and neutrons respectively, employing N neutron and Z proton levels. The adequacy of this prescription over a larger mass region is presently being investigated. The term $G \sum_\nu 1$ represents the subtracted diagonal pairing corresponding to a sharp Fermi surface.

Finally, the total potential energy of deformation, constructed according to the above prescriptions, is given by[§]

$$E = E_{\text{surf}} + E_{\text{coul}} + E_{\text{shell}} + E_{\text{pair}} \quad (5)$$

As reported in ref. ³⁾ the single-particle energies have been calculated for the potential

$$V = \frac{1}{2} \hbar \omega_0 (\epsilon, \epsilon_4) \rho^2 \left(1 - \frac{2}{5} \epsilon P_2 + 2 \epsilon_4 P_4 \right) - 2 \kappa \hbar \omega_0 \left(\underline{\ell}_t \cdot \underline{s} - \mu (\rho^4 - \langle \rho^4 \rangle_N) \right) \quad (6)$$

where ρ^2 and $\underline{\ell}_t$ are defined in terms of the stretched coordinates of ref. ¹²⁾ and where $\langle \rho^4 \rangle_N$ represents the average matrix element of this correction term within a shell N . This potential differs formally from that used in ref. ³⁾ by the replacement of $-\frac{1}{2}(\underline{\ell}_t^2 - \langle \underline{\ell}_t^2 \rangle_N)$ by $(\rho^4 - \langle \rho^4 \rangle_N)$. These expressions have identical matrix elements within one major oscillator N shell (in the "stretched" representation), but the second form is believed to be more adequate at large deformations.

[§]Since for the pairing energy no averaging procedure has been applied, we systematically end up, on the average, a few MeV on the negative side of the liquid drop energy.

Since at the present time only matrix elements within each N shell are taken into account, the potentials are identical in their effect. For $\epsilon_4 \rho^2 P_4$, matrix elements between the shells N and N±2 have been taken into account, and their inclusion is found to be responsible for more than half the ground state hexadecapole equilibrium distortion.^{6,7)} In the final diagonalisation, shells up to N = 12 have been included. We have used the extrapolated values $\kappa = 0.0540$, $\mu = 0.681$ for protons and $\kappa = 0.0634$, $\mu = 0.266$ for neutrons; for $\hbar\omega_0$ we use $41 A^{-1/3}$ MeV.

The single-particle energies e_ν obtained from this potential are employed in eq. (4) to calculate the shell and pairing corrections. The surface and Coulomb energies have been calculated exactly for a set of ϵ values = -0.5(0.1)0.9 and ϵ_4 values = -0.08(0.04)0.16. The Coulomb energy corresponds to that of a homogeneously charged body (with a first order diffuseness correction), and it has been evaluated numerically in accordance with a method suggested in ref. ¹³⁾. The calculated values of the surface and Coulomb energies are given in tables 1 and 2, respectively.

For nuclei in the actinide region the shell structure potential parameters κ and μ are very well known. However, in that region the barrier extends to very large distortions and the parametrisation employed in terms of ϵ and ϵ_4 may be rather inadequate. Thus, e.g., for the U and Pu isotopes, the liquid-drop saddle energy is found to be higher by about 0.6 and 0.3 MeV respectively than that obtained from the more general parametrisation used in ref. ¹⁵⁾. The saddle points in these two cases occur at ϵ approximately equal to 0.75 and 0.85, respectively. For nuclei heavier than Cm the error in the liquid drop energy at the saddle is less than 0.1 MeV, however, and the prospect of an extension of reliable calculations to this region of deformation appears relatively hopeful.[§] More serious appears the deficiency of $\frac{\hbar^2}{2m} \cdot \nabla^2$ term at large distortions, the unsatisfactory treatment of the ρ^4 term, and the neglect of higher oscillator

[§] Preliminary evaluation of the ²⁵⁴U No fission barrier, which just falls within the distortion region calculated, gives a half life of the correct order of magnitude using the semi-empirical averaged inertia values II to be discussed below.

shells ($N \geq 13$). We find, e.g., that the inclusion of the $N = 12$ shell for protons for $A \approx 300$ lowers the energy by about 0.4 MeV at $\epsilon \approx 0.9$. This effect does not come about because $N = 12$ levels cross the Fermi surface but because the background energy (4) appears somewhat sensitive to level densities at an energy of $\hbar\omega_0$ away.

On the other hand, for the super-heavy nuclei the saddle lies much closer to the spherical shape and the $(\epsilon, \epsilon_{II})$ parametrisation appears sufficient. Here the uncertainty lies in extrapolation of the parameters κ and μ of the nuclear potential, as described above. (The difference in half lives between calculations based on extrapolated and unextrapolated actinide parameters may be studied in figs. 15 and 16.)

The potential energy barrier, in particular the second maximum of the barrier, depends rather sensitively on the liquid drop constants assumed. These were determined in ref. 9) from a mass fit under the assumption of particular shell corrections; we intend to redetermine these liquid drop parameters by using the improved shell corrections presently calculated.

There furthermore remains the problem of a possible dependence of the pairing matrix element G on deformation, which has been discussed by Stępień and Szymański¹⁷), and also to what extent such an effect is already included in the fitted parameters of the liquid drop model. In the absence of a clear alternative we have presently assumed G to be constant/ under deformation of the nuclear potential.

Finally, the fission inertial mass parameter B_e has been calculated from microscopic theory (as well as estimated in other ways; see below). The expression for the inertial parameter B_Q for the quadrupole degree of freedom

is the following

$$B_Q = \frac{\hbar^2}{2} \frac{\Sigma_3}{(\Sigma_1)^2} \quad , \quad (7)$$

where

$$\Sigma_n = \sum_{\mu, \nu} \frac{\langle \mu | q | \nu \rangle^2}{(E_\mu + E_\nu)^n} (U_\mu V_\nu + V_\mu U_\nu)^2 \quad . \quad (8)$$

The inertial parameter associated with the ϵ coordinate is then given approximately by

$$B_\epsilon \approx \left(\frac{dQ}{d\epsilon} \right)^2 B_Q \quad . \quad (9)$$

Calculations involving a study of the entire (ϵ, ϵ_4) plane are presently being carried out in Warsaw, and a more detailed account will be given in a forthcoming publication.⁷⁾ In eq. (8) U_ν and V_ν are the pairing occupation factors encountered in eq (4), E_ν is the quasi-particle energy $\sqrt{(e_\nu - \lambda)^2 + \Delta^2}$, and $\langle \mu | q | \nu \rangle$ are matrix elements of the single-particle mass quadrupole moment q between single-particle states ν and μ . In (9) Q is the total mass quadrupole moment. The matrix elements to higher N shells are important in the evaluation of eq.(7) as is the elimination of the particle number fluctuation spurion.

In calculating the spontaneous fission half lives a number of simplifying assumptions have been made in addition to the most important one that a one-dimensional WKB approximation can be employed. First, we have assumed that

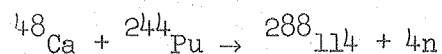
the zero-point vibrational energy in the nuclear ground state is 0.5 MeV for all cases. Secondly, as is seen from figs. 3-6, in all likelihood the path to fission exploits the ϵ_4 degree of freedom to a high degree, circumventing the barriers existing along the ϵ axis. For simplicity we have used a minimum-energy curve, obtained by seeking the minimum with respect to ϵ_4 for each ϵ and projecting on the ϵ axis. This assumes the ϵ_4 degree of freedom to be optimally exploited with no regard for dynamics. This oversimplification of the dynamical problem in general underestimates somewhat the fission half life. On the other hand, a confinement along the actual energy curve of the ϵ axis gives a gross over-estimate. Finally, the inertial parameter, in the following denoted simply by B , is assumed to be independent of deformation.

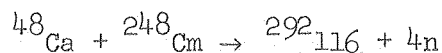
In figs. 7-14 we exhibit the fission barrier curves for a series of isotopes of $Z = 110, 112, \dots, 124$. These curves are obtained as described above by an energy minimization with respect to ϵ_4 for each ϵ . One may note that for all $Z = 110$ isotopes calculated, the ground state is deformed and the fission barrier virtually nonexistent. For $Z = 114$, isotopes lighter than $A = 286$ are still deformed in the ground state. First for $A \geq 286$ is the near-spherical configuration favored, a fact which leads to a substantial barrier. Of great interest is the systematic occurrence of a secondary minimum in the barrier. Note that with increasing Z the secondary maximum in the barrier weakens due to the increase with Z of the Coulomb energy.

In fig. 15 the calculated spontaneous-fission half lives are given for various isotopes of $Z = 114$ corresponding to the extrapolated values of the parameters κ and μ , and in fig. 16 the half lives corresponding to the unextrapolated actinide values of these parameters. Results for elements $Z = 116-124$ are given in figs. 17 and 18 for the extrapolated parameters. The results are presented

as functions of the inertial parameter B divided by $A^{5/3}$, A being the mass number. Four different estimates are given for this quantity. The left vertical solid line corresponds to the irrational-flow value of B , and is relevant only as a lower limit. The right vertical line represents an average value of the microscopic results, which vary by a few tens of % with mass number and distortion. The dependence of B on the parameters κ and μ appears less significant. The two shaded regions correspond to semi-empirical estimates obtained from analyses of experimental spontaneous-fission half lives and fission-barrier heights for nuclei in the actinide region. The shaded area denoted by I corresponds to the assumption that the fission barrier is cubic in shape, has a spherical ground state minimum, and the correct liquid-drop curvature at its maximum value.¹⁴⁾ The cubic approximation generally tends to over-estimate the barrier thickness, since it neglects the barrier indentation corresponding to the deformed ground state. Hence this value of the inertial parameter is probably an underestimate. The shaded area II corresponds to an analysis by Moretto and Swiatecki¹⁶⁾ and is based on the assumption that the fission barrier is the sum of the shell-correction function of ref. ⁹⁾ and a part that is cubic in shape with the correct liquid-drop curvature at the spherical shape. The semi-empirical values II (as well as I) suffer from the weakness that they are extrapolated from the actinide region to $A \approx 290$ and furthermore that the distortion parameter employed in refs. ^{9,14,16)} cannot be simply related to ϵ . However, we believe this latter semi-empirical analysis (II) to provide the most reliable estimate of the inertial parameter B , in particular in view of the fact that by the Strutinsky procedure we have forced our barrier on the average to equal the liquid drop barrier. The semi-empirical estimate II is in turn normalized to this barrier in the actinide region. We have used this estimate for the inertial parameter in summarizing our half-life predictions listed in table 3.

In summary, the following conclusions may be drawn from our calculations, the reliability of these conclusions resting largely on the accuracy of the extrapolation of the nuclear potential to unknown regions. (1) An island of near-stability appears associated with the intersections of the neutron line $N = 184$ with the proton line $Z = 114$ and to a minor extent $Z = 124$ (or 126). Actually the latter island appears largely submerged by the rising Coulomb distortion energy. (2) For nucleides associated with the center of these crossings the barriers encountered are of the order of 9 and 7 MeV respectively and the spontaneous-fission half life longer than the age of the universe in the first case. (3) For $Z = 114$ as well as other Z values in this region the dependence ^{of the half life} on N is strong. Thus for $N = 170$ the ground state is deformed and the barrier negligible. For $Z = 114$, $N = 176$, on the other hand, the ground state is spherical and the barrier of the order of 4 MeV and the expected half life of the order of minutes. A change in N from 174 to 176 appears to change the half life by ten orders of magnitude. (4) Values of Z larger than 114 may also have long half lives. As a rule, the addition of two neutrons ^(up to $N = 184$) appears roughly to compensate the addition of two protons. Thus elements of $Z = 116$ with $A \geq 292$, of $Z = 118$ with $A \geq 296$ etc., may all have half lives long enough to be observable. Near $Z = 124$ the situation appears to be additionally favorable due to the closed shell effect of $Z = 124$ (although somewhat weaker than that at $Z = 114$). (5) As seen from table 3, a series of heavy reactions that would just reach this line of observable spontaneous fission half lives corresponds approximately to $N-Z = 60$. Among these are ¹⁸):





To further explore the stability with respect to other decay processes, e.g. α -decay, a detailed study of the calculated masses in the region in question is later to be undertaken. (6) Below $Z = 114$ the relative stability again requires isotopes with higher N values than 174, which presently appear inaccessible. The studied lighter isotopes of $Z = 112$ and 110, shown in figs. 13 and 14, which may be of interest as decay products in α -decay series from ${}^{290}_{114}$ etc., have very short half lives relative to spontaneous fission. In particular is this true of the 110 isotopes.

