CONF-8505172--1

The submitted manuscript has been authored by a contractor of the U. S. Government under contract No. W-31-109-ENG-38. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U. S. Government purposes.

Invited Paper Presented at the Conf. on Nuclear Structure with Heavy Ions, May 27-31, 1985, Legnaro (Padua), Italy

FEW-NUCLEON TRANSFER REACTIONS ON DEFORMED NUCLEI*

A. M. van den Berg†

Argonne National Laboratory, Argonne, IL 60439, USA

CONF-8505172--1

DE85 013869

1. Introduction.

In this paper I will discuss a few aspects of transfer reactions on deformed nuclei and will focus on the following recent developments; first α-transfer reactions on deformed nuclei, second quasi-elastic neutron transfer reactions induced by ^{58}Ni beams on spherical and deformed samarium nuclei, and finally the population of low-lying states in neutron-rich nuclei using (particle,γ) or (particle,e) concidence methods. The main experimental problem in the study of transfer reactions on deformed nuclei is the high level density encountered already at low excitation energies. Therefore transfer reactions that involve heavy ions will in most cases give no detailed information on the population of a particular state, but only on the yield for the population of a group of states in a given excitation energy range. An exception to this rule is the strong selective population of high-spin states by heavy-ion induced reactions as those studied by Bond et al.[1]. In general

*This research was supported by the U. S. Department of Energy under Contract W-31-109-Eng-38.

†Present address: Robert J. van de Graaff Laboratorium, Rijks Universiteit Utrecht, Utrecht, The Netherlands.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

cases, however, the analysis of heavy-ion transfer reaction data in terms of a Distorted Wave Born Approximation (DWBA) will be complicated since individual levels will not be resolved (in particular the pure elastic scattering can not be measured in most cases). On the one hand, an analysis of data for strongly deformed nuclei in terms of a Coupled Channel Born Approximation (CCBA) calculation should be more appropriate instead of a simple DWBA calculation. But on the other hand, coupling to a great number of states in a rotational nucleus will make a detailed CCBA analysis for a transfer reaction virtually impossible because of computational limits. Therefore one has to rely on results of a simple CCBA or even a DWBA calculation. However, one knows that matching of the reaction Q-value and of the transferred angular momentum is a dominant factor in a heavy-ion transfer reaction and in most cases a simple diffractional model calculation might be useful to understand the total yield measured in a given excitation energy range.

2. Alpha-transfer on deformed nuclei.

The study of the population of individual levels in deformed nuclei at low excitation energies using an α-transfer reaction has been mainly restricted to the (d,^{6}Li) or its inverse reaction. Systematic α-transfer studies on heavy deformed nuclei have been reported by several groups[2-5]. Some of the recent α-transfer reactions on deformed nuclei in the actinide mass region have been motivated because of suggested[3,6] "α-clustering" in these nuclei. It should be noted that up to now no conclusive evidence has been established for "α-clustering" states and in addition to the available α-pickup and two-neutron transfer data, a systematic investigation of two-proton transfer reactions is needed. From an experimental point of view it is easier to study nuclei in the A = 190 mass region, where two-proton, two-neutron and α-transfer reactions leading to the same final nucleus can be studied. As an example I show in fig. 1 spectra for the $^{182}W(d,^{6}Li)$ and the $^{194}Pt(d,^{6}Li)$ reactions at E_d = 45 MeV[7]. It is seen from this figure that similar to what is observed in the transfer reactions on Th nuclei[3,5] a strong population of states around and above 1 MeV occurs. A peak at an excitation energy of 2.04 MeV in ^{178}Hf, for instance, coincides with a $(0^+,2^+)$ doublet which has a strength of only 5% of that of the ground-state transition in the $^{180}Hf(p,t)$ reaction[10]. Recently Casten[11] suggested that in this mass region the transition from spherical to deformed nuclei is due to a change in the proton number Z and not in the neutron number N, as e.g. in the rare-earth mass region and in the Zr and Mo isotopes. A further investigation of the α-transfer reaction in this mass region might therefore be worthwhile especially if there are predictions available for the strengths of two-nucleon and alpha-transfer reactions.

It was already noted by Milder et al.[2] and Becchetti[12] that the ground-state to ground-state strength for α-pickup reactions changes rapidly if one goes from spherical to deformed nuclei in the same mass region. Such transitional regions in the periodic table are well known and they form an interesting topic to study. Figure 2 shows ground-state α-spectroscopic factors for $(d,^{6}Li)$ reactions on Se- [ref. 13)], Mo- [ref. 14)], Te- [ref. 15)], and Sm-isotopes[2]. The spectroscopic factors - deduced from a standard DWBA cluster analysis - are normalized for each chain of isotopes individually. In addition to these α-particle pickup data, fig. 2 shows for the even-A polonium isotopes the normalized ground-state reduced width for α-decay[16] which is related in a direct way to the α-spectroscopic factors for an α-transfer reaction. On the right side of this figure I have plotted the ratio R_4, being the excitation energy of the 4_1^+ state to that of the 2_1^+

state for the target and residual nuclei. This ratio is taken to be a measure of the deformation of the ground state. That is to say, one can roughly divide nuclei in the three different classes [cf. ref. 17)]: "magic" nuclei with $R_4 < 1.8$, "spherical" nuclei with $1.8 < R_4 < 2.2$ and "deformed" nuclei with $2.2 < R_4 < 3.3$. The figure illustrates that spherical nuclei show a strong increase in the α-spectroscopic strength S or in the α-decay reduced width γ^2 as the number of valence neutrons increases. However, if the addition of more valence neutrons is associated with a nucleus whose R_4 value is 2.5 or larger (i.e. a nucleus with a deformed ground-state) the α-spectroscopic ground-state strength drops quite fast. The strong increase of the strength for the (d,^{6}Li) reaction on the tellerium isotopes, and the increase of the ground-state reduced widths for the α-decay of the polonium isotopes, which in both cases is correlated with an increase of the number of valence nucleons, has been attributed to the microscopic (shell model) structure of proton- and neutron pairs in the initial and final nuclei [see refs. 18,16), respectively]. In the spherical nuclei one usually finds a strong population of the ground state and the 2_1^+ and 3_1^- states only. In deformed nuclei, on the other hand, the strength for the (d,^{6}Li) reaction is distributed over many levels. It is interesting to see whether this "redistribution of strengths" is related to a sum-rule limit. It is well known that sum-rule models play an important role in the interpretation of one-nucleon transfer data, but until now only a few examples have been reported for sum-rule models for two-nucleon transfer reactions [see Birse[19]), and references therein]. The only systematic study of two-nucleon transfer data was presented by Lanford[20]) who found good agreement between the Bayman-Clement sum-rule model and (p,t) data obtained on even-A Pb isotopes. For α-transfer reactions no sum-rule model has been proposed until now, but in view of the strength redistribution mentioned before it is a challenging study.

