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Groening, H.

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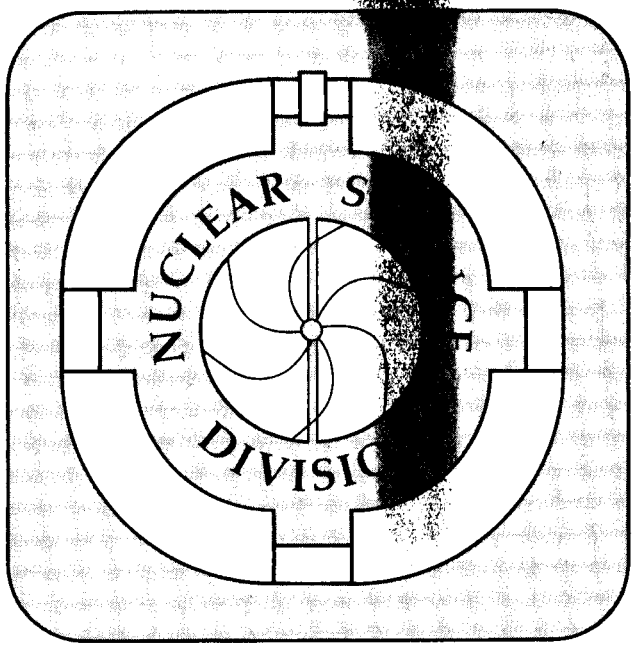

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DISCLAIMER

ISOMER RATIO MEASUREMENTS FOR THE REACTION

$^{29}Si(^{18}O,p2n)^{44}Sc^{m},^{44}Sc^{g}$

H. Groening,* K. Aleklett,** K. J. Moody, P. L. McGaughey, W. Loveland,***

and G. T. Seaborg

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

* On leave from Universidad Simón Bolívar, Caracas, Venezuela
** Present address: Studsvik Science Res. Lab. S-611 82 Nyköping, Sweden
*** Present address: Radiation Ctr., Oregon State Univ., Corvallis OR 97331

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Lawrence Berkeley Laboratory, University of California, Berkeley CA 94720

ABSTRACT

Isomer ratios for the reaction $^{29}Si(^{18}O,p2n)^{44}Sc^{m},^{44}Sc^{g}$ have been deduced from the activity measurements for projectile energies between 30 and 99 MeV. Statistical model calculations show that the isomer ratio dependence on projectile energy up to about 80 MeV can be adequately described by assuming a fixed ratio of quadrupole to dipole gamma-ray strengths. Such a ratio of E2/E1 strengths agrees substantially well with corresponding values deduced from the literature. The values of the gamma-ray strength ratios needed to fit the experimental isomer ratios are extremely sensitive to the relative amounts of quadrupole gamma-ray admixture and to the presence of discrete levels other than those which conform to the yrast line.

KEY WORDS

NUCLEAR REACTIONS $^{29}Si(^{18}O,p2n)$, E = 30-99 MeV; measured relative $\sigma(E)$ for pairs of isomeric states. Enriched targets.

1. INTRODUCTION

During the last twenty years, many studies have been made of nuclear reactions in which nuclear isomers are produced. In general, isomer ratios have been used to predict properties of nuclei such as

* On leave from Universidad Simon Bolivar, Caracas, Venezuela
** Present address: Studsvik Science Res. Lab. S-611 32 Nyköping, Sweden
*** Present address: Radiation Ctr., Oregon State Univ., Corvallis OR 97331

spin cutoff parameters and relative strengths of quadrupole to dipole radiation. Perhaps most importantly, they have been used to test the general theory of compound nuclear reactions.

The first serious attempt to state in theory a way to determine the angular momenta of capturing states in nuclear reactions by measuring isomer ratios was carried out by Vandenbosch and Huizenga.[1,2] In 1962, Grover[3] tried to extend the theory of the compound nucleus to determine the functional variation of the energy level density with excitation energy by introducing effective competition between particle emission and gamma-ray decay after compound nucleus formation. Equally important, Grover introduced the concept of the yrast level and demonstrated the necessity of accounting properly for such levels in determining isomeric yields.