ACKNOWLEDGMENTS

We have profited very much from discussions with W. J. Swiatecki. In fact, many of the ideas exploited in these calculations are due to him. We are grateful to P. Seeger for making his results available to us prior to publication. We also recognize the great stimulation of the experimental groups at UCLRL working in this field. The extraordinary helpfulness of L. Meissner of the computer division is highly appreciated. One of us (SGN) wishes to express his gratitude to the Nuclear Chemistry Division of the UCLRL for the pleasant hospitality granted.

REFERENCES

- 1) A. Sobiczewski, F. A. Gareev, and B. N. Kalinkin, Phys. Letters 22 (1966) 500
- 2) H. Meldner, Proc. of the International Symposium on "Why and How Should We Investigate Nuclides Far Off the Stability Line," Lysekil, Sweden, August 21-27, 1966 (Almqvist and Wiksell, Stockholm, 1967) p. 593; and Arkiv Fysik 36 (1967) 593
- 3) C. Gustafson, I. L. Lamm, B. Nilsson, and S. G. Nilsson, *ibid.*, p. 613; and Arkiv Fysik 36 (1967) 613
- 4) E. Rost, Phys. Letters 26B (1968) 184
- 5) D. Bès and Z. Szymański, Nucl. Phys. 28 (1961) 42
- 6) P. Möller, B. Nilsson, S. G. Nilsson, A. Sobiczewski, Z. Szymański, and S. Wycech, Phys. Letters (in press)
- 7) B. Nilsson, to be published; and C. Gustafson, P. Möller, S. G. Nilsson, A. Sobiczewski, Z. Szymański, and S. Wycech, to be published
- 8) V. M. Strutinsky, Nucl. Phys. A95 (1967) 420
- 9) W. D. Myers and W. J. Swiatecki, Lysekil Symp., *op. cit.*, p. 343; and Arkiv Fysik 36 (1967) 343
- 10) S. A. E. Johansson, Nucl. Phys. 22 (1961) 529
- 11) P. A. Seeger and R. C. Perisho, Los Alamos Scientific Laboratory Report LA-3751, Oct. 20, 1967; and private communication from P. A. Seeger
- 12) S. G. Nilsson, Mat. Fys. Medd. Dan. Vid. Selsk. 29, No. 16 (1955)
- 13) J. R. Nix, University of California Lawrence Radiation Laboratory Report UCRL-11338, April 1, 1964
- 14) J. R. Nix, Ann. of Phys. 41 (1967) 52
- 15) S. Cohen and W. J. Swiatecki, Ann. of Phys. 22 (1963) 406
- 16) L. Moretto and W. J. Swiatecki, private communication
- 17) W. Stępień and Z. Szymański, Phys. Letter 26B (1968) 181
- 18) W. J. Swiatecki, private communication

FIGURE CAPTIONS

Fig. 1a. Spherical single-proton level order in the region $200 < A < 300$.

To the left are plotted levels and degeneracies of the present model calculated for $A=208$, 242 , and 290 based on interpolation and extrapolation between "empirical" parameters κ and μ for nuclei near $A=165$ and $A=242$. To the right is the extrapolated level order obtained by Rost⁴⁾ for $A = 298$. Note the low density and low degeneracy of levels between $Z=114$ and $Z=126$. Note also the indication of a shell closing at $Z=164$.

Fig. 1b. Same as

/ fig. 1a. for spherical neutron levels. Note the low level density and degeneracy around and below $N=184$.

Fig. 2. Topographical map for the (ϵ, ϵ_4) plane of $E_{\text{shell}} + E_{\text{pair}}$ for ${}^{290}_{114}$. Note the large fluctuating contributions between $\epsilon = 0.0$ and 0.4 and the damped undulations for larger distortions.

Fig. 3. Topographic map in the (ϵ, ϵ_4) plane of the total nuclear potential energy for ${}^{282}_{114}$. The contours are spaced at intervals of 1 MeV. Note the ultimate dominance for large ϵ of large positive ϵ_4 values representing the development of a nuclear neckline.

Fig. 4. Same as fig. 3 for ${}^{290}_{114}$.

Fig. 5. Same as fig. 3 for ${}^{298}_{114}$.

Fig. 6. Same as fig. 3 for ${}^{308}_{124}$.

Fig. 7. Minimum energy projection along the ϵ axis for $Z=114$, $A=284-298$ and extrapolated κ and μ parameters. Each point along the curve corresponds to an energy minimum with respect to ϵ_4 .

Fig. 8. Same as fig. 7 for isotopes of $Z=116$.

Fig. 9. Same as fig. 7 for isotopes of $Z=118$.

- Fig. 10. Same as fig. 7 for isotopes of $Z=120$.
- Fig. 11. Same as fig. 7 for isotopes of $Z=122$.
- Fig. 12. Same as fig. 7 for isotopes of $Z=124$.
- Fig. 13. Same as fig. 7 for isotopes of $Z=110$.
- Fig. 14. Same as fig. 7 for isotopes of $Z=112$.
- Fig. 15. Spontaneous-fission half lives of $Z=114$ isotopes as functions of the inertial parameter B for barrier penetration. Of the four estimates shown for $B/A^{5/3}$ (see text), we consider the estimate denoted by "semi-empirical II" (based on half life data in the actinide region) the most reliable.
- Fig. 16. Same as fig. 15 but based on unextrapolated actinide parameters for the nuclear potential. This figure is given only as a reference. Compared to fig. 15 one may note that for these parameters already the nucleus $^{282}_{114}$ should have a half life long enough to permit observation. On the other hand $N=184$ is less of a magic number and the $A=296$ isotope has a longer half life than the $A=298$ one.
- Fig. 17. Spontaneous fission half lives for isotopes of $Z=116$. See caption to fig. 15. Note that $^{294}_{116}$ has nearly the same half life as $^{290}_{114}$.
- Fig. 18. Spontaneous fission half lives for isotopes of $Z=118, 120, 122,$ and 124 . See caption to fig. 15.

Table 1

Surface energy as a function of ϵ and ϵ_4 . The quantity tabulated is $B_S - 1$, where B_S is the ratio of the surface energy to the surface energy of a sphere.

$\epsilon_4 \backslash \epsilon$	-0.08	-0.04	0.0	0.04	0.08	0.12	0.16
-0.5	0.05834	0.04883	0.04234	0.03885	0.03840	0.04102	0.04673
-0.4	0.03975	0.03197	0.02720	0.02541	0.02658	0.03072	0.03784
-0.3	0.02521	0.01880	0.01540	0.01498	0.01749	0.02289	0.03117
-0.2	0.01478	0.00930	0.00691	0.00752	0.01106	0.01745	0.02665
-0.1	0.00853	0.00353	0.00175	0.00304	0.00728	0.01438	0.02426
0.0	0.00667	0.00163	0.00000	0.00157	0.00618	0.01369	0.02401
0.1	0.00946	0.00380	0.00181	0.00323	0.00784	0.01545	0.02593
0.2	0.01730	0.01033	0.00742	0.00820	0.01239	0.01975	0.03012
0.3	0.03074	0.02166	0.01715	0.01673	0.02004	0.02678	0.03673
0.4	0.05053	0.03836	0.03147	0.02921	0.03111	0.03679	0.04597
0.5	0.07777	0.06125	0.05103	0.04616	0.04602	0.05014	0.05815
0.6	0.11402	0.09151	0.07673	0.06831	0.06538	0.06735	0.07373
0.7	0.16170	0.13080	0.10987	0.09671	0.09007	0.08914	0.09332
0.8	0.22470	0.18172	0.15236	0.13288	0.12133	0.11658	0.11784
0.9	0.30993	0.24842	0.20712	0.17910	0.16105	0.15125	0.14867

Table 2

Coulomb energy (for a charged drop with a sharp surface) as a function of ϵ and ϵ_4 . The quantity tabulated is $1 - B_C$, where B_C is the ratio of the Coulomb energy to the Coulomb energy of a sphere.

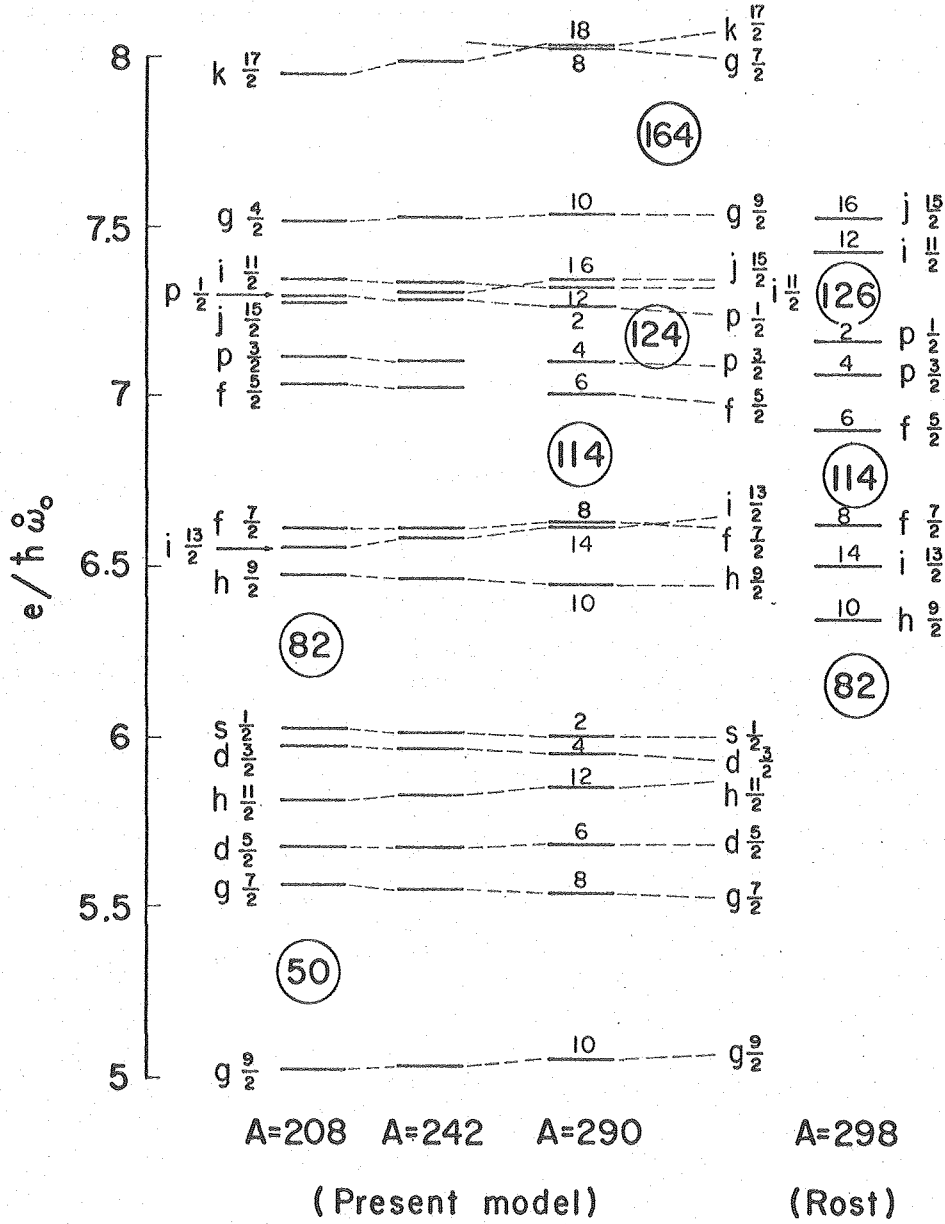
$\epsilon_4 \backslash \epsilon$	-0.08	-0.04	0.00	0.04	0.08	0.12	0.16
-0.5	0.02261	0.02057	0.01901	0.01795	0.01737	0.01727	0.01766
-0.4	0.01525	0.01363	0.01251	0.01186	0.01169	0.01200	0.01279
-0.3	0.00929	0.00801	0.00724	0.00696	0.00715	0.00782	0.00896
-0.2	0.00485	0.00382	0.00332	0.00332	0.00381	0.00478	0.00624
-0.1	0.00211	0.00120	0.00086	0.00106	0.00177	0.00298	0.00468
0.0	0.00126	0.00031	0.00000	0.00029	0.00113	0.00251	0.00440
0.1	0.00255	0.00135	0.00092	0.00117	0.00204	0.00349	0.00549
0.2	0.00629	0.00460	0.00384	0.00390	0.00466	0.00608	0.00809
0.3	0.01288	0.01036	0.00903	0.00869	0.00920	0.01044	0.01237
0.4	0.02283	0.01905	0.01682	0.01584	0.01588	0.01681	0.01852
0.5	0.03682	0.03118	0.02764	0.02570	0.02504	0.02546	0.02679
0.6	0.05574	0.04744	0.04202	0.03872	0.03706	0.03673	0.03750
0.7	0.08088	0.06873	0.06070	0.05551	0.05245	0.05107	0.05105
0.8	0.11409	0.09639	0.08463	0.07684	0.07189	0.06909	0.06799
0.9	0.15832	0.13217	0.11515	0.10380	0.09630	0.09160	0.08907

