UCRL-93983
PREPRINT

# Levels in $^{142}$Sm: Two-Proton, Two-Neutron-Hole States in the Doubly Magic Nucleus $^{146}$Gd Populated by the (p,t) Reaction

R. A. Dewberry, R. T. Kouzes, R. A. Naumann,
and F. Loeser
Princeton University

and

G. L. Struble, L. G. Mann, and R. G. Lanier
Lawrence Livermore National Laboratory

This paper was prepared for submittal to
*Physical Review C*

January 1986

Lawrence Livermore National Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

CIRCULATION COPY
SUBJECT TO RECALL
IN TWO WEEKS

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California 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 products, 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 the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

# Levels in $^{142}$Sm: Two-Proton, Two-Neutron-Hole States in the Doubly Magic Nucleus $^{146}$Gd Populated by the (p,t) Reaction*

R. A. Dewberry, R. T. Kouzes, R. A. Naumann, and F. Loeser
Department of Physics
Princeton University
Princeton, New Jersey 08544

and

G. L. Struble, L. G. Mann, and R. G. Lanier
Nuclear Chemistry Division
Lawrence Livermore National Laboratory
Livermore, CA 94550

## Abstract

We have used the (p,t) reaction to investigate the two-neutron-hole structure of $^{142}$Sm and have identified several positive-parity states with angular momentum 0, 2, and 4. Two close-lying states with spin and parity of $5^-$ and $7^-$ have been resolved. We interpret the levels in terms of the weak coupling of two-proton and two-neutron holes to a $^{146}$Gd core.

[Nuclear Reactions: $^{144}$Sm(p,t)$^{142}$Sm with isotopically enriched target; $E_p$ = 34.5 MeV; measured ($E_t$, $\theta_t$); DWBA analysis; deduced levels $J^\pi$.]

The nucleus $^{146}$Gd may have a major shell closure for both neutrons ($N$ = 82) and protons (Z = 64).[1] If $^{146}$Gd is indeed doubly magic, it follows that nuclei differing by one or two particles or holes will exhibit predictable low-energy structures. Thus, the systematics of one- and two-particle (-hole) structures in the vicinity of $^{146}$Gd are of interest.

In the work reported here, we examined the levels in $^{142}$Sm by high-resolution (p,t) reaction spectroscopy. Previously, high-resolution (p,t) investigations were performed on $N$ = 82 targets of Ba, Ce, and Nd.[2-4] However, only low-resolution studies were performed with a Sm target.[5,6]

* This work was performed under the auspices of the U. S. Department of Energy by by the Lawrence Livermore National Laboratory under Contract Number W-7450-ENG-48.

The best experimental information on the levels in $^{142}$Sm comes from the low-resolution (p,t) studies of Struble *et al.*[6] and the $\beta^+$ decay of 1.22-min and 2.4-s $^{142}$Eu.[7] Studies with a Gd target remain unfeasible because $^{146}$Gd is highly radioactive, having a 48.3-d half-life.

We performed the $^{144}$Sm(p,t)$^{142}$Sm reaction at Princeton University using 34.5-MeV protons from the AVF cyclotron and analyzed the tritons for momentum in a QDDD magnetic spectrometer.[8] The target material was isotopically enriched to 95% $^{144}$Sm and evaporated on a 35-$\mu$g/cm$^2$ carbon foil. The Sm thickness was about 100 $\mu$g/cm$^2$. The QDDD spectrometer was operated with a solid angle of 14 msr and an acceptance angle of 120 mr in the reaction plane.

Because there is only one excited state below 1.449 MeV (an intensely populated $2^+$ state at 769 keV),[6] we designed our experiments to detect tritons that populate levels lying between 1.4 and 2.7 MeV. We measured angular distributions in 5° steps from 10 to 60°. These measurements included most of the interesting and interpretable region of the spectrum indicated in Ref. 6. We also observed the region from 2.0 to 3.3 MeV at 15, 35, and 45°. Figure 1 shows a representative spectrum with an energy resolution (FWHM) of 13 keV.

The spectra were fitted with the computer code AUTOFIT[9] and were calibrated internally with levels previously known from the decay of $^{142}$Eu.[7] Thirty levels below 3.2 MeV were identified, as listed in Table I. We normalized the intensities of the peaks in the different runs by counting the elastically scattered protons with a solid-state detector mounted at 45° in the scattering chamber. We determined absolute differential cross sections by combining a DWBA calculation[10] of the cross section for the elastically scattered protons with the measured relative solid angles of the QDDD spectrograph and the monitor detector.