3. Quasi-elastic neutron transfer reactions on samarium isotopes.

Recently much interest has been paid to the study of quasi-elastic reactions induced with very heavy ions ($A > 40$). It appeared[21] that at energies roughly 25% above the Coulomb barrier angle-integrated cross sections for all quasi-elastic neutron transfer reactions yield as much as 25% of the total reaction cross section (inelastic excitation was not separated from elastic scattering and thus the reaction cross section does not include the yield from inelastic excitations). Another feature is that the yield for these quasi-elastic neutron transfer reactions seems to be determined by the available phase-space. Results of a systematic study[22] of ^{58}Ni and ^{64}Ni induced reactions on even-A tin isotopes show a strong increase of the angle-integrated cross section for one-neutron transfer reactions as a function of ($Q_{gg} - Q_{opt}$). Here Q_{gg} is the ground-state to ground-state Q-value and Q_{opt} is the optimum Q-value for a quasi-elastic transfer reaction [calculated according to ref. [23]]. This behaviour (Q_{gg} systematics) is very similar to results obtained with light heavy-ion induced reactions as studied by the Dubna group[24] in the early 70's. In this context it is interesting to note that one of the stable nuclei with a very small one-neutron separation energy is ^{149}Sm, which is located just in the middle of a transitional region from spherical nuclei (e.g. ^{144}Sm, $N = 82$) to strongly deformed nuclei (e.g. ^{154}Sm). Both circumstances (see fig. 3) make it interesting to study the yield for quasi-elastic neutron transfer reactions on the Sm isotopes induced by heavy ions. Earlier studies of heavy-ion induced reactions have been performed by Hildenbrand et al.[25] using the ^{144}Sm(^{144}Sm,X) and the ^{154}Sm(^{154}Sm,X) reactions at beam energies of 30% above the Coulomb barrier and by Macchiavelli et al.[26] who used the ^{154}Sm(^{132}Xe,X) reaction at 10% above the barrier, respectively. Hildenbrand et al.[25] observed an enhancement in the yield of charge-transfer reactions in the ^{144}Sm + ^{144}Sm system compared to the ^{154}Sm + ^{154}Sm system and attributed this effect to a difference in nuclear structures.

We choose a ^{58}Ni beam to bombard the Sm isotopes at a center of mass energy of 245 MeV which is roughly 30% above the Coulomb barrier[27]. A magnetic spectrograph was used to momentum analyze the reaction products which were detected in a focal-plane gas counter from which an unambiguous mass and Z identification was obtained (see fig. 4). Results for the elastic scattering (note that this includes inelastic excitation to the low-lying states) are shown in fig. 5 together with results from CCBA calculations using a standard heavy-ion potential (V_o = 100 MeV, W = 40 MeV and r_o = 1.25 fm, a = 0.5 fm) and coupling strengths taken from the literature[28]. From these CCBA calculations we find for the total reaction cross section a value of 1320 mb and 1472 mb for the ^{58}Ni on ^{144}Sm and ^{58}Ni on ^{154}Sm reactions, respectively. These values compare rather well with those obtained from the simple quarter-point angle recipe method[29] which yielded (1300 +/- 50) mb and (1460 +/- 50) mb, respectively. Though the reaction cross sections differ by only 10% for these two cases, the calculated total yield for inelastic excitation is very much different: i.e. 1.5 b for the ^{58}Ni + ^{144}Sm reaction versus 12 b for the ^{58}Ni + ^{154}Sm reaction. This difference arises mainly from the large probability for Coulomb excitation predicted for the heavier target.

Figure 6 shows angular distributions for measured quasi-elastic (i.e. $Q > -30$ MeV) neutron transfer reactions. As observed in other heavy-ion induced transfer reactions these angular distributions peak at angles somewhat smaller than the quarter-point angle for elastic scattering and they can be fitted with a Gaussian function to extract the angle-integrated cross sections. There is an enhancement of the total neutron transfer cross section for the $^{58}Ni(^{154}Sm,^{154-X}Sm)^{58+X}Ni$ reaction compared to the $^{58}Ni(^{144}Sm,^{144-X}Sm)^{58+X}Ni$ reaction (total angle-integrated values are (224 +/- 11) mb and (148 +/- 9) mb, respectively), giving further support for the conclusions made by Hildenbrand et al.[25].

As mentioned in the introduction it seems virtually impossible to do realistic DWBA or CCBA calculations for these very heavy-ion reactions. However, a diffractional model calculation might reveal whether this increase can be attributed to Q-value and angular momentum matching or to the increase in deformation for the heavier targets. Mermaz et al.[23] used the diffractional model code FAST to describe energy spectra and relative cross sections for a number of heavy-ion induced transfer reactions between 3 and 40 MeV/nucleon leading to the population of continuum states in the residual nuclei. The main underlying assumptions for these calculations are: 1.) the reaction mechanism is a direct one-step process, and 2.) the level density can be described by a particle-hole state density[30] weighted by an exponential spin law distribution. The parameters in this model are an overall normalization and the difference between the critical angle for pure Coulomb scattering compared with that for Coulomb plus nuclear scattering. Using the code FAST[23] we calculated energy spectra and angular distributions for the one- and two-nucleon pickup reactions and for the one-nucleon stripping reaction studied in our experiment. Angle-integrated cross sections are shown in fig. 7 which shows that in general the measured trend of the cross sections are rather well reproduced by the calculations. It should be noted that all calculated cross sections are normalized to the yield for the $^{154}Sm(^{58}Ni,^{59}Ni)$ reaction. Apparently the requirements for the matching of Q-values and transferred angular momenta seem to give an explanation for the differences in the yield for a certain type of reaction as a function of the target mass.

The increase of the deformation of the target nuclei seems to be a less important effect. Finally we make in fig. 8 a comparison of the calculated energy spectra with those measured. It is seen from this figure that the calculations for the (^{58}Ni,^{59}Ni) reaction at θ_{lab} = 47.5° are somewhat broader than the data, but in general the description of the energy spectra is fair. It is seen from fig. 7 that for the two-neutron pickup reaction a factor of 5.10^{-4} was used to scale the calculated cross sections. Such a "happiness" factor seems to be inherent to the code FAST, and plays a role only in a comparison of cross sections for reactions associated with different numbers of transferred nucleons. A further study of this behaviour and additional calculations and measurements seem to be necessary to get a better understanding of heavy-ion induced reactions on transitional nuclei.