In 1967, Grover and Gilat[4,5,6] derived a formalism to calculate relative probabilities of formation of the ground and excited states in heavy ion compound nuclear reactions, explicitly accounting for the different types of particle decay, as well as gamma-ray emission. Their work also focused on the importance of considering properly not only the dipole part of the gamma-ray spectrum, but also the quadrupole contribution, particularly near the yrast region of the energy-angular momentum plane. This last point was also considered in detail by Sperber and Mandler[7] the following year.

Liggett and Sperber[8] calculated values of spin cutoff parameters and also the relative amounts of quadrupole admixture in several intermediate mass systems, by fitting isomer ratios as a function of projectile energy. Isomer ratios also offer some hope in contributing to the understanding of the mechanism of angular momentum transfer between projectile and target in high energy heavy ion nuclear reactions. The

reason for this is that a key to such mechanisms could perhaps be provided by the initial angular momentum distributions of the reaction products, and isomer ratios are expected to reflect such distributions.[9] The initial population distribution in the evaporation residues prior to most of the γ-ray emission can be approximately inferred if the evaporation residues have isomeric pairs whose spins are significantly different, and if no important side feeding from other species occurs in their decay.

^{44}Sc is a product formed in many high energy heavy ion nuclear reactions, and has the advantages that we have just mentioned. It is quasi-shielded; the ground state has spin and parity of 2+, while the 0.27 MeV isomeric state is a 6+ level. Isomer ratios involving ^{44}Sc have been extensively studied in photonuclear reactions,[10,11] and in systems involving projectiles of relatively low mass[12,13,14,15,16,17] or energies.[18]

In the present work, we wish to report on the results of measuring the independent yield isomer ratios in the reaction ^{29}Si(^{18}O,p2n) ^{44}Sc^{m},^{44}Sc^{g} at projectile kinetic energies of 30, 40, 50, 58.5, 70, 80, 87, and 99 MeV. We will discuss the results of our attempts to fit the isomer ratio dependence on projectile energy with essentially one parameter, i.e., the ratio of quadrupole to dipole gamma-ray strengths in the γ-ray de-excitation of the residual nuclei. In a subsequent paper, we will discuss the reliability of using the ^{44}Sc isomer ratios in inferring energy-angular momentum distributions of evaporation residues.

2. EXPERIMENTAL

The targets used in this experiment consisted of 90 to 100 μg/cm^2

$^{29}SiO_2$ evaporated onto 1.9 cm diameter, .013 mm thickness Ta foil backings. Each target was irradiated with an ^{18}O beam of one of eight energies (30, 40, 50, 58.5, 70, 80, 87, and 99 MeV), which was provided by the Lawrence Berkeley Laboratory 88-inch cyclotron. The length of the irradiation period varied between 45 and 60 minutes. The Sc nuclei produced by the reaction recoiled into the Ta backing and were stopped. Their subsequent decays were measured after the end of the irradiation by gamma-ray spectroscopy using a Ge(Li) detector.

For beam energies above 70 MeV, the ^{18}O projectile energy exceeded the coulomb barrier of the Ta target backing, allowing the production of activities with large cross-sections that obscured those of interest. Therefore, a chemical separation was performed to isolate the Sc activities from the targets bombarded with the three highest energy beams. The chemical separation technique involved coprecipitation of Sc with LaF_3. Each target was placed in 0.25 ml of a 4:1 mixture of concentrated HF and HNO_3, with HNO_3 added dropwise until dissolution was complete. This solution was diluted to approximately 5 ml with H_2O, then 0.20 ml of La carrier solution (10 mg/ml La as $La(NO_3)_3$ in H_2O) was added. The solution was heated briefly, then cooled in ice, and the resultant precipitate was filtered out on a nitrocellulose filter, where it was washed with an aqueous solution 2 molar in HCl and HF. The precipitate was then mounted for counting.