To identify the spins and parities of the levels, we fit the angular distributions using one-step DWBA theory.[10] In our initial calculations, we chose the proton optical-model parameters of Helton *et al.*,[11] which were adjusted for the difference in proton bombarding energies by using the empirical equations of Becchetti and Greenlees.[12] The triton parameters were those obtained by Flynn *et al.*,[13] adjusted for the differences in target $A$ and $Z$ by means of the empirical equations provided in Ref. 12. The fits to the experimental data, particularly for the maxima of the $L = 0$ angular distributions and the cross sections at forward angles for the $L = 5$ and $L = 7$ angular

distributions, were not good. We therefore made systematic small changes in the optical parameters to obtain a "best" fit. These optical parameters are presented in Table II. Figure 2 shows fits to the experimental data. Such fits were used to assign the $L$ values shown in Table I. The fits to the data demonstrate that intense peaks with $L = 0$ and $L = 2$ are unambiguously assigned, but that states with higher $L$ values are not assigned with as much certainty.

To interpret individual levels, we assumed that $^{146}$Gd is doubly magic. Then, in analogy to other doubly magic regions, we expected the levels in $^{142}$Sm to arise from a relatively weak coupling of low-lying core states, two-proton-hole states, and two-neutron-hole states. The (p,t) reaction preferentially populates those states that have large two-neutron-hole components. Further, according to the DWBA theory, the (p,t) reaction has a strong selection rule against unnatural-parity states. Thus, only even-spin, positive-parity and odd-spin, negative-parity states should be observed.

All five of the predicted neutron single-hole shell-model orbitals ($2d_{3/2}$, $3s_{1/2}$, $1h_{11/2}$, $2d_{5/2}$, and $1g_{7/2}$) have been identified below 1.4 MeV in $^{143}$Sm (Ref. 14). These should play a role in the description of the $^{142}$Sm levels. The states of lowest energy are probably dominated by the $s_{1/2}$ and $d_{3/2}$ neutron orbitals because they lie nearly 700 keV lower in energy in $^{143}$Sm than the other single-hole levels. Any significant negative-parity strength must involve the $h_{11/2}$ neutron orbital.

The particle-hole core-excited states can be found from the level scheme of $^{146}$Gd (Ref. 15); the two-proton-hole states can be identified from the level scheme of $^{144}$Sm (Ref. 15). In the following discussion, we refer to both classes of states simply as core states. We interpret the physical states of $^{142}$Sm as combinations of these "elementary" pairs of neturon holes and core excitations.

The $0^+$ levels are the easiest to assign because of the unique nature of the $L = 0$ angular distribution. We identify three $0^+$ excited states, in contrast to the (p,t) results for other $N = 80$ isotones. Only the ground state is observed in $^{136}$Ba (Ref. 2), and only the ground state and one excited $0^+$ state are populated in $^{138}$Ce and $^{140}$Nd (Refs. 3,4). In $^{142}$Sm we observe $0^+$ states at 1449, 2171, and 2283 keV with relative intensities (integrated between 7.5 and 62.5°) of 1.0:1.1:1.4. These results agree with previous measurements.[6] Although we did not measure the angular distribution

of the ground state, we assume that these three excited states have the same relative intensity to the ground state as was found in Ref. 6. With this assumption, which is supported by DWBA calculations, the excited states have 5.6, 6.2, and 7.8% of the ground-state intensity.

Five shell-model basis states, each consisting of two neutron holes coupled to $0^+$, can be constructed with the five neutron single-particle states. The residual monopole-pairing interaction mixes these five states in a way that is constructive for (p,t) population of the ground state but destructive for the population of the four other states. Therefore, one expects nearly all the low-energy, $0^+$ intensity to reside in the ground state. This expectation is consistent with the two-nucleon-transfer data for $N = 80$ isotones: no excited $0^+$ state with more than 14% of the ground-state cross section has been found. Thus, the weakly populated $0^+$ states that we observe in $^{142}$Sm are either the noncoherent two-neutron-hole states, for which the destructive interference is not complete, or $0^+$ core states that have small admixtures of two-neutron-hole configurations.