4. Population of low-lying states in ^{234}Th with the (^{18}O,^{16}O) reaction.

The study of low-lying states in nuclei of the actinide mass region has attracted many experimentalists in the last decade. The most popular techniques make use of (particle,xn) reactions where the particle is a light (e.g. α) or medium-heavy (e.g. ^{12}C) projectile. These types of reactions have proven to be successful for the study of the lighter (neutron-deficient) nuclei in the actinide mass region (see among others ref. 31). However, only little information is available for high-spin states in neutron-rich nuclei such as ^{227,228}Ra, ^{233,234}Th, and ^{239,240}U. A natural way to study low-lying states in the even-A nuclei is the use of two-neutron stripping reactions on long-lived targets. Studies have been performed by Casten <u>et al.</u>[32] who made a systematic investigation of the (t,p) reaction in the actinide mass region, which did not yield information for levels with J > 4. Heavy-ion induced reactions at energies above the Coulomb barrier, however, are able to populate higher spin states as well, but with the reaction in mind [i.e. $(^{18}O,^{16}O)$] individual levels are not likely to be resolved using regular binary reaction techniques. The decay of the excited levels, on the other hand, can be monitored with the measurement of in-beam γ-ray or conversion-electron spectra. In order to get an identification of the decaying nucleus γ-rays and/or conversion-electrons can be measured in coincidence with the ejectiles from the binary reaction. The advantage of using a magnetic spectrograph for the momentum analysis of the ejectiles is that one can put the elastically scattered particles off the focal-plane detector and thus improve the ratio of true to random coincidences substantially. Such (HI,HIγ) coincidence measurements have been used in a study of the $(^{18}O,^{16}O)$ reaction on ^{100}Mo and ^{104}Ru leading to neutron-rich molybdenum and ruthenium nuclei. At energies of 50% above the Coulomb barrier Koenig et al.[33] were able to identify levels up to $J^{\pi} = 8^{+}$ in the residual nuclei ^{102}Mo and ^{106}Ru. More recently the ^{286}Pb + ^{232}Th reaction has been used to study the decay of high-spin states of Th isotopes populated with a transfer reaction[34]. Also in this study data were obtained only for isotopes lighter than ^{232}Th.

In order to study neutron-rich Th-isotopes the $^{232}Th(^{18}O,^{16}O)$ reaction at an energy of 130 MeV has been used and some preliminary data will be presented[35]. The heavy ions were momentum analyzed in an Enge split-pole spectrograph with a solid angle of 5.6 msr and coincident γ-rays were detected in an 80 cm^3 Ge(Li) detector at a distance of about 10 cm from the target. From this experiment levels to J = 8 (10) could be identified. The main drawback of this detection technique is the huge random rate due to decay of fission products and the flux of neutrons from the reaction products causing some concern for the life-time of the Ge(Li) detector. Fig. 9 shows calculated[36] values of internal conversion coefficients for E2 transitions in

Th isotopes leading to the emission of K- and L-shell electrons (these give the dominant contribution to the total internal conversion coefficient for $E_\gamma > 45$ keV). It is seen that for γ-ray energies below 180 keV the total internal conversion coefficient is greater than 1, and that the contribution of electrons from the L_2 subshell is dominant. We therefore replaced the γ-ray detector by a Si(Li) electron detector (resolution of 1.8 keV at an electron energy of 620 keV) which was used to detect conversion-electrons from the decay of the excited states in the residual nuclei. The replacement of the γ-ray detector by a conversion-electron detector is favourable because the internal conversion coefficient goes roughly as Z^3 and thus the internal conversion is much more important for the residual thorium nuclei than for the fission products that are produced with cross sections near the geometrical cross section limit. To suppress the detection of reaction products, neutrons, γ-rays and δ-electrons we used a mini-orange permanent magnet system as decribed by Van Klinken et al.[37] which has the advantage that the detection efficiency can be as high as (or even higher than) the detection efficiency of the Ge(Li) detector used in the original setup. I will now discuss the preliminary data obtained for a heavy-ion transfer reaction leading to the neutron-rich ^{234}Th isotope using (heavy-ion,conversion-electron) coincidence methods. We studied the ^{232}Th(^{18}O,^{16}O e) reaction at Argonne using the split-pole spectrograph with a 5.6 msr opening angle at a bombarding energy of 104 MeV. The measured transfer cross section integrated over Q > -15 MeV is (6.6 +/- 0.7) mb/sr at a center of mass angle of 82° (i.e. 7° less than the quarter-point angle for elastic scattering). True and random coincidences were identified by measuring the time difference between the signals from the heavy-ion and the electron detector. The true to random coincidence ratio obtained was about 4.0 with most of the random coincidences due to δ-electrons which have low energies (less than 20 keV). Figure 10 shows electron spectra for true and random coincidences generated with the same width for the time window in the time difference spectrum. The accumulated beam charge is of the order of 3mC. The only two peaks which can be clearly identified are the L-conversion electron lines for the (known) E_γ = 49.4 keV transition from the 2_1^+ state to the ground-state. Though we cannot separate the L_1 from the L_2 conversion line it is seen from fig. 9 that the contribution from L_1 conversion can be neglected. The ratio of the yield for L_2 to L_3 electron conversion of this line is (1.2 +/- 0.3), in perfect agreement with the predicted value that can be obtained from fig. 9. It is seen from this figure that for a measurement of conversion-electron lines for higher energy transitions (i.e between states of higher spin in a rotational model) two orders of magnitude better statistics will be needed. This might be achieved by 1) using a mini-orange spectrometer with a sharp cutoff in the transmission curve at small electron energies (E_γ < 25 keV) and with a better transmission in the energy range from 200 - 500 keV and 2) using a spectrograph with a large solid angle for the detection of the heavy ions.

Further studies of these neutron-rich nuclei using (heavy ion,electron) coincidence methods will be fruitful not only for transitions between high-spin states in even-even nuclei, but also in odd-A nuclei. In addition, these studies may give information on excited 0^+ states in even-A radium and thorium nuclei which are predicted at excitation energies around 1 MeV.

5 Summary and conclusions.

I have discussed some recent studies of transfer reactions used to populate low-lying states in deformed nuclei using different techniques. Most of these reaction studies are difficult because of the low cross sections. A systematic study of α-transfer reactions on deformed nuclei might be performed if it goes together with a study of two-nucleon transfer reactions and with theoretical efforts to get predictions for transfer cross sections. For these reaction studies as well as for the quasi-elastic reaction studies it seems worthwhile to see whether sum-rule models can be applied successfully. The study of low-lying states in neutron rich deformed actinide nuclei can be performed using (heavy ion,electron) or (heavy ion,γ) coincidence techniques, but the experimental setups discussed before need to be improved in order to get good statistics. The results presented in this paper were made possible by contributions from many people of which I especially acknowledge U. Garg, H. Helppi, R. Holzmann, R. V. F. Janssens, T. L. Khoo, D. G. Kovar, W. Kutschera, L. L. Lee, S. C. Pieper, K. E. Rehm, R. H. Siemssen, and G. S. F. Stephans.

References

1) P. D. Bond, J. Barrette, C. Baktash, C. E. Thorn, and A. J. Kreiner, Phys. Rev. Lett. 46 (1981) 1565.

