Contribution to 2nd International Symposium on Nuclear Excited States, LODZ, Poland June 22-26, 1992

ANL/CP--76821

DE92 019673

GAMMA SPECTROSCOPY OF MULTIPLE NUCLEON TRANSFER REACTIONS IN Sn

Z. W. Grabowski, R. H. Mayer, B. Fornal, D. T. Nisius, I. G. Bearden, P. J. Daly
Purdue University, W. Lafayette, Indiana U.S.A.

R. Broda
Institute of Nuclear Physics, Krakow, Poland

M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, T. Lauritsen
Argonne National Laboratory, Argonne, Illinois, U.S.A.

1. INTRODUCTION

According to the nuclear shell model, the shell that is being filled with from 50 to 82 nucleons includes, among other orbitals, a $h_{11/2}$ "intruder" orbital. Since this orbital has the highest j-value in the shell and odd-parity, it is expected that the $(h_{11/2})^n$ configurations should be particularly pure, especially at the highest spin. Assuming a seniority to be a good quantum number, the multiplets based on $(h_{11/2})^n$ $v = 2$ and $(h_{11/2})^n$ $v = 3$ configurations exhibiting a characteristic level pattern and terminating at an isomeric state at highest spin for each configuration are expected in the middle of the shell containing between 50 and 82 nucleons. The reduced $E2$ transition probability within such a multiplet is predicted to depend in a simple way on the number of particles (n) occupying the $(h_{11/2})^n$ subshell [1]

$$B(E2) \propto \left(\frac{6-n}{6-v}\right)^2 \left(e_{eff}\langle r^2\rangle\right)^2 .$$

In the expression above, v represents seniority, e_{eff} is the effective nucleon charge, and $\langle r^2\rangle$ is the radial matrix element of r^2 between the $h_{11/2}$ single particle states. Accordingly, abnormally long-lived seniority isomers should occur in the nuclides where the $h_{11/2}$ subshell is close to being half-filled.

The decay of $(\pi h_{11/2})^n$ yrast isomers was studied in a series of proton-rich $N = 82$ isotones culminating in determination of $B(E2)$ values in ^{153}Lu and ^{154}Hf [2]. In the $N = 82$ isotones however, it seems unlikely that the measurements could be extended beyond ^{154}Hf ($n = 8$). The opportunity to investigate the $(h_{11/2})^n$ isomers across the whole $h_{11/2}$ subshell exists, at least in principle, in Sn isotopes where the counterpart $\nu h_{11/2}$ subshell is being filled with neutrons starting at ^{116}Sn. Before our measurements [3] were initiated, the $(\nu h_{11/2})^n$ 10^+ isomers were known to exist in ^{116,118,120}Sn [4,5], where the $\nu h_{11/2}$ subshell begins to fill, and in ^{128,130}Sn [6] at the other end. Important information, however, was missing about the 10^+ isomers in ^{122,124,126}Sn where the long lifetimes are expected. The $v = 3$ $(h_{11/2})$ isomers in odd tin isomers for $A \geq 119$ were also not identified. A serious experimental difficulty in populating high spin states in heavier Sn isotopes is that they are not accessible by fusion-evaporation reactions. We decided to search for these missing tin isotopes among the products of heavy ion reactions on ^{122,124}Sn targets. Using this approach we were able to identify the isomeric decays and measure the lifetimes of the $(\nu h_{11/2})^n$ $v = 2$ isomeric states in ^{122,124}Sn [3]. In odd tin isotopes we identified new $I = 19/2^+$ yrast isomers in ^{119,121,123}Sn and measured their lifetimes [7]. In addition $(\nu h_{11/2})^n$ $v = 3$, $I = 27/2^-$ isomers in ^{119,121}Sn were observed for the first time. The $B(E2)$ values calculated from the measured lifetimes of $v = 2$ $(\nu h_{11/2})^n$ yrast isomers allow us to determine half filling of the $\nu h_{11/2}$ subshell at $N \approx 73$. The absence of tin isotopes with $A \gtrsim 125$, surprising at first since neutron-rich projectiles (^{76}Ge,^{80}Se) were used, was subsequently understood in terms of "N/Z equilibration" in these transfer reactions [8].