Table 3

Spontaneous-fission half lives in years for various isotopes of $Z = 114-124$. The estimates are based on the inertial parameter denoted by "Semi-empirical II" in figs. 15-18.

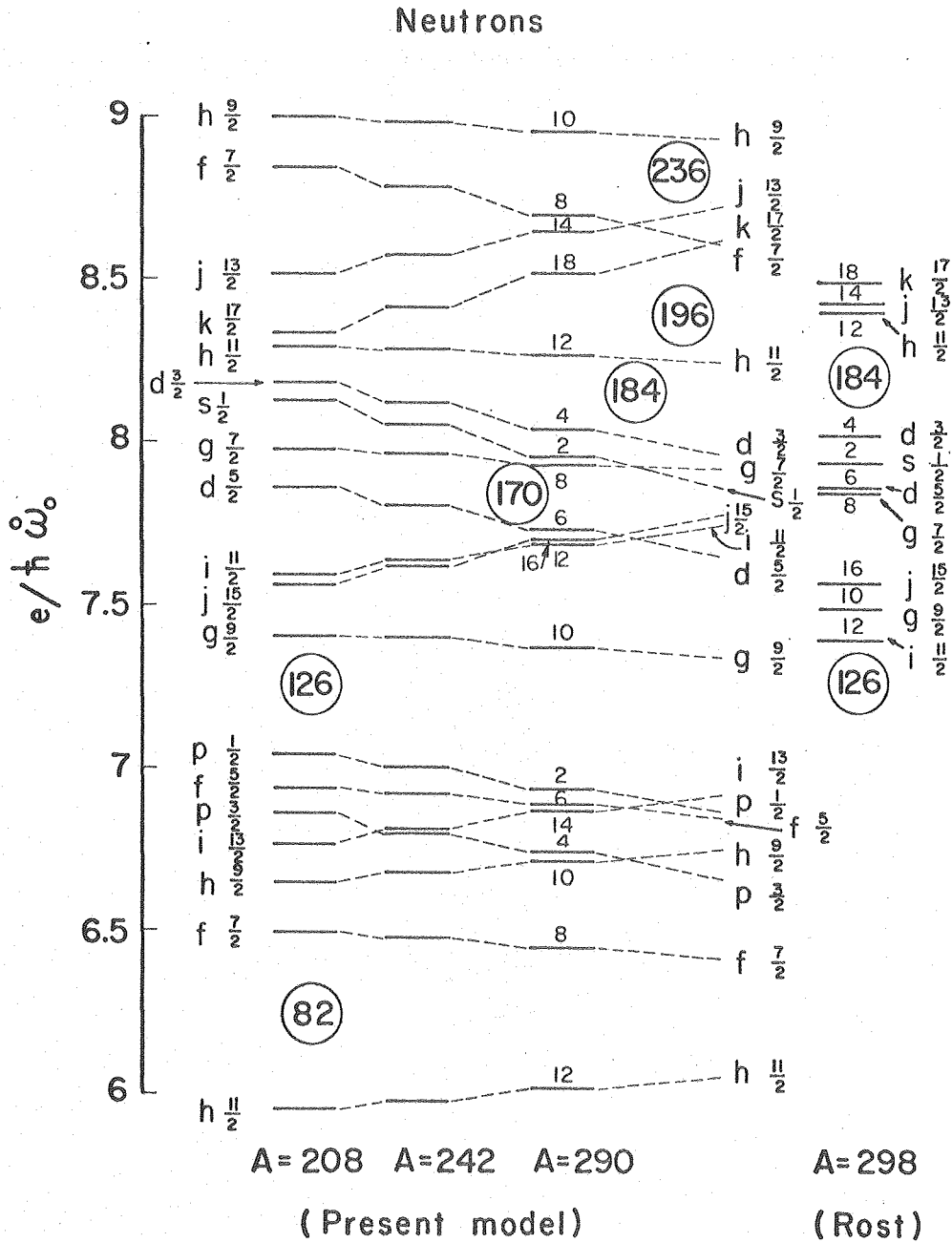
		Z					
		114	116	118	120	122	124
	188						2×10^{-9}
	186					4×10^{-6}	2×10^{-8}
N	184	2×10^{19}			9×10^0	2×10^{-5}	1×10^{-7}
	182	2×10^{14}	8×10^8	5×10^2	2×10^{-5}	1×10^{-8}	1×10^{-10}
	180	3×10^8	6×10^2	2×10^{-7}	5×10^{-11}	1×10^{-12}	
	178	1×10^2	2×10^{-5}	1×10^{-11}			
	176	7×10^{-6}	2×10^{-11}				
	174	5×10^{-15}					