2) F. L. Milder, J. Jänecke, and F. D. Becchetti, Nucl. Phys. A276 (1977) 72.

3) J. Jänecke, F. D. Becchetti, D. Overway, J. D. Croissairt, and R. L. Spross, Phys. Rev. C23 (1981) 101.

4) A. M. van den Berg, R. Bijker, N. Blasi, M. Sambataro, R. H. Siemssen, and W. A. Sterrenburg, Nucl. Phys. A422 (1984) 61; and A. M. van den Berg, N. Blasi, R. H. Siemssen, and W. A. Sterrenburg, Phys. Rev. C27 (1983) 2377.

5) A. M. van den Berg, N. Blasi, R. H. Siemssen, W. A. Sterrenburg, and Z. Sujkowski, Nucl. Phys. A422 (1984) 45.

6) F. Iachello, and A. D. Jackson, Phys. Lett. 108B (1982) 151.

7) A. M. van den Berg, Ph. D. thesis, unpublished.

8) L. R. Greenwood, Nucl. Data Sheets 13 (1974) 549.

9) M. R. Schmorak, Nucl. Data Sheets, 9 (1973) 401.

10) M. A. Oothoudt and M. N. Hintz, Nucl. Phys. A213 (1973) 221.

11) R. F. Casten, Phys. Rev. Lett. 54 (1985) 1991.

12) F. D. Becchetti, Conf. on Clustering Aspects of Nucl. Struct. and Nucl. Reactions, Winnipeg 1978, eds. W. T. H. van Oers, J. P. Svenne, J. S. C. McKee, and W. R. Falk, AIP Conf. Proc. 47 (1978) 308.

13) A. M. van den Berg, R. V. F. Janssens, G. T. Emery, A. Saha, and R. H. Siemssen, Nucl. Phys. A379 (1982) 239.

14) A. Saha, G. D. Jones, L. W. Put, and R. H. Siemssen, Phys. Lett. 82B (1979) 208; and A. M. van den Berg, A. Saha, G. D. Jones, L. W. Put, and R. H. Siemssen, Nucl. Phys. A429 (1984) 1.

15) J. Jänecke, F. D. Becchetti, and C. E. Thorn, Nucl. Phys. A325 (1979) 337.

16) H. J. Mang, Phys. Rev. 119 (1960) 1069.

17) W. F. Hornyak, Nuclear Structure, Academic Press Inc., New York 1975.

18) A. Vitturi, L. Ferreira, P. D. Kunz, H. M. Sofia, P. F. Bortignon, and R. A. Broglia, Nucl. Phys. A340 (1980) 183.

19) M. C. Birse, Nucl. Phys. A385 (1982) 233.

20) W. A. Lanford, Phys. Rev. C16 (1977) 988.

21) K. E. Rehm, D. G. Kovar, W. Kutschera, M. Paul, G. Stephans, and J. Yntema, Phys. Rev. Lett. 51 (1983) 1426.

22) A. M. van den Berg, W. F. Henning, L. L. Lee, K. T. Lesko, K. E. Rehm, J. P. Schiffer, G. S. F. Stephans, F. L. H. Wolfs, and W. S. Freeman, Bull. Amer. Phys. Soc. 29 (1984) 1027; and to be submitted to Nucl. Phys. A.

23) M. C. Mermaz, F. Auger, and F. Fernandez, Phys. Rev. C28 (1983) 1857; M. C. Mermaz, J. Barrette, and H. E. Wegner, Phys. Rev. C24 (1981) 2148; M. C. Mermaz, Il Nuova Cimento 81A (1984) 291; M. C. Mermaz, R. Dayras, J. Barrette, B. Berthier, D. M. de Castro Rizzo, O. Cisse, R. Legrain, A. Pagano, E. Pollaco, H. Delagrange, W. Mittig, B. Heusch, G. Lanzano, A. Palermi, Saclay preprint; and M. C. Mermaz, Saclay preprint.

24) A. G. Artukh, V. V. Avdeichikov, J. Erö, G. F. Gridnev, V. L. Mikheev, V. V. Volkov, and J. Wylczynski, Nucl. Phys. A160 (1971) 511.

25) K. D. Hildenbrand, H. Freiesleben, A. Gobbi, U. Lynen, A. Olmi, H. Sann, and E. C. Wu, Nucl. Phys. A405 (1983) 179.

26) A. O. Macchiavelli, M. A. Delaplanque, R. M. Diamond, F. S. Stephans, E. L. Dines, and J. E. Draper, Nucl. Phys. A432 (1985) 436.

27) A. M. van den Berg, K. E. Rehm, D. G. Kovar, W. Kutschera, and G. S. F. Stephans, Bull. Amer. Phys. Soc. 30 (1985) 732.

28) The coupling parameters for the ^{58}Ni + ^{A}Sm reaction are given as (Nuclear and Coulomb deformations were taken to be equal):

^{58}Ni BE(2) = 0.25 e^2b^2, BE(3) = .01 e^2b^3, β_2 = .079, β_3 = .10

^{144}Sm BE(2) = 0.07 e^2b^2, BE(3) = .19 e^2b^3, β_2 = .17 , β_3 = .14

^{154}Sm BE(2;0^+>2^+) = 4.26 e^2b^2, BE(2;2^+>4^+) = 2.13 e^2b^2, BE(2;4^+>6^+) = 1.99 e^2b^2, BE(4;0^+>4^+) = 0.23 e^2b^4, BE(6;0^+>6^+) = 0.07 e^2b^6, β_2 = 0.72 , β_4 = 0.06, Q = -1.3 b.

29) W. E. Frahn, Nucl. Phys. A302 (1978) 267.

30) F. C. Williams Jr., Nucl. Phys. A166 (1971) 231.

31) R. V. F. Janssens, J. F. W. Janssen, G. T. Emery, D. C. J. M. Hageman, and J. Lukasiak, Phys. Lett. 90B (1980) 209; K. Hardt, P. Schüler, C. Günther, J. Recht, and K. P. Blume, Nucl. Phys. A407 (1983) 127; T. Nomura, K. Hiruta, M. Yoshie, H. Ikezoe, T. Fukuda, and O. Hashimoto, Phys. Lett. 58B (1975) 273; D. Ward, G. D. Dracoulis, J. R. Leigh, R. J. Charity, D. J. Hinde, and J. O. Newton, Nucl. Phys. A406 (1983) 591.

32) R. F. Casten, E. R. Flynn, J. D. Garrett, O. Hansen, T. J. Mulligan, D. R. Bess, R. A. Broglia, and B. Nilsson, Phys. Lett. 40B (1972) 333.

33) J. Koenig, H. Bohn, T. Faestermann, P. Kienle, H.J. Körner, W. A. Mayer, D. Pereira, K. E. Rehm, and H. J. Scheerer, Phys. Rev. C24 (1981) 2076.