2. EXPERIMENTS

The primary reaction chosen for the present investigation was ^{124}Sn + 325 MeV ^{76}Ge (~ 15% above Coulomb barrier) since it appeared to offer the best prospects for populating Sn isotopes in the $A \sim 124$ region. Subsequently the ^{122}Sn + 325 MeV ^{76}Ge and ^{122,124}Sn + 344 ^{80}Se reactions were also utilized. Targets containing 1 mg/cm^2 ^{122,124}Sn were enriched to > 96% and backed with lead. The μs pulsed beams of ^{76}Ge and ^{80}Se were from the ATLAS superconducting linear accelerator at Argonne National Laboratory [9]. Data was obtained with the Argonne–Notre Dame γ-ray facility consisting of 12 Compton-suppressed Ge detectors and an inner ball of 50 BGO hexagons. The Ge detectors recorded γ-ray singles spectra in E_γ versus time and $E_\gamma - E_\gamma$ versus time mode in-beam as well as off-beam. In some cases the time interval between a Ge-detector pulse and delayed firing (up to 10 μs later) of a BGO hexagon was also recorded.

3. RESULTS

3.1 Even-*A* Sn Isomers

The quality of the data is illustrated in Fig. 1 for the ^{124}Sn + 325 MeV ^{76}Ge reaction. This experiment was performed in a 60 μs beam on and 210 μs beam off configuration. Evident in this figure is the absence of lines that could be identified with ^{126}Sn, but at the same time there is clear evidence of transitions depopulating 10^+ isomers in ^{120,122,123}Sn. The $10^+ \rightarrow 8^+$ transitions with energy 75.2 keV in ^{122}Sn and 78.2 keV in ^{124}Sn that are not visible in Fig. 1 have been seen clearly when gated by 281 keV γ-ray and 253 keV γ-ray, respectively.

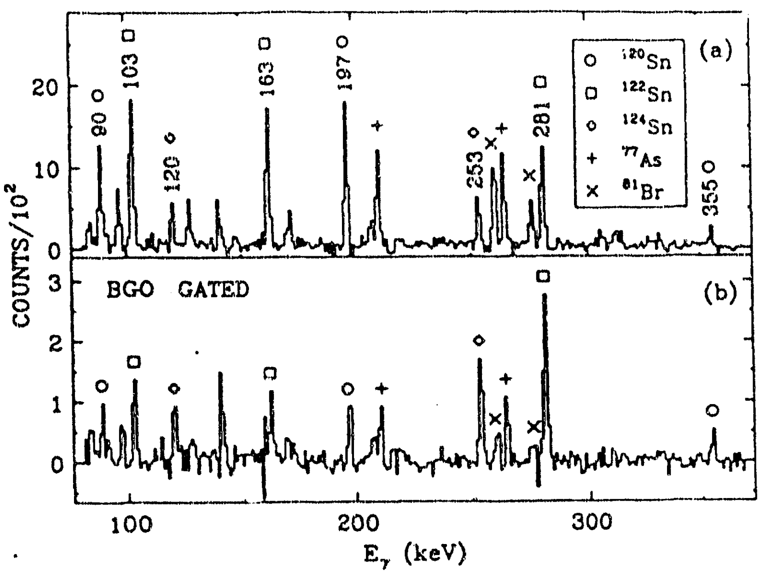

Fig. 1. Off-beam γ-ray spectra for the reaction ^{124}Sn + 325 MeV ^{76}Ge measured 2–80 μs after the beam bursts, with radioactivities subtracted. The upper spectrum is ungated whereas the lower required a delay BGO hexagon pulse 1–9 μsec after the Ge detector signal. Random coincidences are not subtracted.