Protons



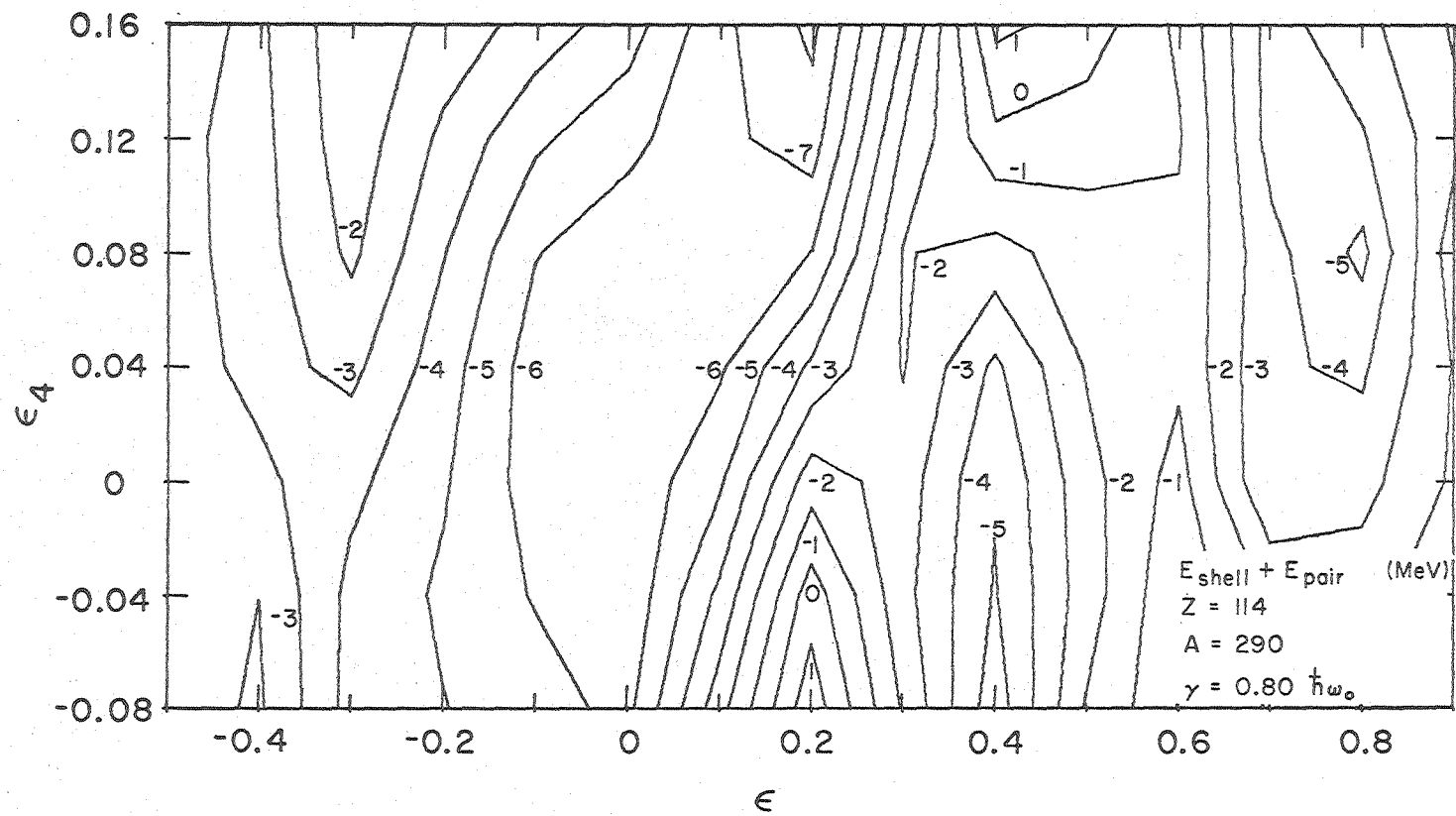
XBL682-1807

Fig. 1a



XBL682-1808

Fig. 1b



XBL683-2118

Fig. 2

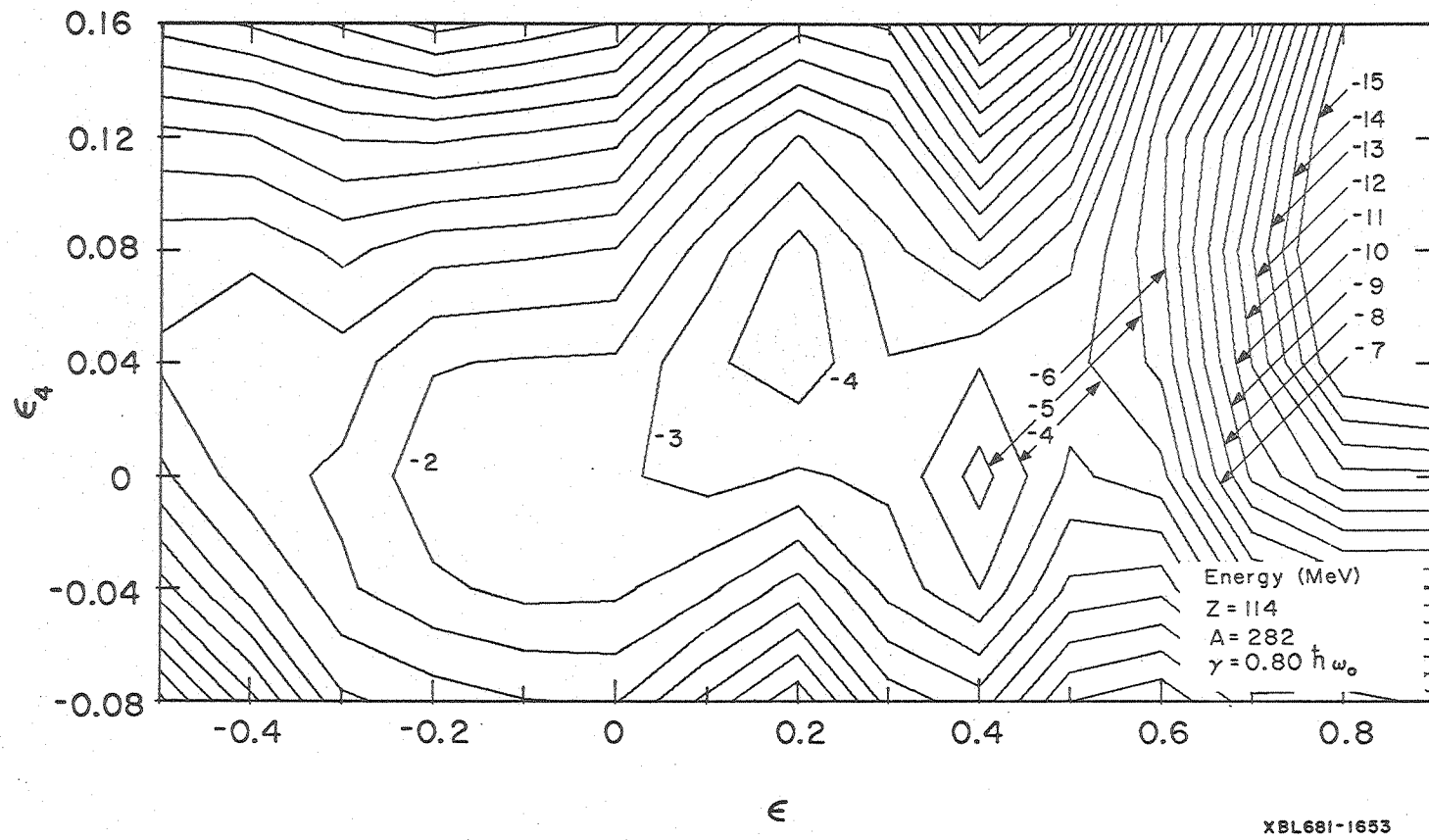
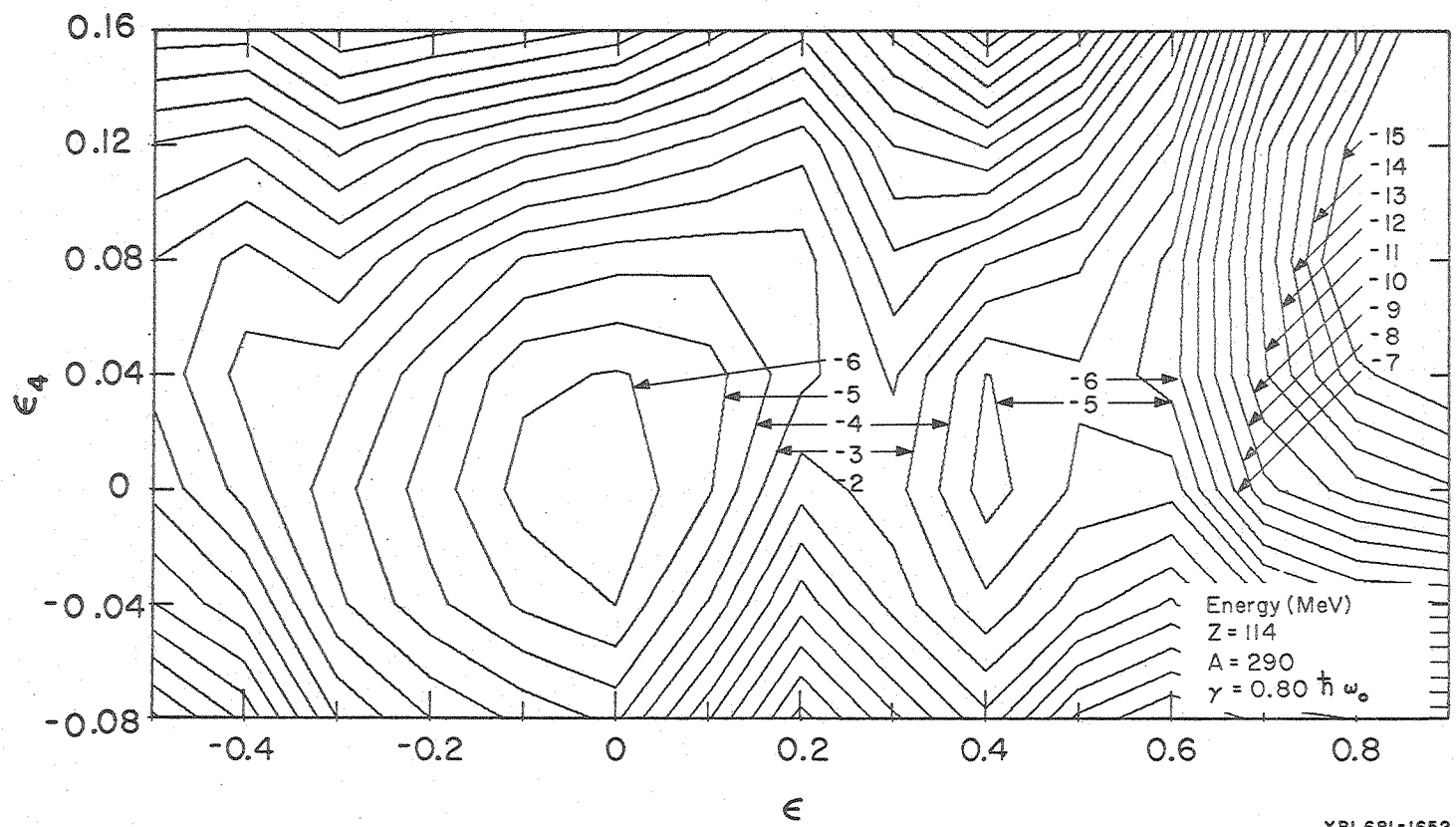