34) H. J. Wollersheim, unpublished.

35) K. E. Rehm, D. Frekers, T. Humanic, R. V. F. Janssens, T. L. Khoo, and W. Kutschera, Argonne National Laboratory, Physics Division Annual Report 1983, ANL-83-25, p. 91.

36) F. Rösel, H. M. Fries, K. Alder, and H. C. Pauli, Atom. and Nucl. Data Tables 21 (1978) 291.

37) J. van Klinken, S. J. Feenstra, and G. Dumont, Nucl. Instr. and Meth. 151 (1978) 433, and references therein.

Figure Captions

Fig. 1. Spectra of the $^{182}W(d,^{6}Li)$ and the $^{194}Pt(d,^{6}Li)$ reactions at E_d = 45 MeV. The indicated spins were taken from refs.[8,9].

Fig. 2. Left side: ground-state strengths for the $(d,^{6}Li)$ reaction on the even-A Se-, Mo-, Te-, and Sm-isotopes and ground-state reduced widths for the α-decay of the even-A polonium isotopes (see text). Data are plotted as a function of n, being the number of valence neutrons (particles or holes). All data are normalized for each chain of isotopes. Right side: ratio R_4 of the excitation energy of the 4_1^+ and the 2_1^+ state of the initial and final nuclei connected by solid and dashed lines, respectively.

Fig. 3. Left: $R_4 = E_x(4_1^+)/E_x(2_1^+)$ for even-A Sm isotopes. Right: Calculated ground-state to ground-state Q-values for the $^{A}Sm(^{58}Ni,^{59}Ni)$ reaction (squares indicate stable isotopes). Solid lines are drawn to guide the eye.

Fig. 4. Top: scatter plot of the ΔE versus $(B.\rho)^2/E_{tot}$ signals for the $^{154}Sm + ^{58}Ni$ reaction at θ_{lab} = 55° and E = 337.5 MeV; Bottom: projection of the scatter plot on the horizontal axis for Z = 28.

Fig. 5. Data points for the sum of elastic and inelastic scattering for ^{58}Ni on ^{144}Sm and ^{154}Sm, respectively. Curves are CCBA calculations performed with the code PTOLEMY using the indicated coupling scheme (see text). Dashed lines indicate the total cross section for inelastic excitation, dot-dashed that for pure elastic scattering, and the solid that for the sum of these two components, respectively.

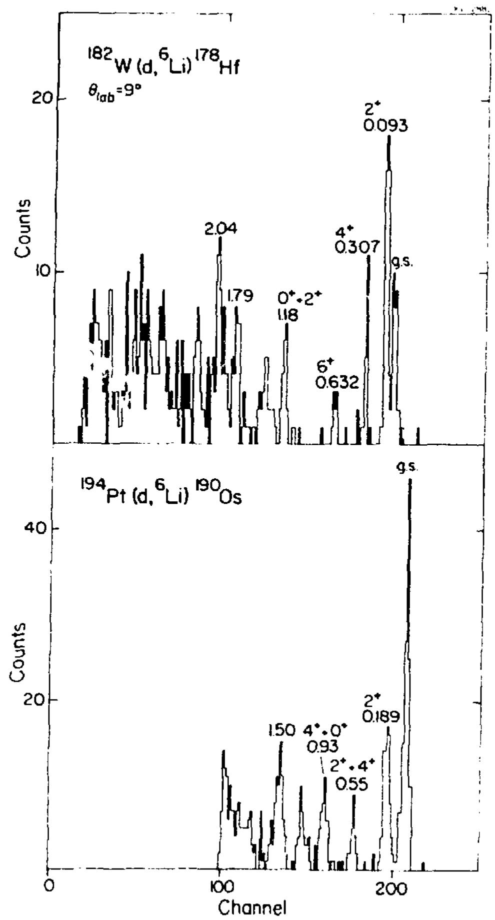
Fig. 6. Angular distributions for one- and two-neutron transfer reactions for ^{58}Ni on ^{144}Sm and ^{154}Sm, respectively. Solid lines are fits using a gaussian function that yields the angle-integrated reaction cross sections.

Fig. 7. Angle-integrated cross sections for quasi-elastic neutron transfer reactions induced by ^{58}Ni on ^{A}Sm isotopes. Solid lines connect points calculated with the code FAST[23)] and are normalized to the measured cross sections for the ^{154}Sm(^{58}Ni,^{59}Ni) reaction.

Fig. 8. Energy spectra for the ^{A}Sm(^{58}Ni,^{59}Ni) reaction at $\theta_{lab} = 47.5°$. Solid lines indicate calculated spectra (folded with the experimental energy resolution). For each reaction the calculated yield has been normalized to the experimental yield and the conversion to reaction Q-values and the Q_{gg} value (arrow) is shown in the figure.

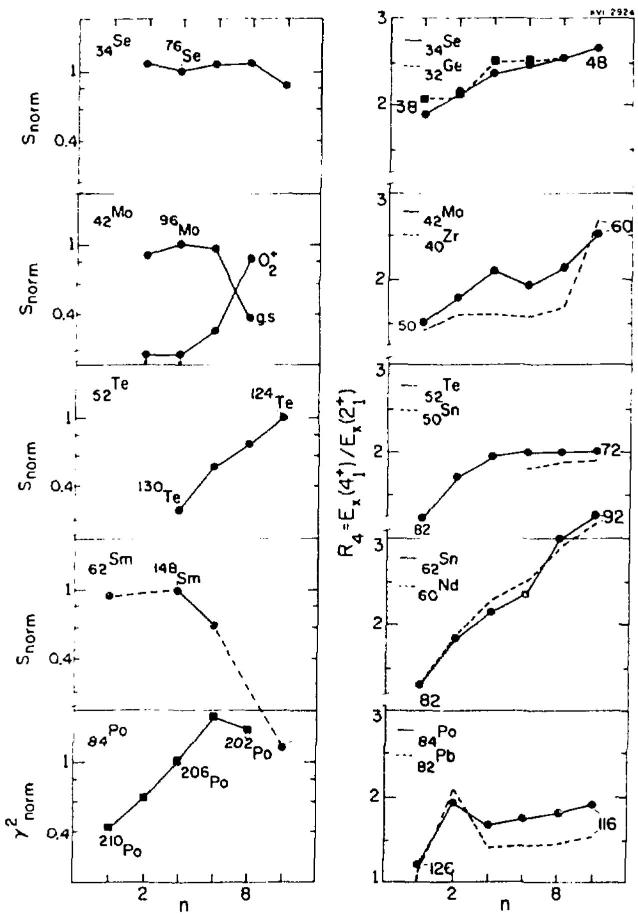
Fig. 9. Calculated[35)] values for coefficients of internal conversion for E2 γ-transitions leading to emission of K- and L-shell electrons. The solid line indicates the total internal conversion coefficient summed over all atomic subshells.