The key 281- and 253-keV γ-rays were decaying, during the off-beam period, together with the γ-rays known to follow the 7^- isomers in ^{122}Sn and ^{124}Sn. The decay data used to determine the half-lives for the new 10^+ isomers in $^{122,124}Sn$ are displayed in Fig. 2 and presented in Table 1. The $\sqrt{B(E2;10^+ \rightarrow 8^+)}$ from Table 1 are plotted versus A in Fig. 3. The intersection of the line connecting the $B(E2;10^+ \rightarrow 8^+)$ values with $\sqrt{B(E2;10^+ \rightarrow 8^+)} = 0$ which occurs at $A \approx 123$ (or $N \approx 73$), indicates half-filling of the $\nu h_{11/2}$ subshell. As mentioned in the Introduction, the crossing point for protons filling the $\pi h_{11/2}$ subshell in $N = 82$ isotones occurs just below $Z = 71$ [2]. The difference between protons and neutrons filling the $h_{11/2}$ subshell could be traced to the relative $s_{1/2}$, $d_{2/3}$ and $h_{11/2}$ single-particle energies. For protons, due to the Coulomb potential that increases the $s_{1/2}$ and $d_{3/2}$ energies more than the $h_{11/2}$ energy, these orbitals are nearly degenerate [12]. For neutrons, on the other hand, the $s_{1/2}$ state, and to a lesser extent, the $d_{3/2}$ state are well below the $h_{11/2}$ state [1,13].

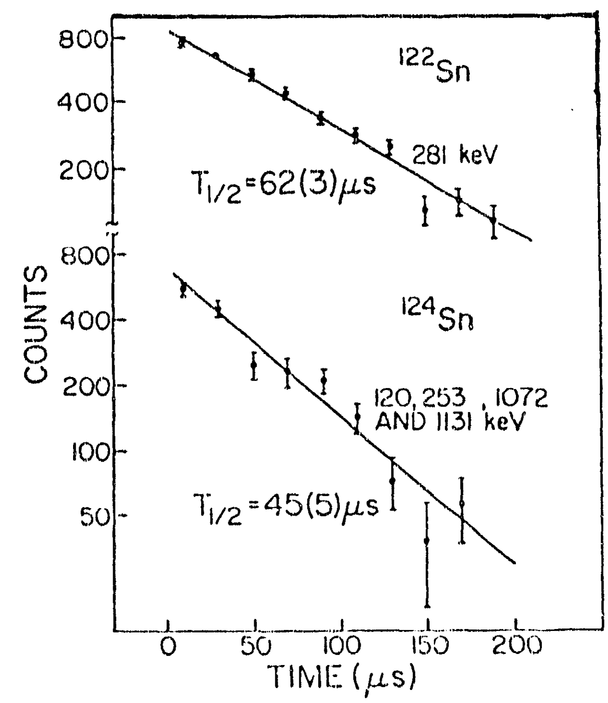

Fig. 2. Data for the ^{122}Sn and ^{124}Sn 10^+ isomeric half-life determinations. To minimize interference from an extraneous 254 keV γ-ray, only BGO-gated events were included for the 253 keV transition in ^{124}Sn.

Table 1. Decay data for the 10^+ isomers in Sn isotopes and the $B(E2; 10^+ \to 8^+)$ values.

Nucleus	$10^+ \to 8^+$ (keV)	$T_{1/2}$ (μs)	$B(E2)$ ($e^2 fm^4$)	Ref.
^{116}Sn	54.7(2)	0.90(1)	54(4)[a]	10
^{118}Sn	55.8(2)	2.63(7)[b]	28.6(8)	4,5,10
^{120}Sn	65.7(2)	6.26(11)	8.9(2)	5
^{122}Sn	75.2(3)	62(3)	0.70(4)	Present work
^{124}Sn	78.8(5)	45(5)	0.89(11)	Present work
^{128}Sn	79.3	2.69(23)	14.4(13)	11
^{130}Sn	96.5	1.61(15)	14.5(14	11

[a]Isomeric $E2$ branching of 63(4)% adopted from Ref. 10.