Fig. 3

XBL681-1653



XBL681-1652

Fig. 4

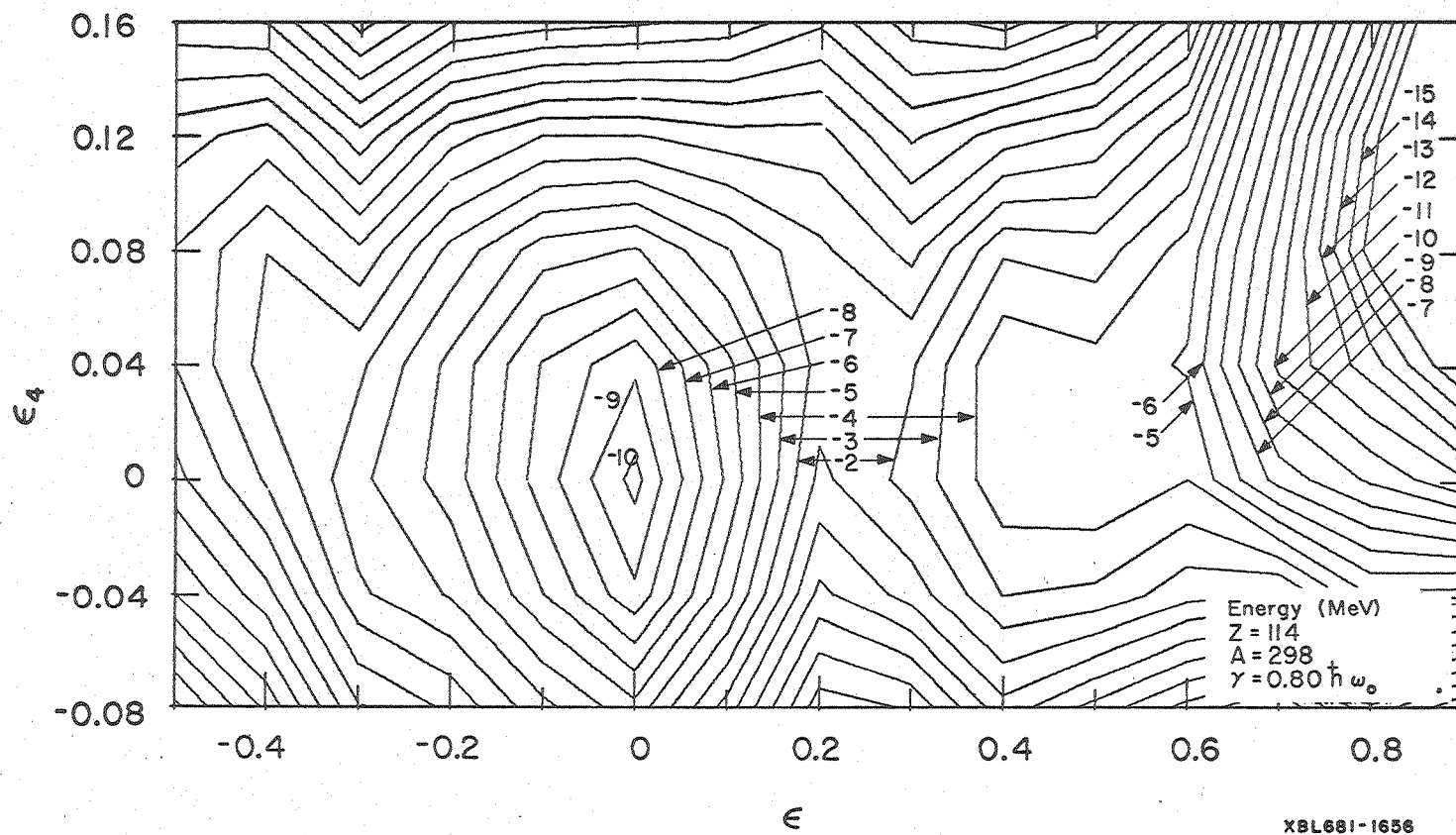


Fig. 5

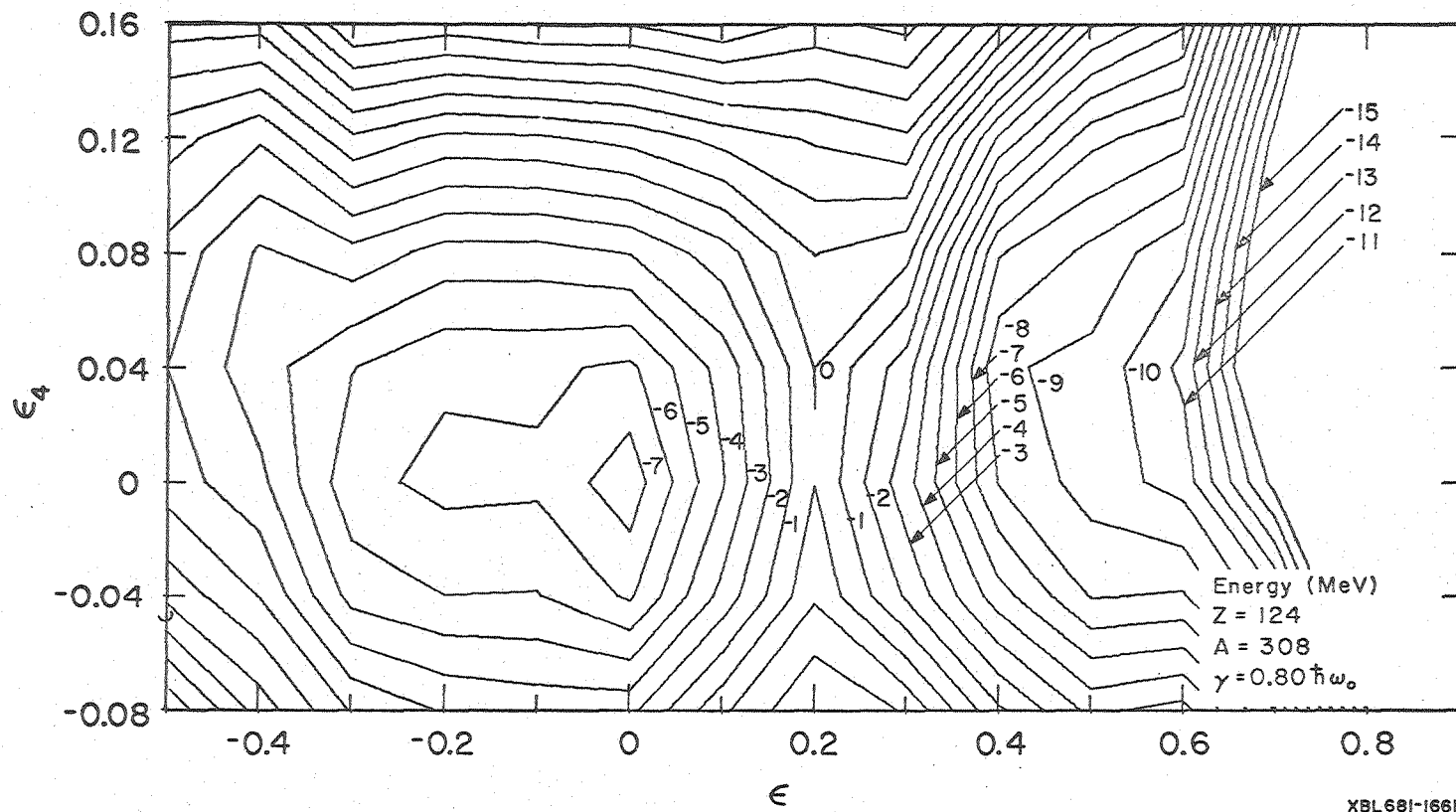
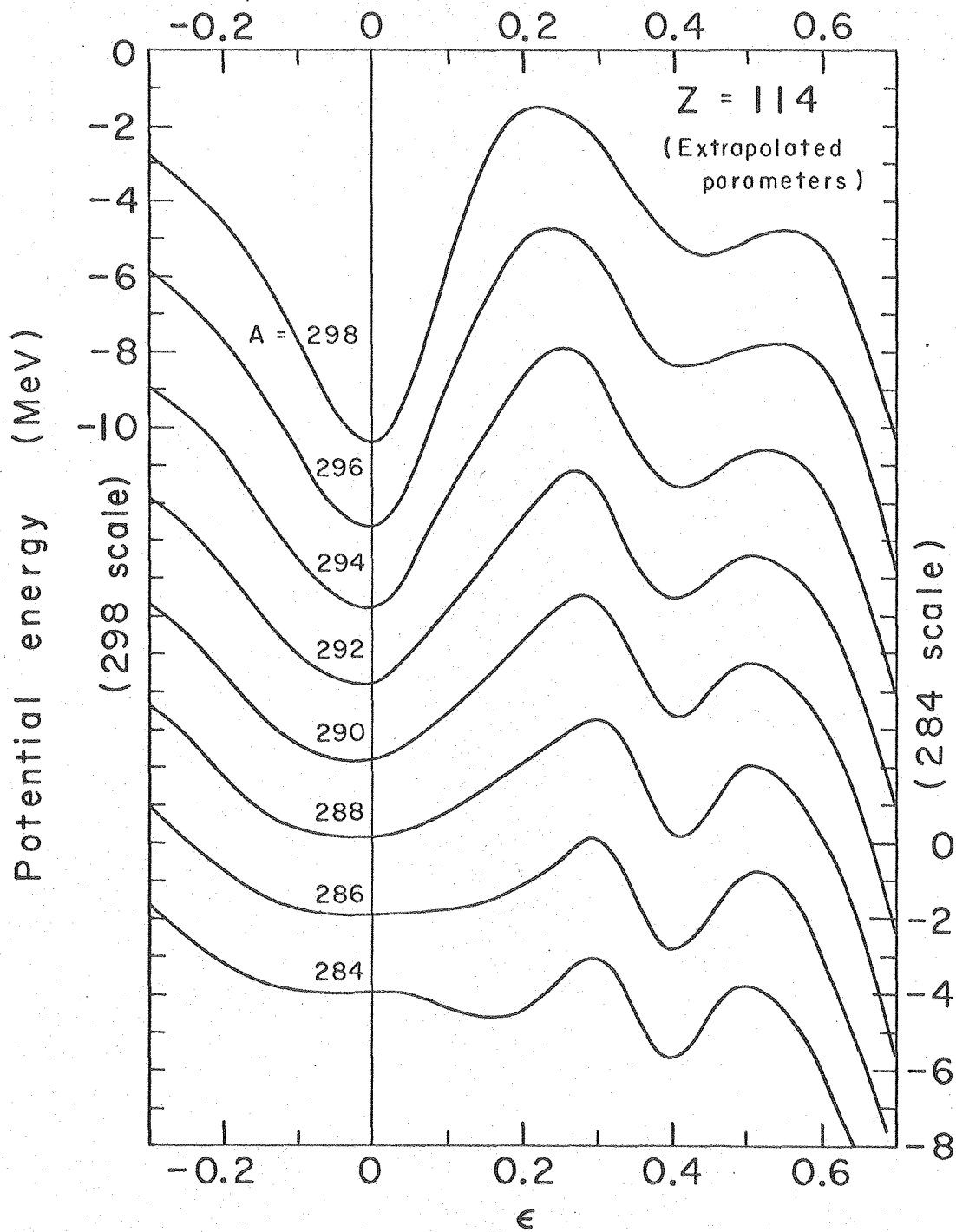
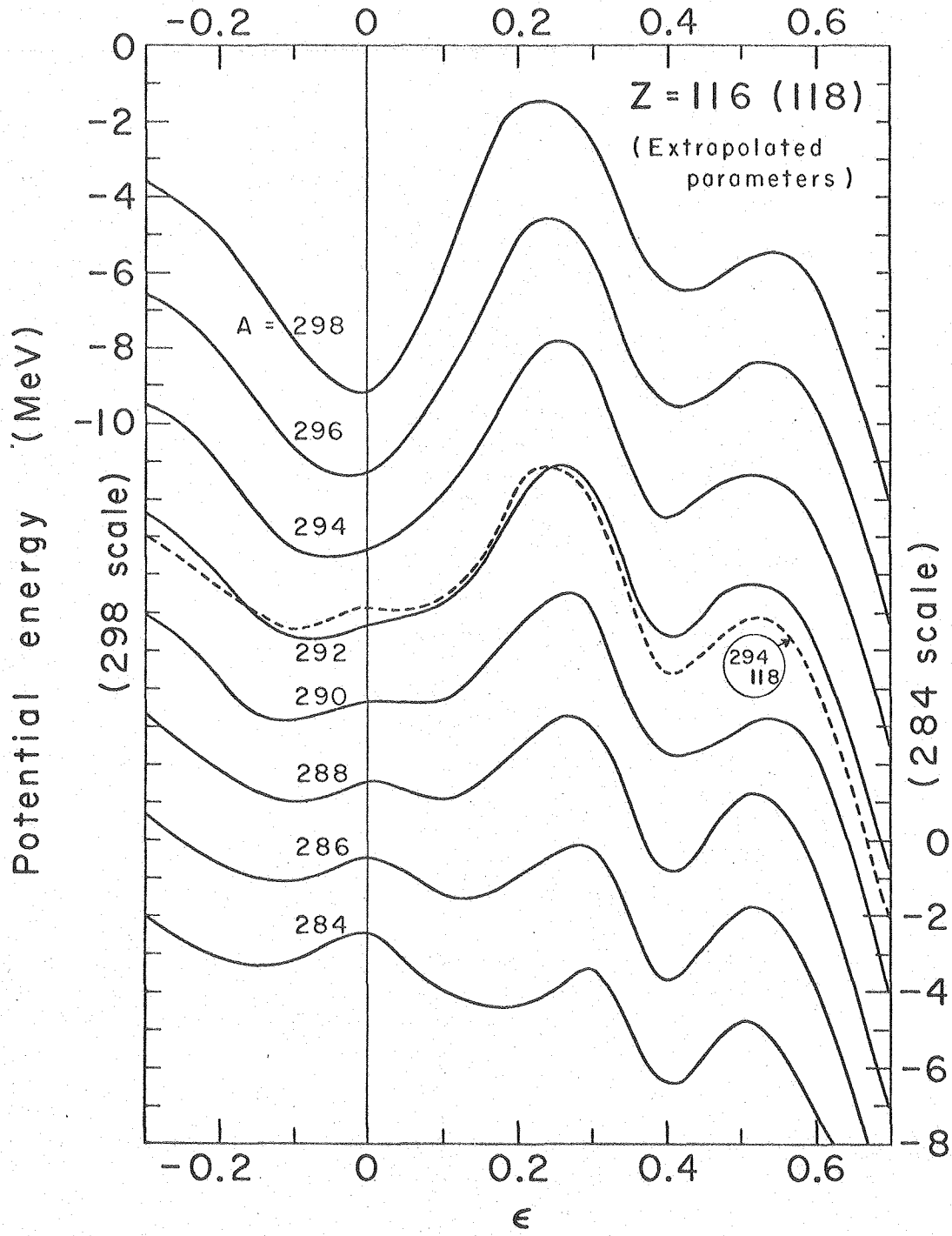