Fig. 10. Conversion-electron spectra for true (top) and random (bottom) coincidences with ^{16}O ions detected in the Enge split-pole spectrograph. Indicated are predicted positions for conversion-electron lines for the known transitions from the 6^+ to 4^+, the 4^+ to 2^+, and the 2^+ to the ground state in ^{234}Th, respectively (see inset).



^{182}W (d, ^{6}Li) ^{178}Hf
θ_{lab}=9°
Counts
2⁺
0.093
2.04
4⁺
0.307
g.s.
1.79
0⁺+2⁺
1.18
6⁺
0.632
^{194}Pt (d, ^{6}Li) ^{190}Os
g.s.
Counts
2⁺
0.189
1.50
4⁺+0⁺
0.93
2⁺+4⁺
0.55
Channel

Fig. 1



$_{34}$Se
^{76}Se
S$_{norm}$
$_{42}$Mo
^{96}Mo
0_2^+
g.s
$_{52}$Te
^{124}Te
^{130}Te
$_{62}$Sm
^{148}Sm
$_{84}$Po
^{206}Po
^{202}Po
^{210}Po
γ^2_{norm}
n
$R_4 = E_x(4_1^+)/E_x(2_1^+)$
$_{32}$Ge
$_{40}$Zr
$_{50}$Sn
$_{60}$Nd
$_{82}$Pb

Fig. 2

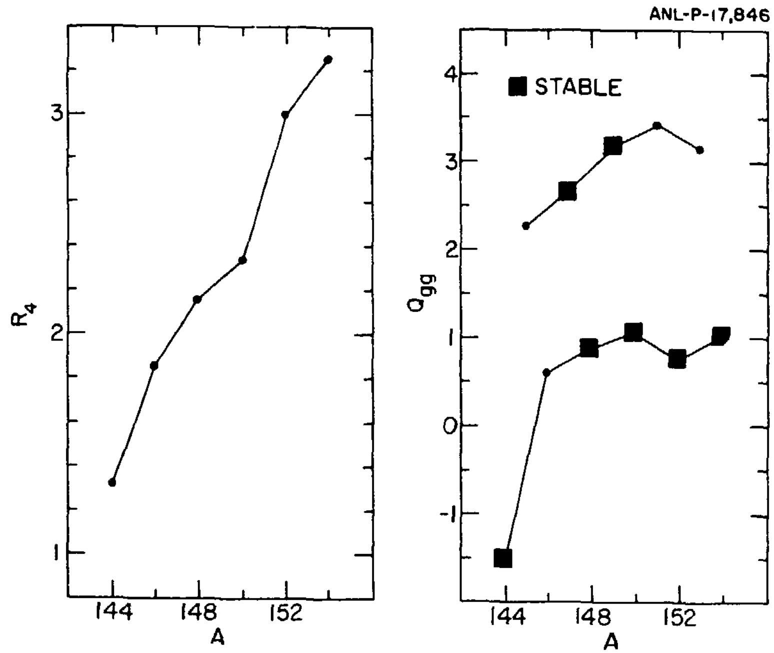


Fig. 3

Reduce to 4 1/4 inches wide

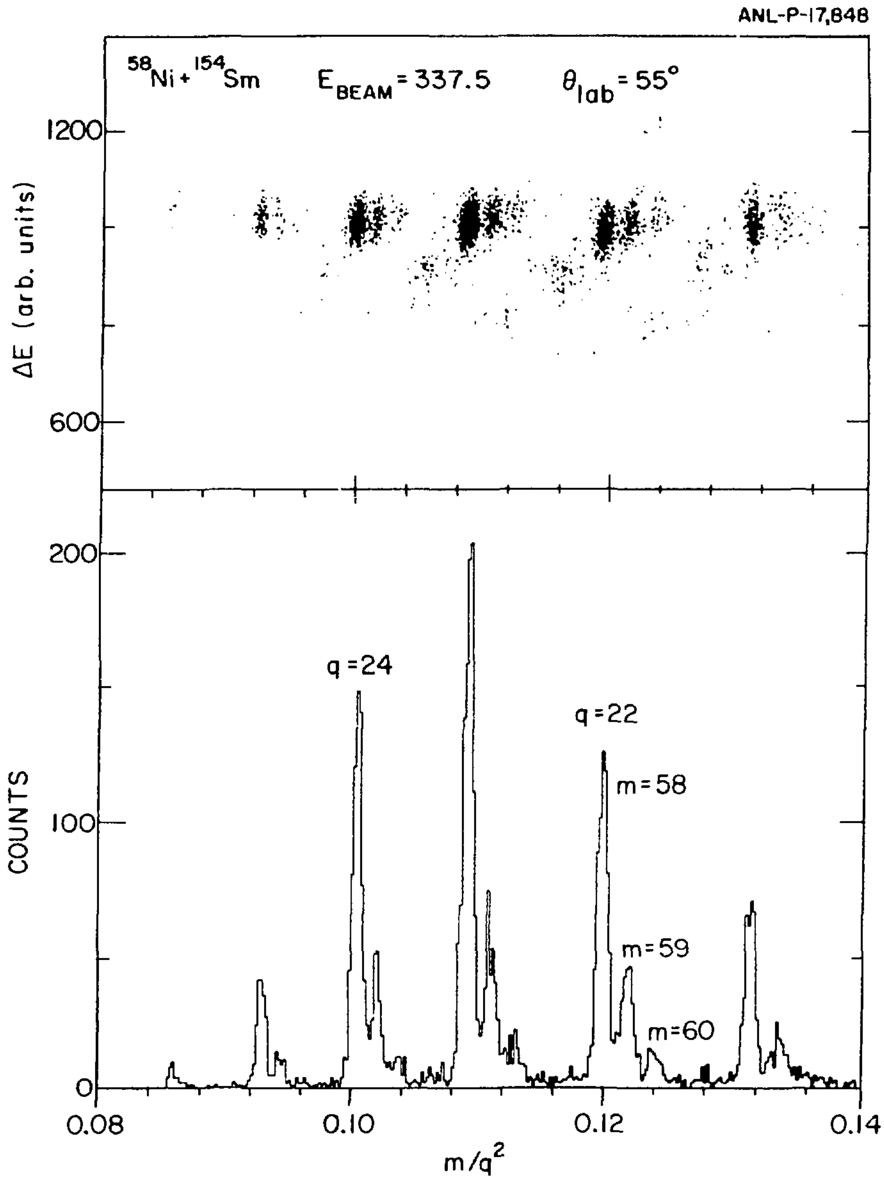

ANL-P-17,848
^{58}Ni + ^{154}Sm
E$_{BEAM}$ = 337.5
θ_{lab} = 55°
1200
600
ΔE (arb. units)
200
100
0
COUNTS
q = 24
q = 22
m = 58
m = 59
m = 60
0.08
0.10
0.12
0.14
m/q^2