[b]Obtained by reanalysis of data from Ref. 5.

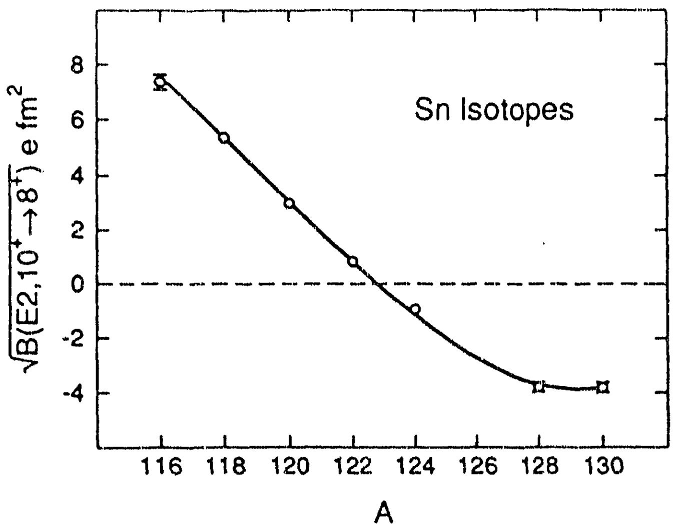

Fig. 3. Measured $E2$ transition amplitudes for the $(\nu h_{11/2})^n$ $10^+ \to 8^+$ transitions in even-A Sn isotopes. Error bars lie within the plotted points.

3.2 Odd-A Sn Isomers

Since detailed analysis of the off-beam spectra in the $^{122,124}Sn$ + ^{76}Ge reactions showed unknown γ-rays decaying with $T_{1/2} \sim 5 - 10$ μs, a follow-up experiment with $^{122,124}Sn$ + ^{80}Se reactions was performed. Previously, a 1.75 μs $19/2^+$ isomer that decays mainly by a $19/2^+ \to 15/2^- \to 11/2^-$ γ-ray cascade was tentatively identified in ^{117}Sn [14], but low-lying $11/2^-$ single particle states are the highest spin states known in the odd $^{119-125}Sn$ isotopes.

Figure 4 shows off-beam γ-ray spectra measured $2 - 12$ μs after $^{122,124}Sn$ + 344 MeV ^{80}Se reactions. With a ^{124}Sn target, six previously unassigned transitions were present. On the basis of coincidence measurements, these six transitions could be grouped in three pairs with the two transitions in each pair decaying with the same half-life. After the half-lives were determined for each group, we assigned these pairs, guided by systematics, to $^{119,121,123}Sn$ isotopes as shown in Fig. 5.

The 9.6 μs isomer is firmly assigned to ^{119}Sn because a low-lying 1220 keV transition in this nucleus was identified in an early ^{116}Cd($\alpha, n\gamma$) study [15], and both the 818 and 1220 keV