Fig. 6



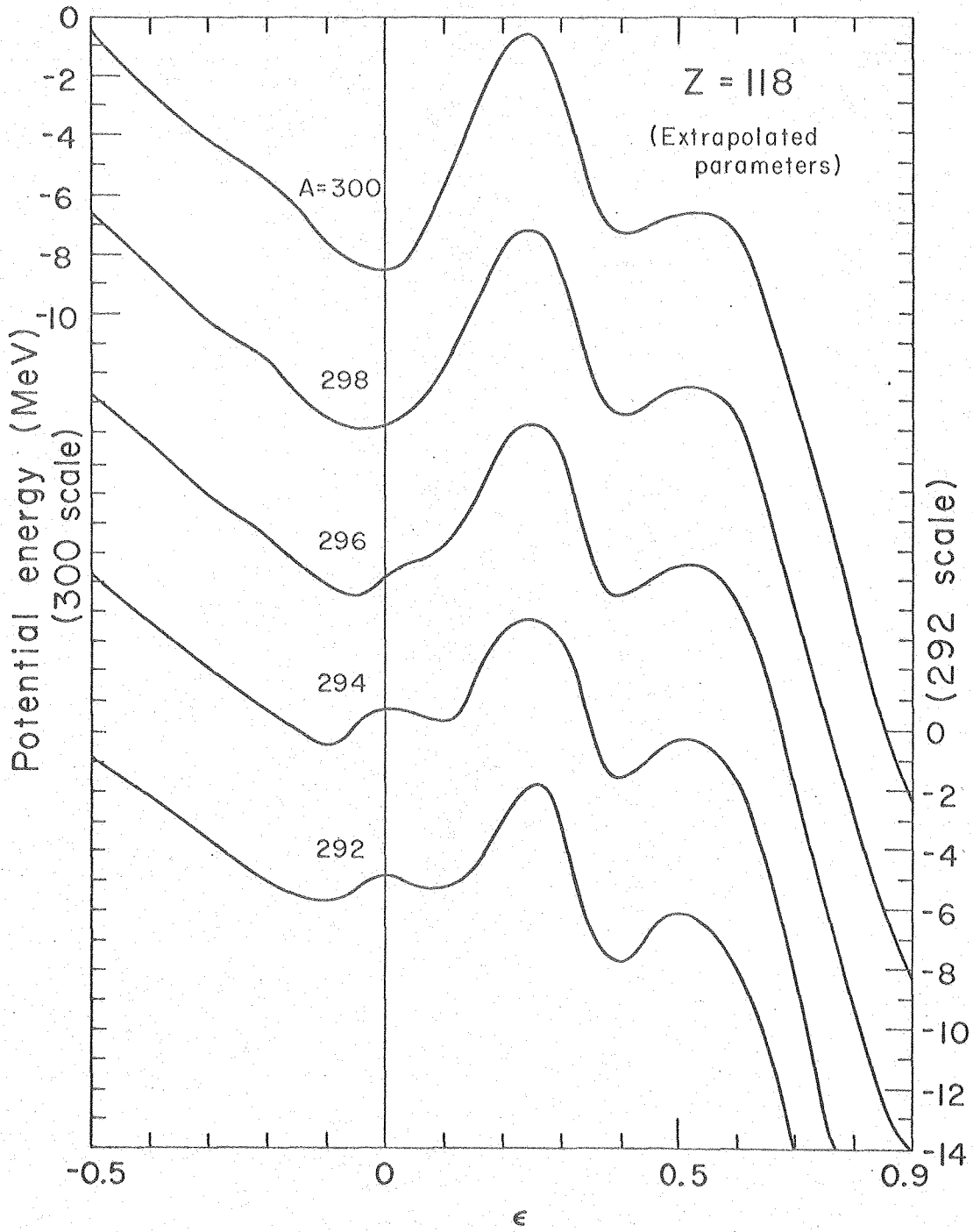
XBL681-1650

Fig. 7



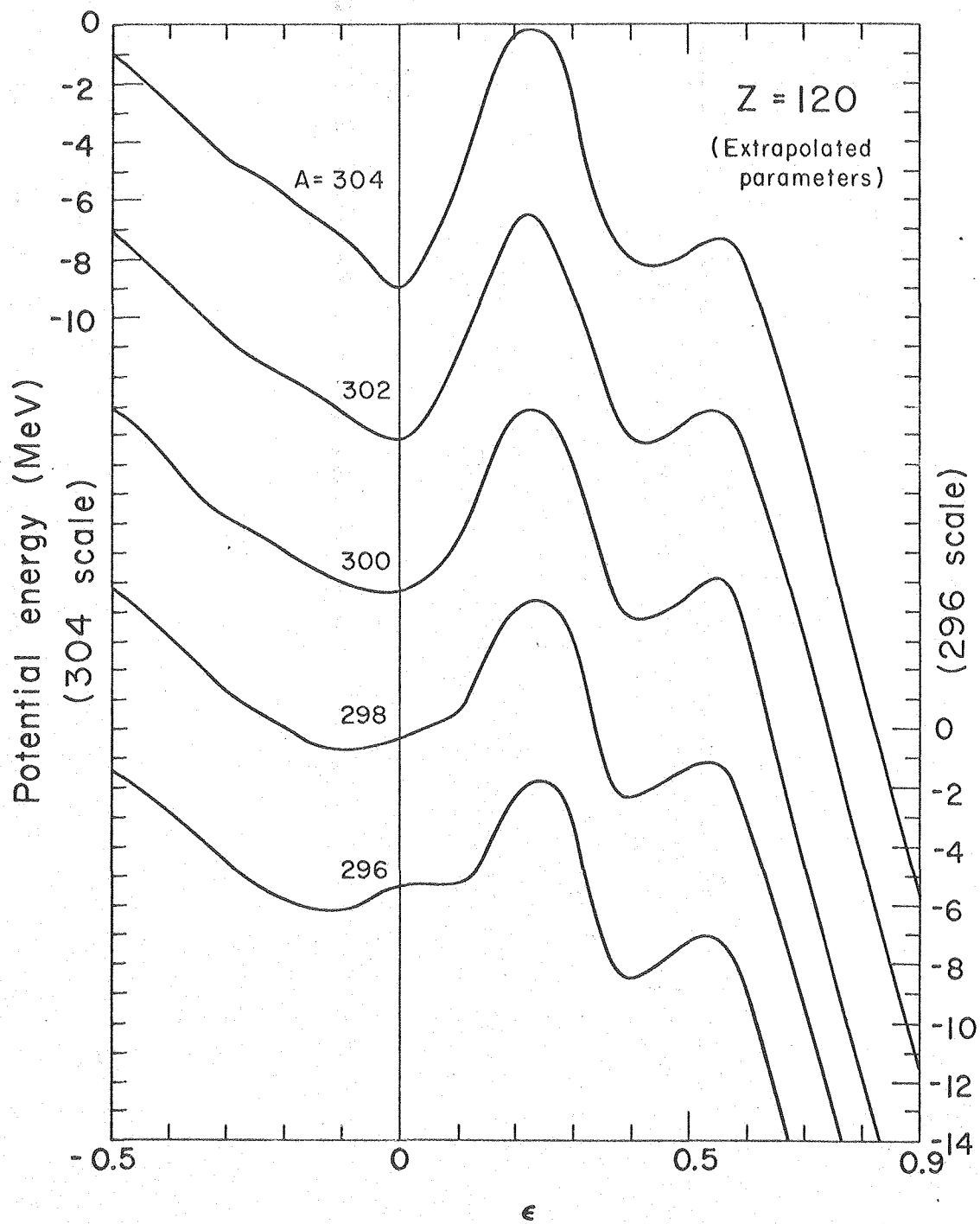
XBL681-1649

Fig. 8



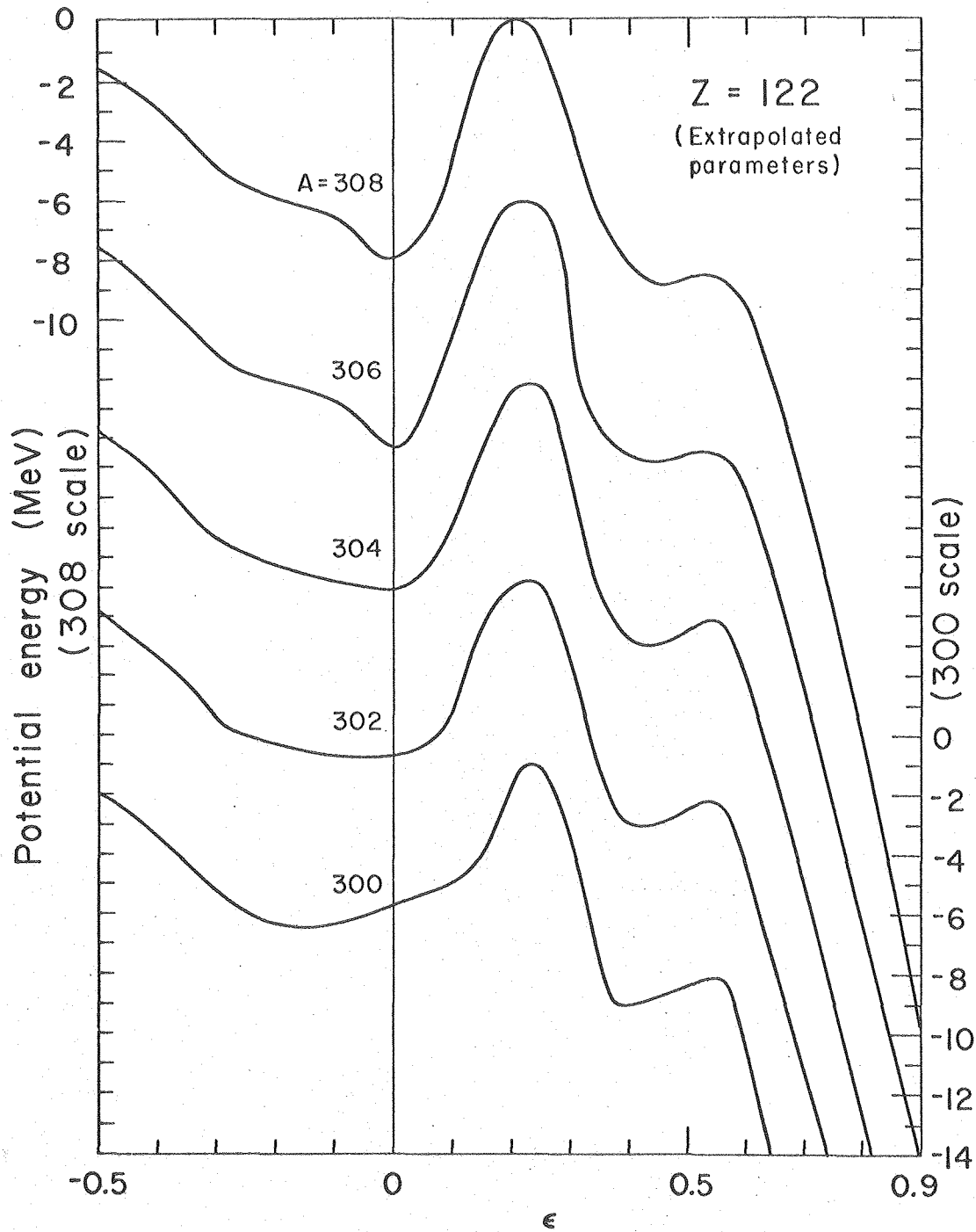
XBL682-1980

Fig. 9



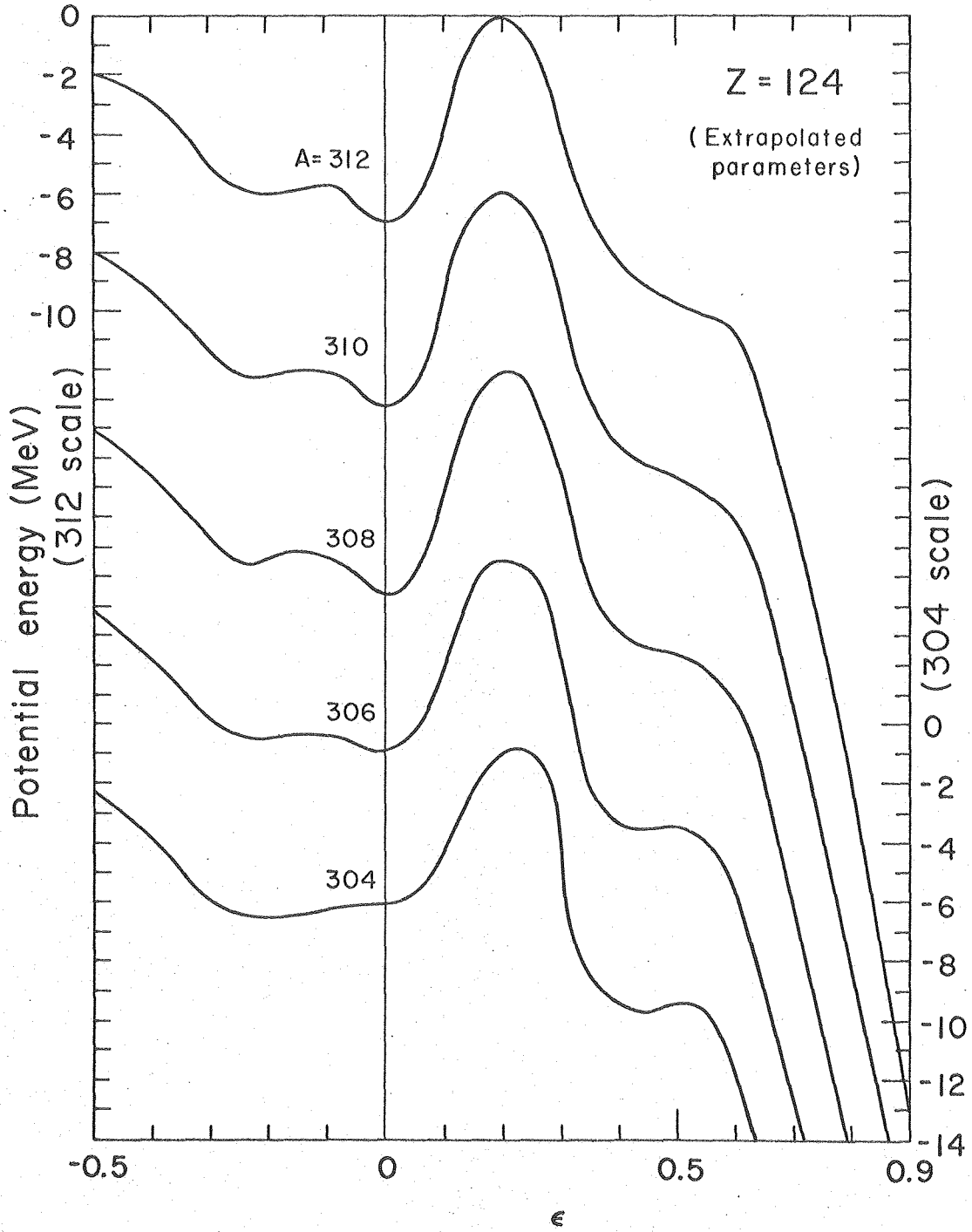
XBL682-1976