We assign five $2^+$ states, at 1657, 2054, 2340, 2435, and 2490 keV, on the basis of their angular distributions. They all have less than 15% of the intensity of the first excited $2^+$ state at 768 keV. From shell theory, there are nine two-neutron-hole basis states that can be constructed from the five single-neutron-hole orbitals. As in the case of the $0^+$ states, a strong residual interaction (quadrupole pairing) causes mixing and a concentration of strength in the $2^+$ state of lowest energy. The state at 1657 keV is very weak and has nearly the same energy as the state seen in $^{144}$Sm at 1660 keV. We therefore assign the 1657-keV state as a core excitation. The remaining $2^+$ states are consistent with the large number of $2^+$ two-neutron-hole states we expect below 3 MeV. However, it is impossible to make precise configurational assignments for these states.

States of higher spin are difficult to assign on the basis of the angular distributions. For example, the position and height of the second maximum for $L = 4$ DWBA angular distributions are quite sensitive to the choice of parameters, so we cannot make completely unambiguous assignments based solely on the fit of our data to DWBA angular distributions. We observe three states, however, at 1793, 2417, and 2575 keV, which are quite intense, have similar angular distributions, and are consistent with the DWBA predictions for $L = 4$. Further, the state at 1793 keV

agrees in excitation energy with the $4^+$ state at 1791.3 keV (Ref. 7) that is seen in the decay of $^{142}Eu^g$. We assign angular-momentum transfers of $L = 4$ for these states.

For levels above 2700 keV, we have data at only three angles. Nevertheless, we assign tentative $L$ values of 4 or 5 in Table I for levels at 2825 and 2965 keV. These assignments are supported by the three-point fits to the DWBA curves and by association with levels populated in Ref. 6, where more complete angular distributions were reported.

The shell model predicts that a two-neutron-hole state with the configuration $(h_{11/2})^{-2}$ and having $J^\pi = 6^+$ should occur at an excitation of about 2 MeV. DWBA calculations indicate that this state should be populated in the (p,t) reaction with an integrated intensity about twice as great as the weakest peaks we have identified. However, we do not find any $L = 6$ strength.

A $6^+$ state at 2420 keV of excitation in $^{142}Sm$ is populated by $\beta^+$ decay of $^{142}Eu^m$ (Ref. 7), and we observe a state with $L = 4$ or 5 at 2417 keV. If we ignore the evidence from the angular distributions, it might be tempting to interpret these as the same state on the basis of the close energy agreement. However, this is very unlikely, since $\beta^+$ decay of $^{142}Eu^m$ to the lowest-lying two-neutron-hole $6^+$ state in $^{142}Sm$ would be highly forbidden on the basis of the most likely shell-model assignments. Kennedy *et al.*[7] suggest that $^{142}Eu^m$ has the shell-model configuration $[\pi(d_{5/2})^{-1}, \nu(h_{11/2})^{-1}(d_{3/2})^{-2}]_{7^-}$. The two-neutron-hole $6^+$ state of lowest energy in $^{142}Sm$ will have a nearly pure $[\pi(d_{5/2})^{-2}\nu(h_{11/2})^{-2}]_{6^+}$ configuration. These two configurations cannot be connected by the decay of one proton.

The state we see at 2417 keV probably has $L = 4$, and it remains a small puzzle that we do not see any $L = 6$ strength to a two-neutron-hole state. Possibly, the DWBA normalization factor (218, from Ref. 3) that we used in our calculations is too large. This normalization correctly reproduces the total observed $L = 0$ intensity; it leads, however, to calculated cross sections that are a factor of 3 or more larger than experiment for states populated by $L$ transfers greater than zero.

All the low-energy, negative-parity (p,t) strength involves the $h_{11/2}$ neutron orbital. We expect the interpretable strength to come from the $\left[\nu(h_{11/2})^{-1}(d_{3/2})^{-1}\right]_{5^-,7^-}$ and $\left[\nu(h_{11/2})^{-1}(s_{1/2})^{-1}\right]_{5^-}$ configurations. Other negative-parity configurations lie at least 1 MeV above these. Thus, we expect

to observe no significant $1^-$ or $3^-$ (p,t) strength. However, we populate a state at 1784 keV which has been assigned as $3^-$ from $\beta^+$ decay.[7] It is very weak in our spectra, and it appears from energy systematics to be the $3^-$ octupole vibration of the core. This state lies at 1810.1 keV in $^{144}$Sm. The observation of this state in our experiment implies that it contains a small admixture of a two-neutron-hole configuration, where one of the holes is in the $h_{11/2}$ orbital.