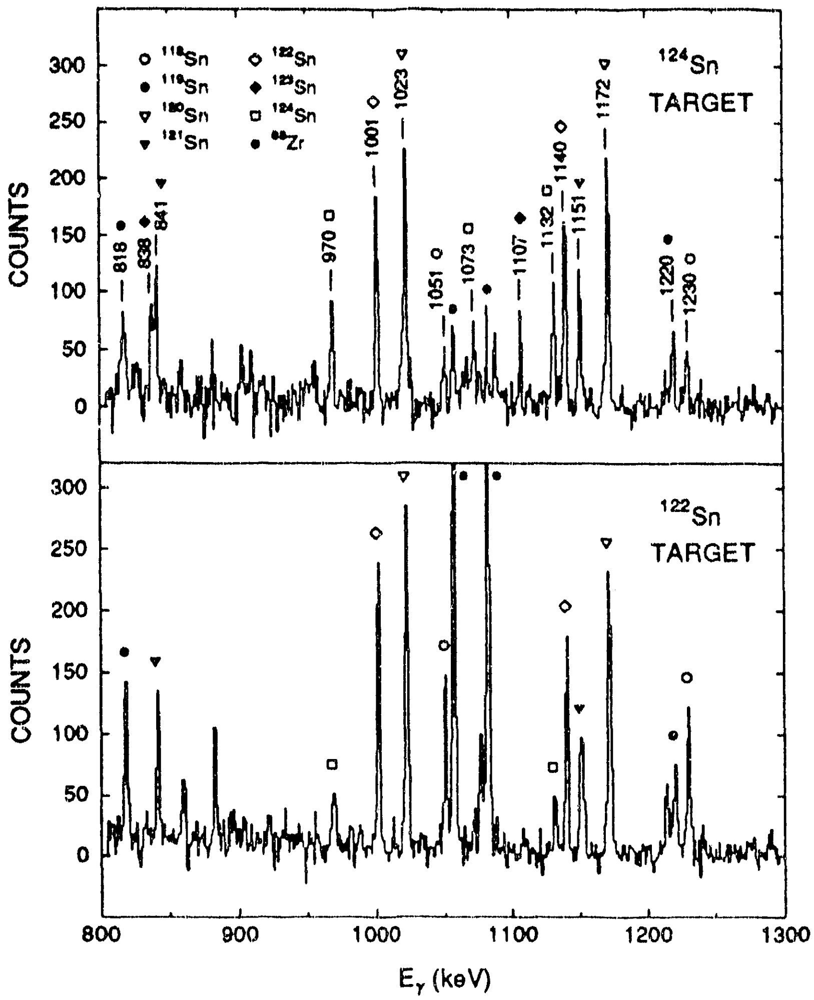

Fig. 4. Off-beam γ-ray spectra measured 2–12 μs after ^{122,124}Sn + 344 MeV ^{80}Se reactions with radioactivities subtracted.

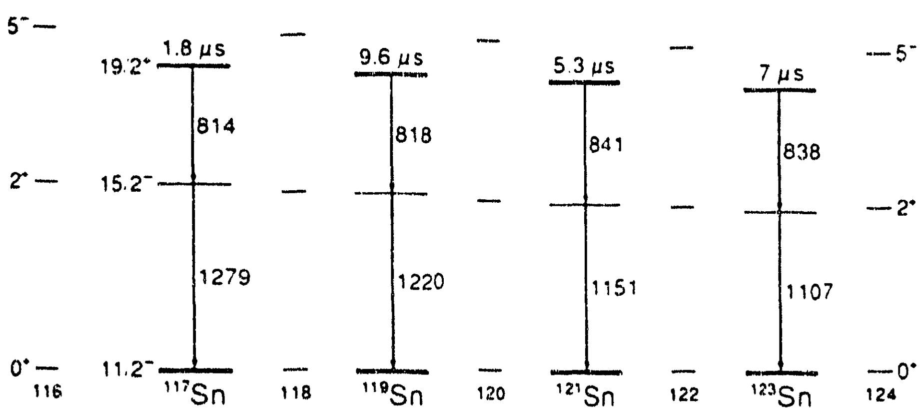

Fig. 5. Energy systematics for even-A and odd-A Sn nuclei in the $A = 116 - 124$ mass range.

γ rays were previously observed in the ^{116}Cd(^{7}Li,$p3n$) reaction [5]. The disappearance of the 838 and 1107 keV γ-rays when the ^{124}Sn target was replaced by the ^{122}Sn one (Fig. 4) provides a forceful indication that these are transitions in ^{123}Sn. However, the strongest arguments for the assignments of the 5.3 μs isomer to ^{121}Sn and the 7.4 μs isomer to ^{123}Sn are based on the energy systematics displayed in Fig. 5. The three new isomers observed in the present work are interpreted by analogy with the known 1.75 μs isomer in ^{117}Sn [14] as $19/2^+$ states of $\nu h_{11/2} \times 5^-$ character in the ^{119,121,123}Sn nuclei, each of which decays to $15/2^-$ and $11/2^-$ states by a cascade of $M2$ and $E2$ transitions. The 0^+, 2^+ and 5^- states in the neighboring even-A Sn nuclei are also shown in Fig. 5. It is obvious that, with the proposed isotopic assignments for the new isomers, the $15/2^-$ and $19/2^+$ energies follow closely the highly regular systematics of the 2^+ and 5^- energies in the even-A isotopes.