Fig. 10



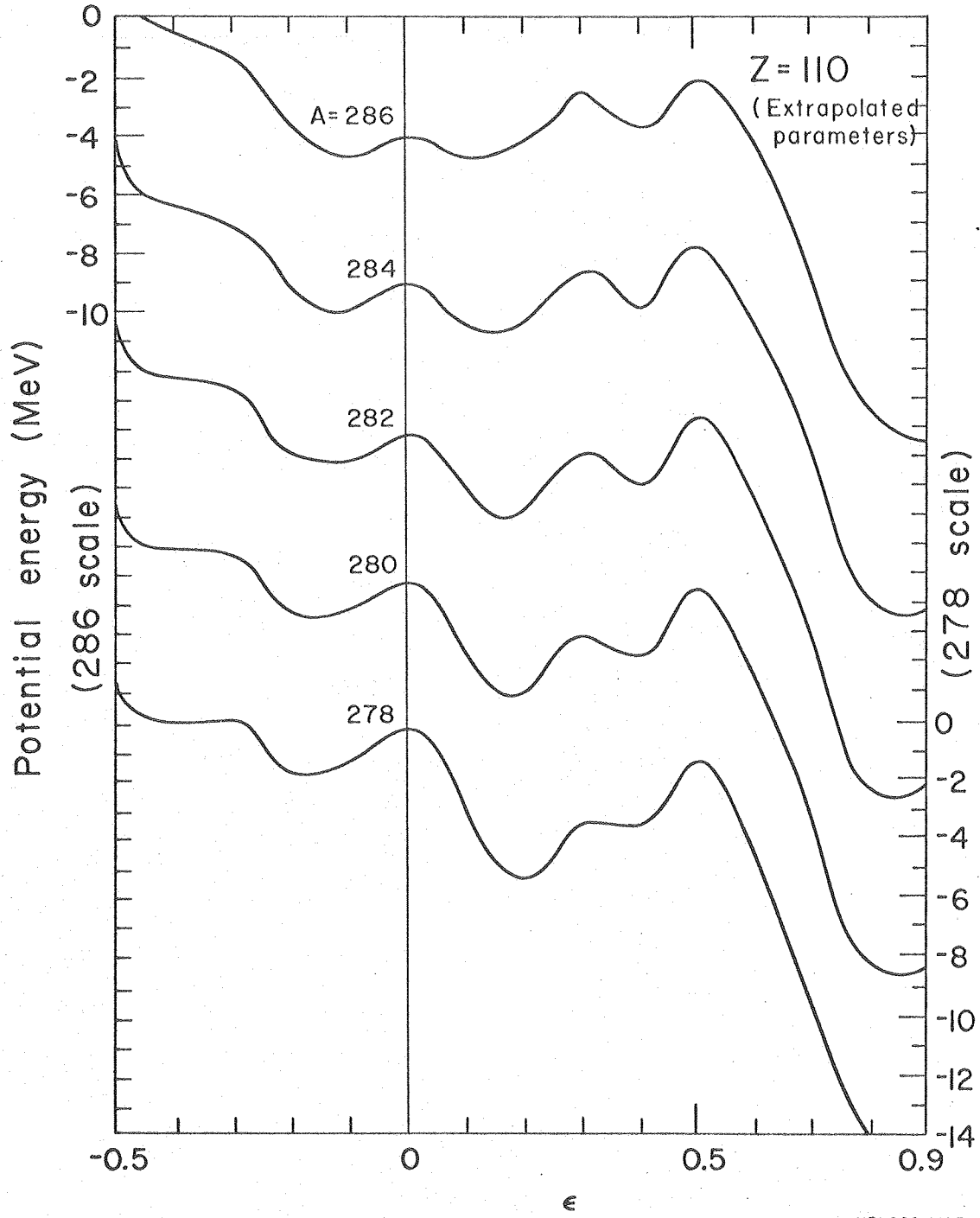
XBL682-1977

Fig. 11



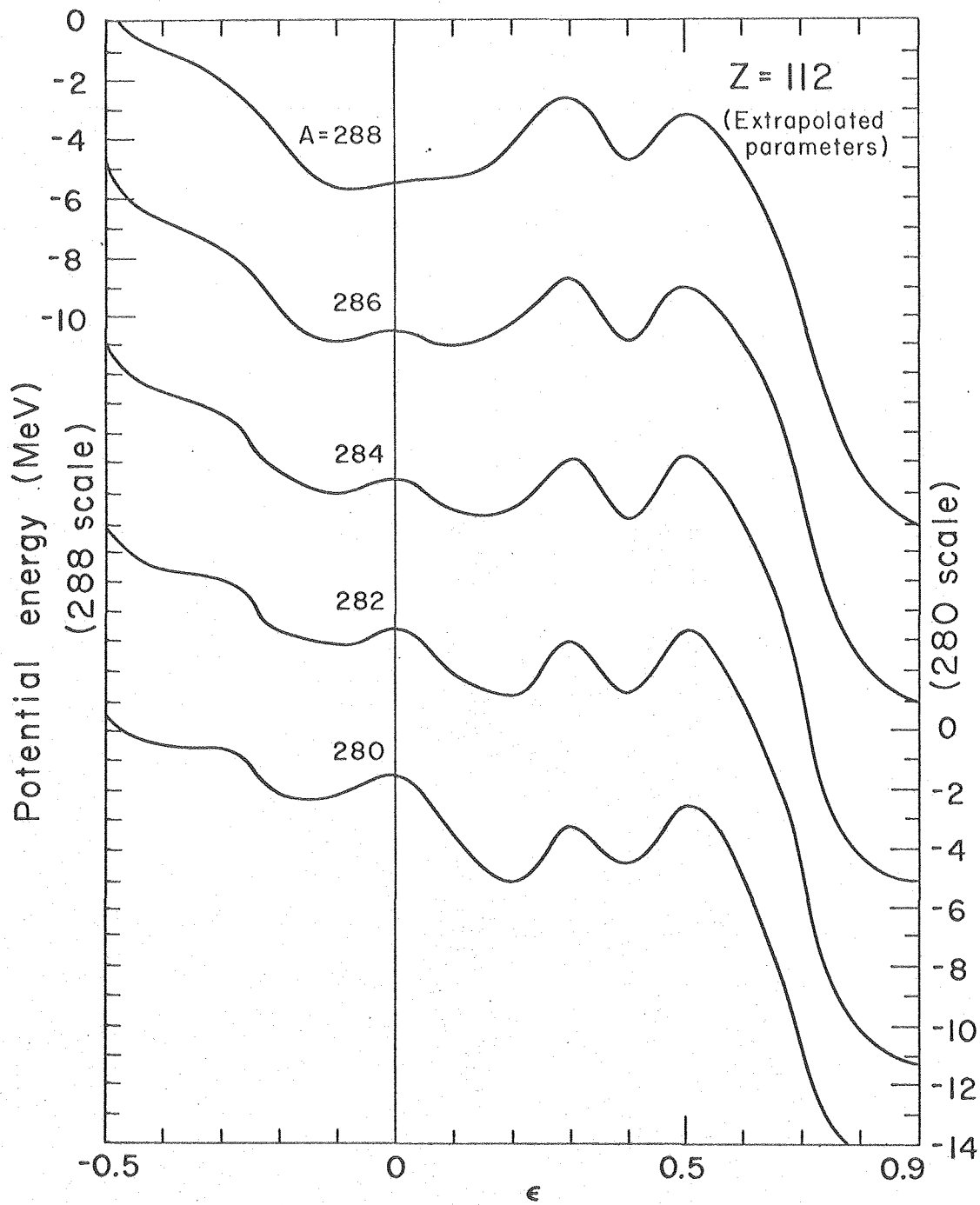
XBL 682-1978

Fig. 12



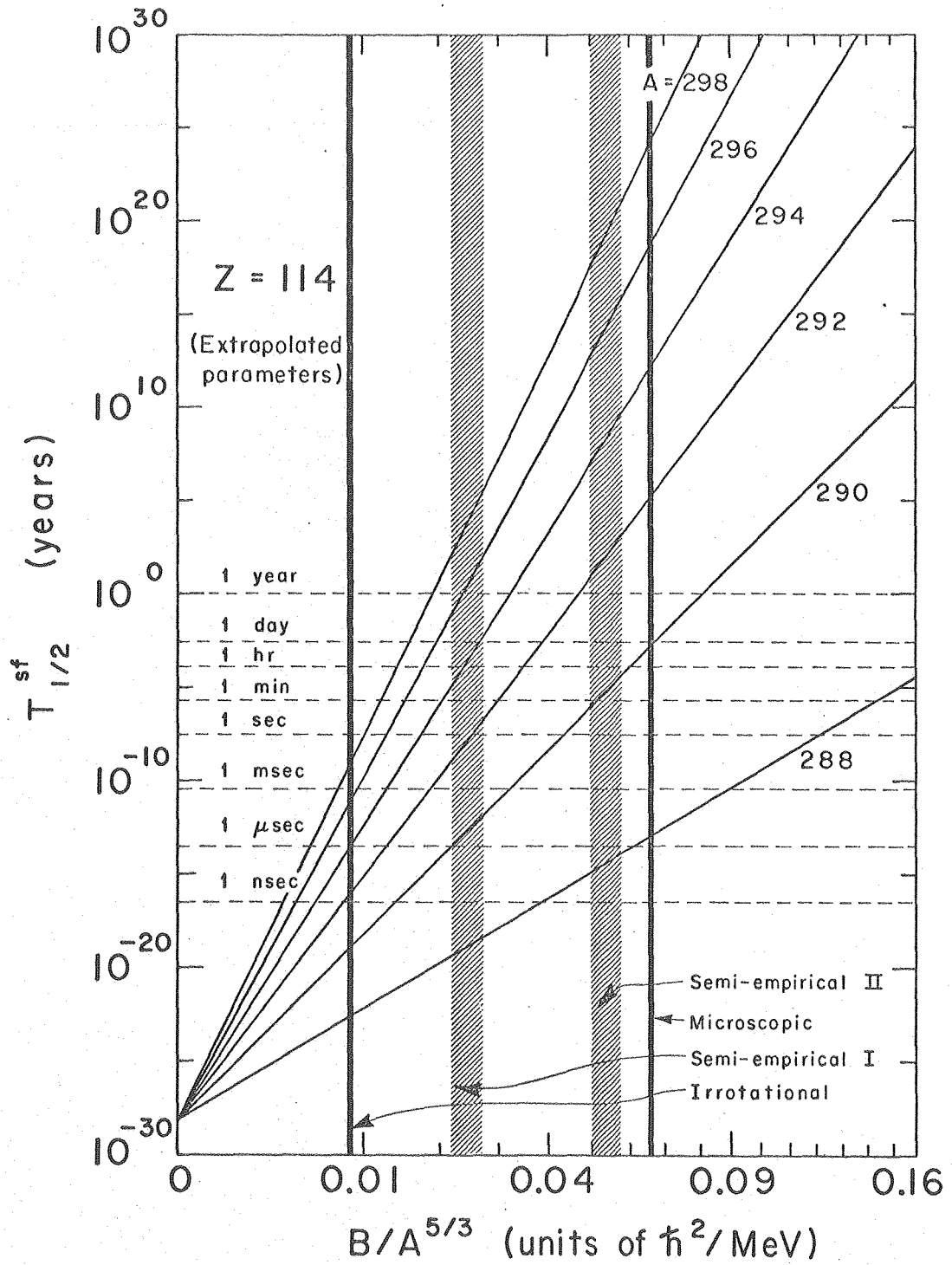
XBL682-1975

Fig. 13



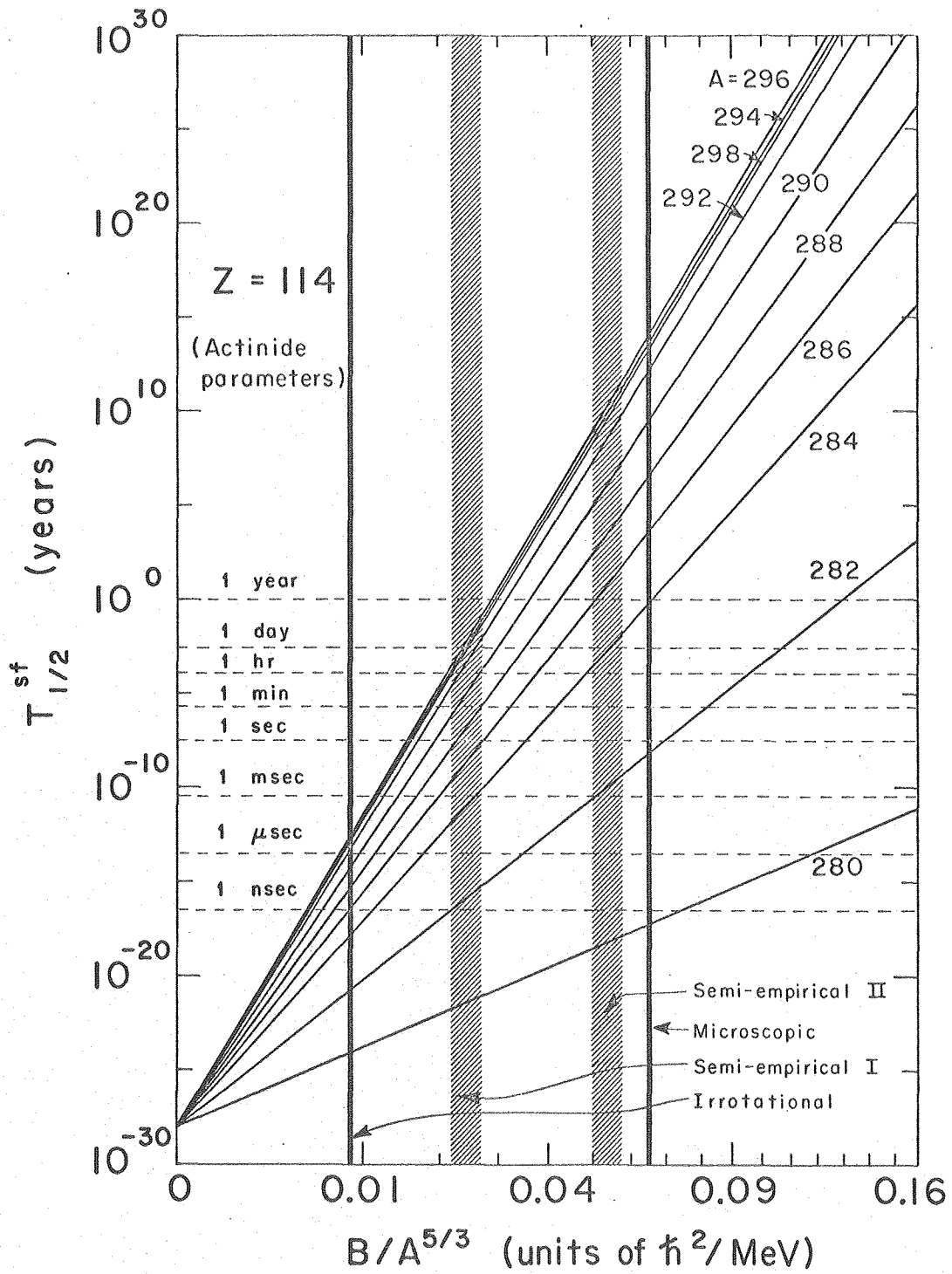