Two of the strongest states in the spectrum occur at 2350 and 2370 keV and have been assigned spins and parities of $5^-$ and $7^-$ from $\beta^+$ decay.[7] Their angular distributions are consistent with this assignment except at forward angles. This anomaly in the DWBA has been observed for the other $N = 80$ isotones.[2,3] It was noted by Struble *et al.*[6] that, although the $5^-$ level can contain components from both the $\left[\pi(h_{11/2})^{-1}\nu(d_{3/2})^{-1}\right]$ and the $\left[\pi(h_{11/2})^{-1}\nu(s_{1/2})^{-1}\right]$ configurations, the $7^-$ level must be nearly pure and involve only the $d_{3/2}$ orbital.

It has not been possible to assign other negative-parity strength unambiguously. However, the state at 2404 keV is a strong candidate for an $L = 5$ transition (see Fig. 2), and it therefore probably contains the remaining $5^-$ strength associated with the $s_{1/2}$ and $d_{3/2}$ orbitals. The $\beta^+$ decay of the $7^-$ state in $^{142}$Eu populates states at 2912 and 3113 keV which have negative parity and possible spins of 6, 7, or 8. We populate states at 2899 and 3101 keV, which are probably the identical states. If so, they arise from the $d_{5/2}$ and $h_{11/2}$ neutron orbitals. However, it is speculative to assign configurations at these excitation energies because the large level density assures extensive configuration mixing.

# References


1. P. Kleinheinz, S. Lunardi, M. Ogawa, and M. R. Maier, Z. *Phys.* **A284**, 351 (1978).
2. H. Kusakari, K. Kitao, S. Kono, and Y. Ishizaki, *Nucl. Phys.* **A341**, 206 (1980).
3. J. D. Sherman, D. L. Hendrie, and M. S. Zisman, *Phys. Rev. C* **15**, 903 (1977).
4. J. B. Ball, R. L. Auble, J. Rapaport, and C. B. Fulmer, *Phys. Lett.* **30B**, 533 (1969).
5. W. Oelert, G. Lindstrom, and V. Reich, *Nucl. Phys.* **A233**, 237 (1974).
6. G. L. Struble, L. G. Mann, R. G. Lanier, W. M. Buckley, J. Kern, G. Crawley, S. Gales, D. Mueller, and F. Girshick, *Phys. Rev. C* **23**, 2447 (1981).
7. G. Kennedy, G. Gujrathi, and S. K. Mark, *Phys. Rev. C* **12**, 553 (1975).
8. R. T. Kouzes and W. H. Moore, *Phys. Rev. C* **12**, 1511 (1975).
9. J. Comfort, Physics Division, Argonne National Laboratory, Argonne, Ill., Informal Report No. PHY-1970B (1970), unpublished.
10. P. D. Kunz, University of Colorado, Boulder, Colo., computer code DWUCK, version 4, unpublished.
11. V. D. Helton, J. C. Hiebert, and J. B. Ball, *Nucl. Phys.* **A201**, 225 (1973).
12. F. D. Becchetti and B. W. Greenlees, *Phys. Rev.* **182**, 1190 (1969).
13. E. R. Flynn, D. D. Armstrong, J. G. Beery, and A. G. Blair, *Phys. Rev.* **182**, 1113 (1969).
14. R. K. Jolly and E. Kashy, *Phys. Rev. C* **4**, 887 (1971).
15. *Table of Isotopes*, C. M. Lederer and V. S. Shirley, Eds (Wiley, New York, 1978).