The identification of the $15/2^- \rightarrow 11/2^-$ transitions in ^{119,121,123}Sn was an important step towards further studies of $(\nu h_{11/2})^n$, $v = 3$ states in these nuclei. Since the lifetimes of $(\nu h_{11/2})^n$ $27/2^-$, $v = 3$ isomers are expected to be about 0.1 μs, the ^{124}Sn + 344 MeV ^{80}Se experiment was repeated with beam pulsing of 0.4 μs on and 0.5 μs off. The off-beam coincidence spectra measured 10 – 320 ns after the reaction are presented in Fig. 6. Our proposed partial level schemes for ^{119,121}Sn are presented in Fig. 7.

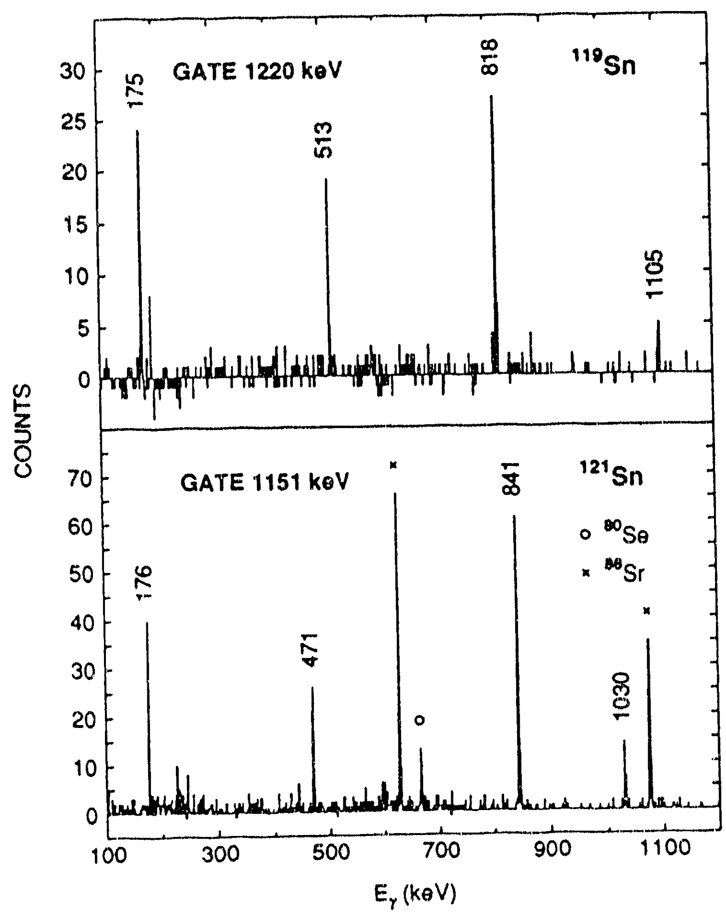

Fig. 6. Off-beam $\gamma - \gamma$ coincidence spectra measured 10 – 320 ns after ^{124}Sn + 344 MeV ^{80}Se reaction.