Fig. 4

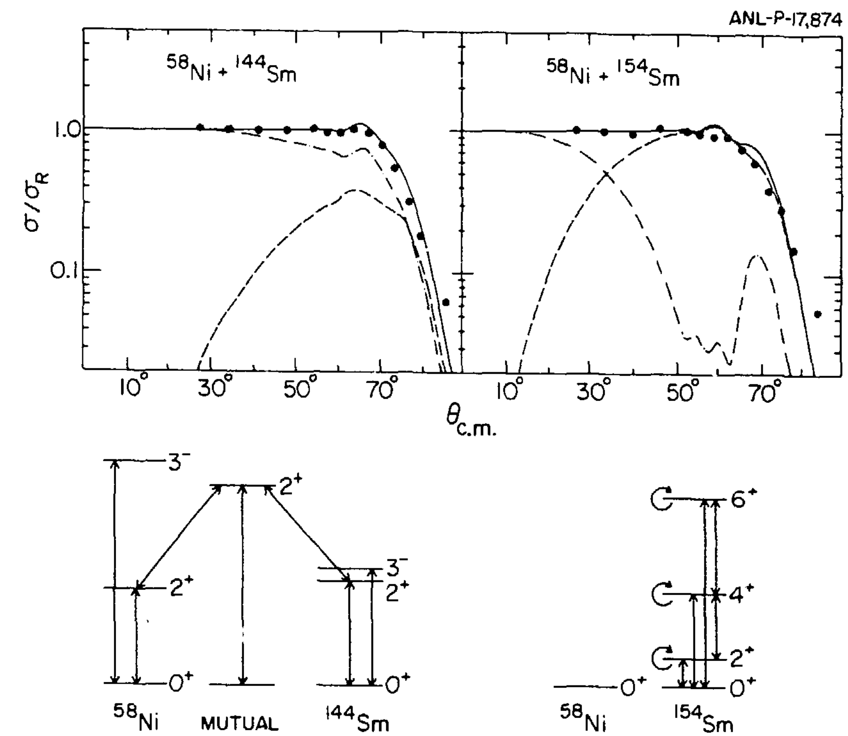

ANL-P-17,874
58Ni + 144Sm
58Ni + 154Sm
1.0
0.1
σ/σR
10°
30°
50°
70°
θc.m.
3⁻
2⁺
0⁺
58Ni
MUTUAL
144Sm
6⁺
4⁺
154Sm

Fig. 5

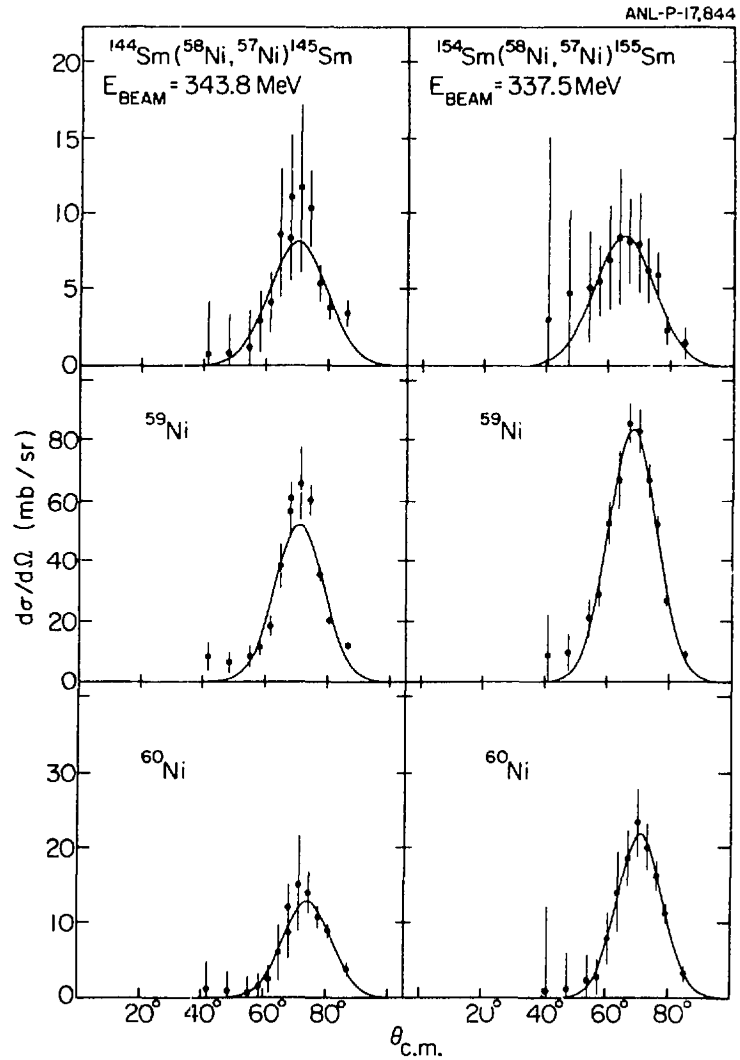

ANL-P-17,844
$^{144}Sm(^{58}Ni,^{57}Ni)^{145}Sm$
E_{BEAM} = 343.8 MeV
$^{154}Sm(^{58}Ni,^{57}Ni)^{155}Sm$
E_{BEAM} = 337.5 MeV
^{59}Ni
^{59}Ni
^{60}Ni
^{60}Ni
$d\sigma/d\Omega$ (mb / sr)
$\theta_{c.m.}$

Fig. 6

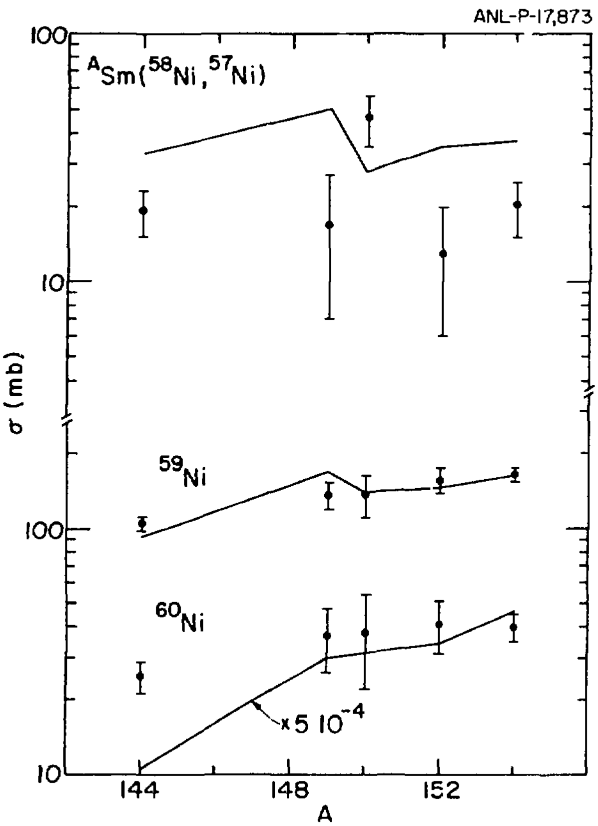

ANL-P-17,873
ASm(58Ni, 57Ni)
59Ni
60Ni
x5 10-4
100
10
100
10
σ (mb)
144
148
152
A