**Table I. Levels populated in the $^{144}Sm(p,t)^{142}Sm$ reaction.**

| Peak No. | $E_x$[a] (keV) | $L$ | Integral cross section[a,b] | $\frac{d\sigma}{d\Omega}(45°)$ $\left(\frac{\mu b}{sr}\right)$ |
|---|---|---|---|---|
| G.S. | 0[c] | 0 | | |
| 1 | 769[c] | 2 | | |
| 2 | 1449 (4)[c] | 0 | 5.8 (1) | 1.5 (2) |
| 3 | 1657 (1)[c] | 2 | 4.2 (1) | 2.1 (2) |
| 4 | 1784 (2)[c] | 3 | 10.2 (2) | 6.1 (9) |
| 5 | 1793 (1)[c] | 4 | 58.4 (5) | 28.7 (10) |
| 6 | 2054 (1)[c] | 2 | 23.6 (3) | 15.9 (8) |
| 7 | 2171 (2) | 0 | 6.3 (1) | 1.1 (2) |
| 8 | 2283 (2) | 0 | 8.2 (2) | 2.1 (2) |
| 9 | 2340 (2) | 2,3 | 31.1 (3) | 33.7 (7) |
| 10 | 2350 (1)[c] | 5 | 77.7 (5) | 40.4 (7) |
| 11 | 2370 (1)[c] | 7 | 35.4 (3) | 74.5 (17) |
| 12 | 2404 (2) | 5 | 5.1 (1) | |
| 13 | 2417 (2) | 4,5 | 20.5 (3) | 11.2 (6) |
| 14 | 2435 (2) | 2,3 | 14.3 (2) | 6.9 (5) |
| 15 | 2490 (3) | 2 | 10.3 (2) | 8.2 (5) |
| 16 | 2500 (4) | | 6.0 (2) | |
| 17 | 2575 (2) | 4,5 | 10.6 (2) | 7.5 (4) |
| 18 | 2619 (9) | | 5.7 (1) | |
| 19 | 2648 (9) | | 9.9 (2) | 10.7 (2) |
| 20 | 2721 (5) | (2,3) | 2.5 (1) | 2.1 (2) |
| 21 | 2825 (10) | (4,5) | | 10.1 (6) |
| 22 | 2899 (15) | | | 10.1 (6) |
| 23 | 2943 (18) | | | 7.8 (4) |
| 24 | 2965 (22) | (4,5) | | 4.8 (7) |
| 25 | 3023 (28) | | | 2.6 (2) |
| 26 | 3091 (12) | | | 9.3 (6) |
| 27 | 3101 (12) | | | 9.2 (6) |
| 28 | 3213 (42) | | | 23.5 (8) |
| 29 | 3241 (45) | | | 5.0 (7) |

[a] Statistical errors in the least significant digit are given in parentheses.

[b] Cross section is obtained by integrating $\frac{d\sigma}{d\Omega}$ between 10 and 60°.

[c] Observed in $\beta^+$ decay.[7]

**Table II. Optical-model parameters used in the DWBA calculations.**

| $V_R$ | $r_R$ | $a_R$ | $W_I$ | $W_O$ | $r_I$ | $a_I$ | $V_{SO}$ | $r_{SO}$ | $a_{SO}$ | $R_C$ | $\lambda$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Proton** | | | | | | | | | | | |
| −52.11 | 1.147 | 0.668 | −4.50 | 3.04 | 1.372 | 0.614 | −7.42 | 1.147 | 0.668 | 1.25 | |
| **Triton** | | | | | | | | | | | |
| −165.5 | 1.26 | 0.783 | −15.90 | | 1.382 | 0.879 | | | | 1.25 | |
| **Neutron** | | | | | | | | | | | |
| a | 1.25 | 0.65 | | | | | | | | | 25 |

[a] Adjusted to reproduce bound-state energy.

# Figure Captions

**Figure 1.** Triton spectrum from the $^{144}$Sm(p,t) $^{142}$Sm reaction at $E_p$ = 34.5 MeV.

**Figure 2.** Experimental angular distributions. Data points may be converted to differential cross sections expressed in mb/sr by multiplying their value by 5.5. The solid curves are the result of the DWBA calculations.

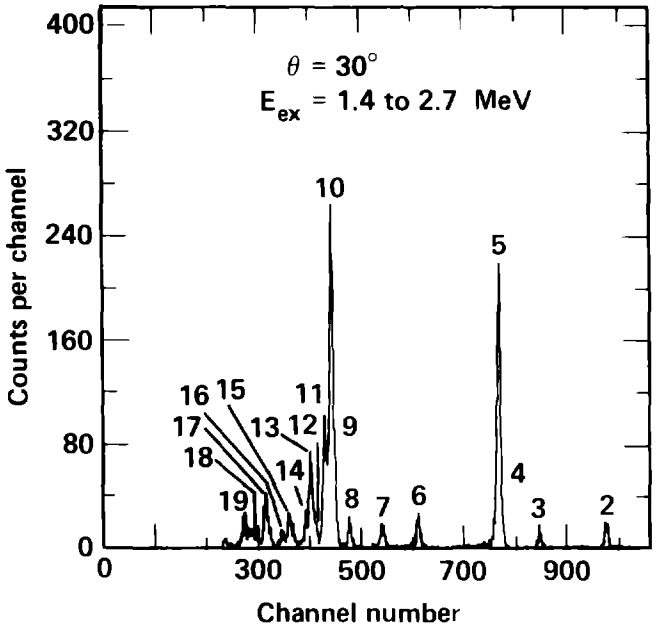
θ = 30°
E_ex = 1.4 to 2.7 MeV
Counts per channel
Channel number
400
320
240
160
80
0
0
300
500
700
900
10
5
16
15
11
17
13
12
9
18
14
4
19
8
7
6
3
2

Fig. 1.