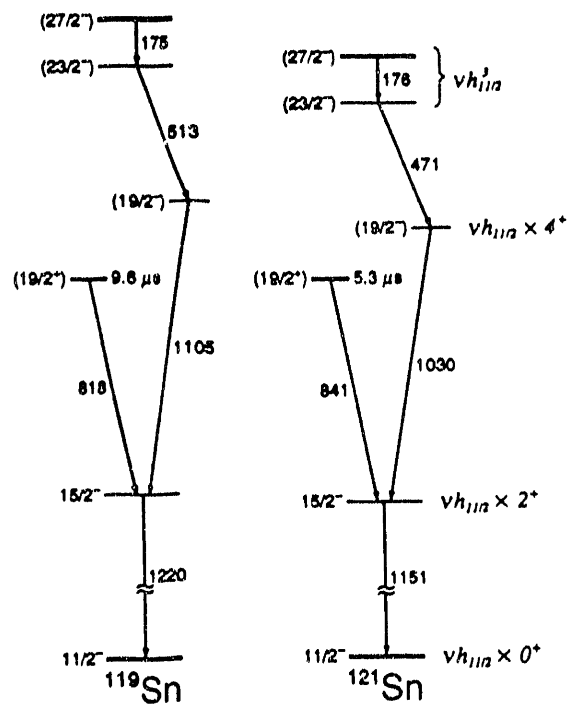

Fig. 7. Proposed partial level schemes for ^{119,121}Sn.

4. COMMENTS ON REACTION MECHANISM

The absence in our spectra of transitions between high spin states for $A \gtrsim 125$ can be understood in terms of the "N/Z equilibration" mechanism [8]. It predicts, in our case, mass flow away from the heavier (target) and into the lighter (projectile) reaction partner. In Fig. 8 the yields of the even–even products of the ^{124}Sn + 344 MeV ^{80}Se reaction are presented as obtained from the $4^+ \rightarrow 2^+ \rightarrow 0^+$ coincidence intensities. The areas of the squares are proportional to the yields. The dashed line represents $\left(\frac{N}{Z}\right)_x = \frac{N_p+N_t}{Z_p+Z_t}$ where x designates the reaction product and p and t stand for projectile and target, respectively. The contours in Fig. 8 represent the liquid drop potential for two touching nuclear drops characterized by (A_x, Z_x) and (A_y, Z_y) [8]. For a fixed Z_x (or Z_y) the potential $V(A_x, Z_x; A_y, Z_y)$ was a minimum at N_x

(or N_y) for which the above requirement for $(N/Z)_x$ is satisfied.