Fig. 7

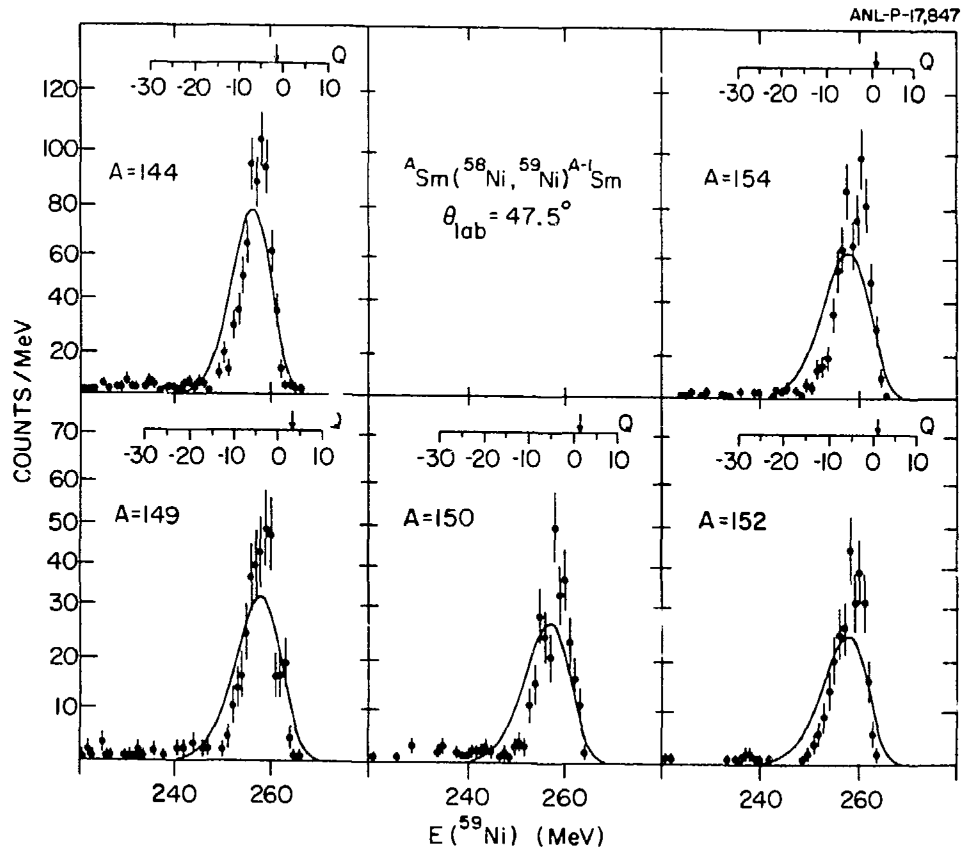

ANL-P-17,847
COUNTS/MeV
A=144
A=154
A=149
A=150
A=152
$^{A}Sm(^{58}Ni, ^{59}Ni)^{A-1}Sm$
$\theta_{lab} = 47.5°$
Q
-30 -20 -10 0 10
240 260
E(^{59}Ni) (MeV)

Fig. 8

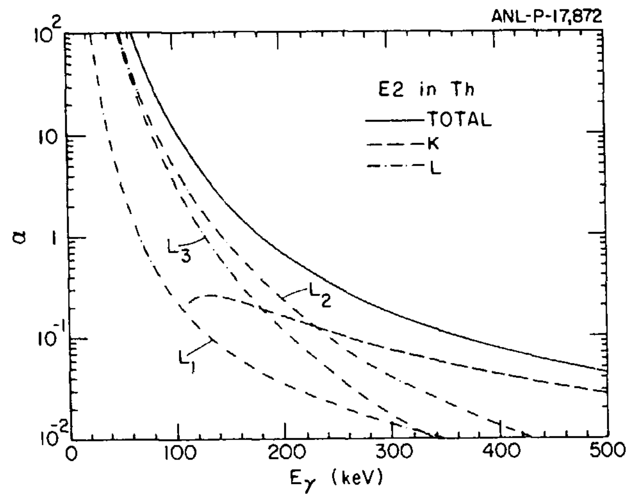
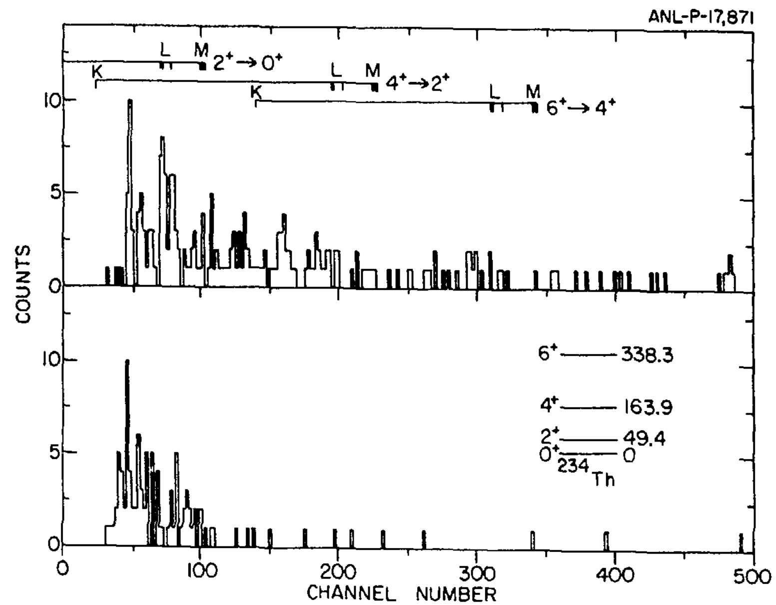

ANL-P-17,872
E2 in Th
TOTAL
K
L
L3
L2
L1
α
10^2
10
1
10^-1
10^-2
0
100
200
300
400
500
Eγ (keV)

Fig. 9



ANL-P-17,871
L M 2⁺→0⁺
K L M 4⁺→2⁺
K L M 6⁺→4⁺
COUNTS
10
5
0
6⁺ 338.3
4⁺ 163.9
2⁺ 49.4
0⁺ 0
234 Th
0
100
200
300
400
500
CHANNEL NUMBER

Fig. 10