XBL662-1979

Fig. 14



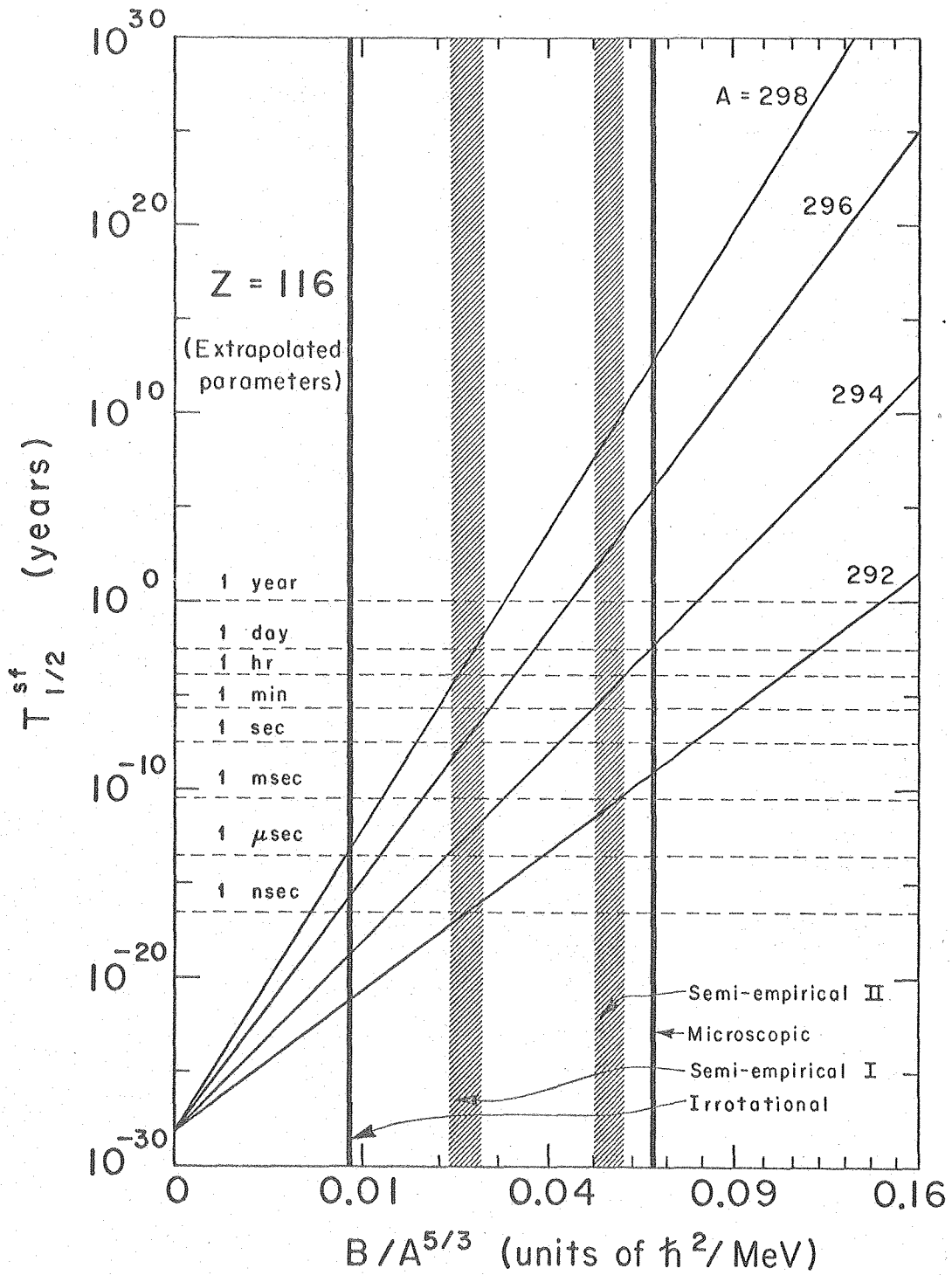
XBL68I-1647

Fig. 15



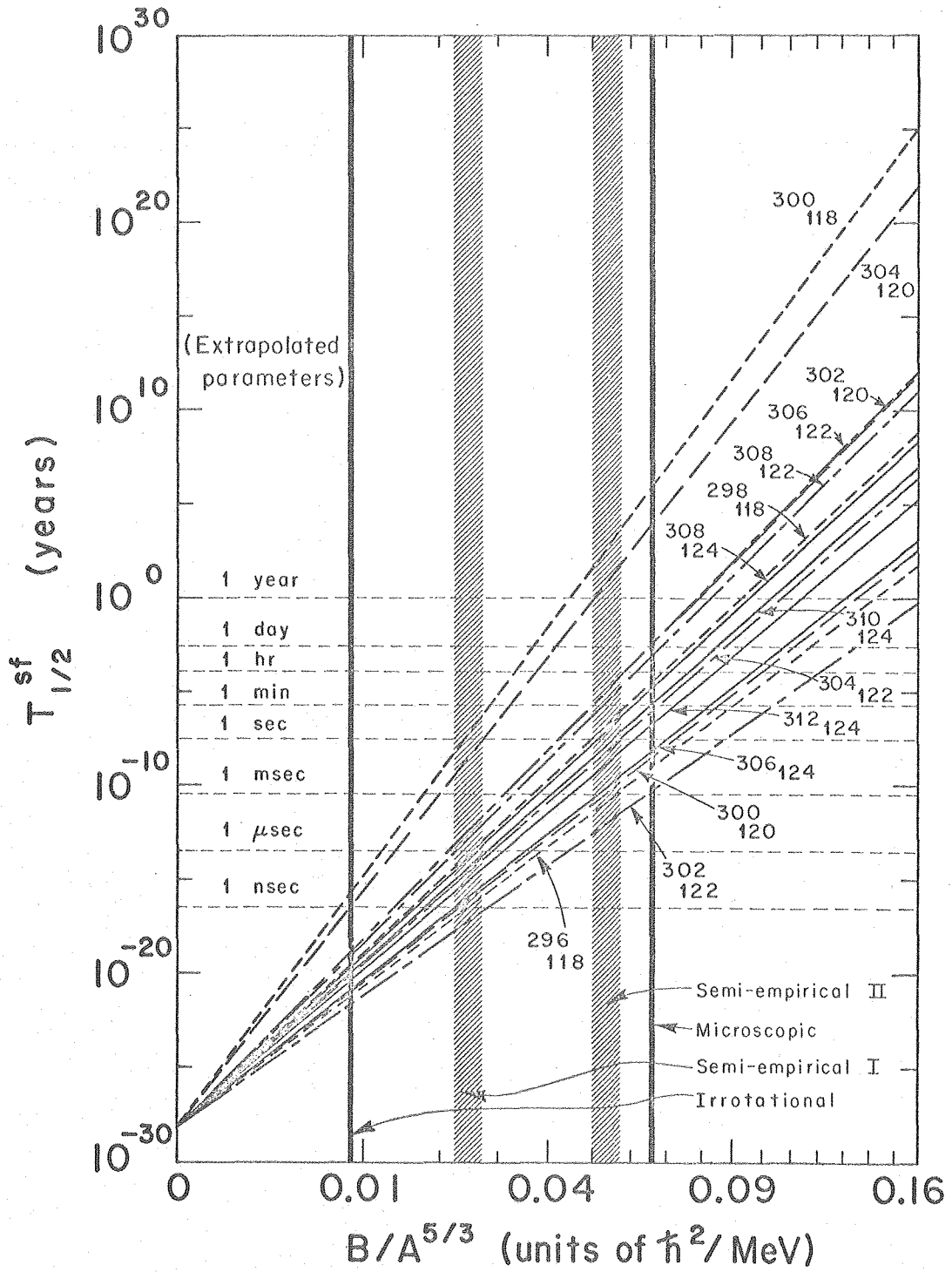
XBL681-1619

Fig. 16



XBL68I-1648

Fig. 17



XBL683-2127

Fig. 18

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.