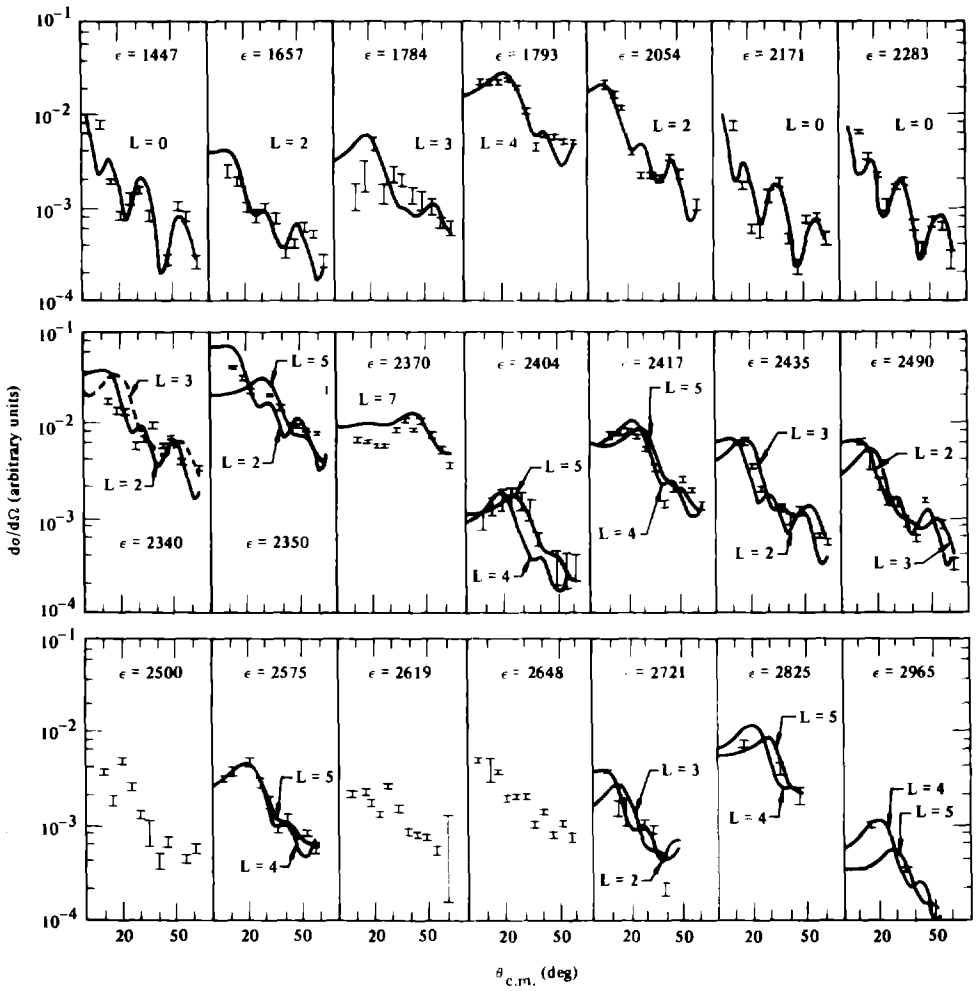
ε = 1447
L = 0
ε = 1657
L = 2
ε = 1784
L = 3
ε = 1793
L = 4
ε = 2054
L = 2
ε = 2171
L = 0
ε = 2283
L = 0
L = 3
L = 2
ε = 2340
L = 5
L = 2
ε = 2350
ε = 2370
L = 7
ε = 2404
L = 5
L = 4
ε = 2417
L = 5
L = 4
ε = 2435
L = 3
L = 2
ε = 2490
L = 2
L = 3
ε = 2500
ε = 2575
L = 5
L = 4
ε = 2619
ε = 2648
ε = 2721
L = 3
L = 2
ε = 2825
L = 5
L = 4
ε = 2965
L = 4
L = 5
dσ/dΩ (arbitrary units)
θc.m. (deg)

Fig. 2.