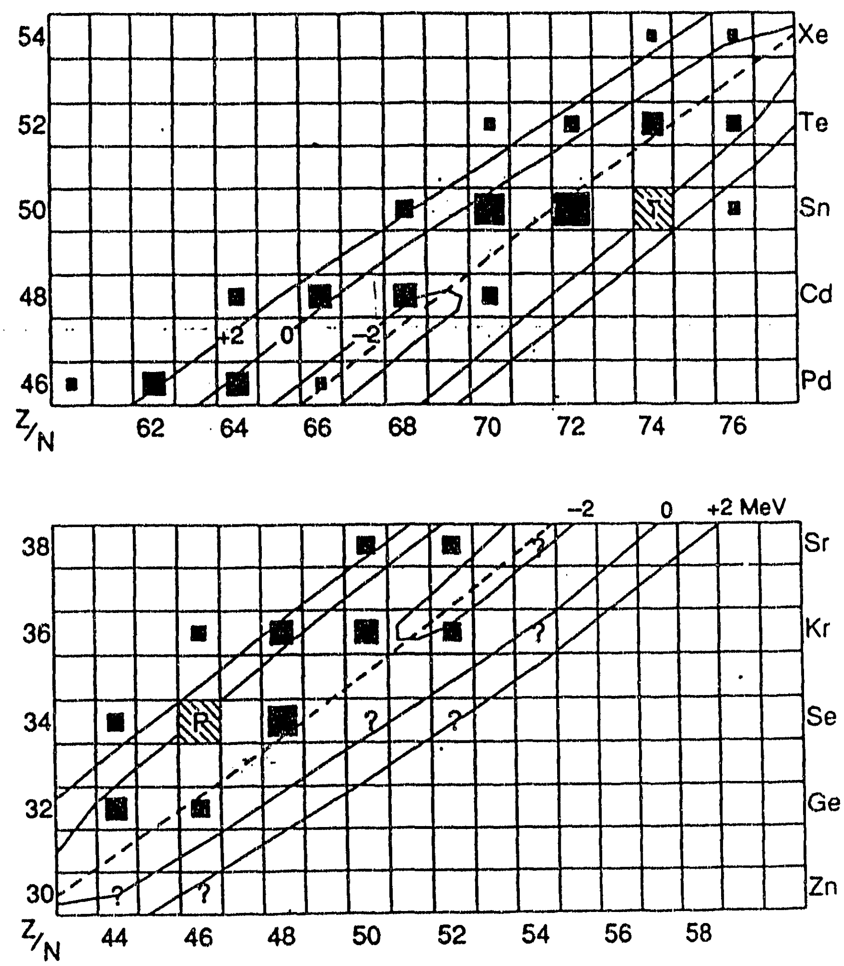

Fig. 8. Relative yields for even–even target-like (above) and projectile-like (below) products of the ^{124}Sn + 344 MeV ^{80}Se reaction. The areas of the squares are proportional to the yields. T and P denote the target and projectile nuclei. Also indicated are the liquid drop potential energy surfaces and $(N/Z)_x$, which is represented by the dashed line (see text). "?" signifies the cases where only $2^+ \rightarrow 0^+$ transitions were identified.

5. SUMMARY

Previously unobserved $(\nu h_{11/2})^n$ $v = 2$ isomeric decays have been identified in ^{122,124}Sn and their lifetimes measured. The calculated $B(E2; 10^+ \rightarrow 8^+)$ transition probabilities indicate that half-filling of the $\nu h_{11/2}$ subshell occurs at about $N = 73$ (or ^{123}Sn). In odd Sn isotopes, the decay schemes of newly observed $(\nu h_{11/2})^n$ $27/2^-$, $v = 3$ have been proposed in ^{119,121}Sn. The lifetimes were measured for $19/2^+$ yrast isomers in ^{119,121,123}Sn, but no transitions above this isomer were observed in ^{123}Sn. In the reactions used in this investigation, it is suggested that absence of a population of Sn isotopes with $A \gtrsim 125$ could be understood on the basis of a simple liquid drop potential.

6. ACKNOWLEDGEMENT

We acknowledge helpful discussions with S. Lunardi and J. Blomqvist. This research was supported in part by the U.S. Department of Energy under contract Nos. DE-FG02-87ER40346 and W-31-109-ENG-38.

References

[1] R. D. Lawson, Theory of the Nuclear Shell Model (Clarendon Press, Oxford, 1980)

[2] J. H. McNeill et al., Phys. Rev. Lett. **63**, (1989) 860

[3] R. Broda et al., Phys. Rev. Lett. **68**, (1992) 1671

[4] A. van Poelgeest et al., Nucl. Phys. **A346**, (1980) 70

[5] S. Lunardi et al., Z. Phys. **A328**, (1987) 487

[6] B. Fogelberg and P. Carle, Nucl. Phys. **A323**, (1979) 205

[7] R. H. Mayer et al., Z. Phys. **A342**, (1992) 247

[8] H. Freiesleben and J. V. Kratz, Phys. Reports **106**, (1984) 1

[9] L. M. Bolinger, Ann. Rev. Nucl. Part. Sci. **36**, (1986) 475

[10] H. Ishihara et al., Nucl. Phys. **1**, (1973) 256

[11] B. Fogelberg et al., Nucl. Phys. **A352**, (1981) 157

[12] Y. Nagai et al., Phys. Rev. Lett. **47**, 1981 1259

[13] E. J. Schneid, A. Prakash and B. L. Cohen, Phys. Rev. **156**, (1967) 1316

[14] O. Hashimoto et al., Nucl. Phys. **A313**, (1979) 145

[15] G. Ch. Madueme et al., Phys. Scripta **13**, (1976) 17

END

DATE FILMED

10/2/92