$^{44}Sc^g$ ($J,\pi = 2+$, $T_{1/2}$ = 3.927 hour) decays by positron emission and by electron capture, emitting an 1157 keV gamma-ray with a 99.89% abundance.[19] $^{44}Sc^m$ ($J,\pi = 6+$, $T_{1/2}$ = 2.442 day) decays primarily (98.61%) to $^{44}Sc^g$ by isomeric transition and internal conversion with the emission of a 271 keV gamma-ray with an abundance of 86.6%. There is a weak electron capture branch (1.37%) to the excited states of

^{44}Ca which in turn emit the 1157 keV gamma-ray. Thus, by performing a standard analysis of the decay curve associated with the 1157 keV transition, the activity of each member of the isomer pair at the end of the irradiation was calculated. Using these activities and correcting for growth and decay during the irradiation and for the branching ratios to each decay mode, the final isomer ratios were computed. These are presented in Table I and Fig. 1.

The measured isomer ratio varies strongly with the incident ^{18}O projectile energy. It rises approximately linearly in the interval from 30 to 50 MeV. As the projectile energy continues to increase, the isomer ratio reaches a maximum value of approximately 5.5 between the energies of 70 and 80 MeV. Above 87 MeV it decreases sharply with increasing energy.

3. THEORETICAL FRAMEWORK AND ANALYTICAL PROCEDURE

We have attempted to understand our experimental data in terms of a standard statistical model calculation of the projectile energy dependence of this isomer ratio. For practical purposes, our calculations were divided into two major parts. The first part is concerned with the formation of the compound nucleus and the subsequent statistical evaporation in which neutrons, protons, α-particles and dipole γ-rays are emitted until a population distribution for ^{44}Sc has been formed. The second part of the calculation consists of selecting the portion of this ^{44}Sc population lying between the yrast line and roughly one neutron binding energy above it (the entry line) and simulating its decay by γ-ray emission until no levels other than the isomeric and ground states have been left populated. Notice that in doing this we have assumed that there is no particle emission below what we have defined as the entry line. Later, when we discuss the emission of

γ-rays from the evaporation residues, the validity of this assumption will be addressed.

3.1 COMPOUND NUCLEUS AND DECAY

In performing the evaporation calculation, we have made use of the computer code "ALERT," which was kindly made available to us by Dr. Marshall Blann. "ALERT" has been extensively described elsewhere,[20] and, therefore, we will only review briefly some of its important features.

The cross section for formation of the initial compound nucleus in heavy ion fusion reactions is given by the expression:

$$\sigma^{cn} = \sum_I \sigma(I) = \pi\lambda\!\!\!^{-2} \sum_I (2I+1) T_I \qquad (1)$$

where $\sigma(I)$ is the initial compound nucleus spin distribution. T_I represents the transmission coefficient for fusion by the Ith partial wave of the projectile and $\lambda\!\!\!^{-}$ is the reduced wave length of the latter. The transmission coefficients for fusion are calculated by assuming that the barrier has the shape of an inverted parabola, according to the formalism introduced by Thomas.[21]

The probability of emitting a particle of type ν with kinetic energy between ε and $\varepsilon+d\varepsilon$, and from a compound nucleus with angular momentum I is given by the Hauser-Feshback-type expression:

$$P_\nu(\varepsilon,I)d\varepsilon = \frac{(2s_\nu+1) \sum_{\ell=0}^{\infty} T_\ell^\nu(\varepsilon) \sum_{J=|I-\ell|}^{I+\ell} \rho(E,J)d\varepsilon}{\int_{\varepsilon=0}^{\infty} \sum_{\nu=1}^{n} (2s_\nu+1) \sum_{\ell=0}^{\infty} T_\ell^\nu(\varepsilon) \sum_{J=|I-\ell|}^{I+\ell} \rho(E,J)d\varepsilon} \qquad (2)$$

where the symbols are defined in Table II. The level densities $\rho(E,J)$ are evaluated according to the expression proposed by Lang.[22]

$$\rho(E,J) \propto (2J+1)\,[E - E_y(J)]^{-2} \exp 2\sqrt{a[E-E_y(J)]} \qquad (3)$$

where $[E - E_y(J)]$ represents the excitation energy above the yrast level of spin J and "a" represents the familiar level density parameter. In practice, the $[E - E_y(J)]^{-2}$ term in the level density expression is written as $[E - E_y(J) + 1]^{-2}$ to keep it from giving unrealistically high values of the level densities at energies near the yrast line.

The $E_y(J)$ quantities in this program are taken as the ground state rotational energies which are calculated from the rotating liquid drop model.[23] Binding energies and values are generated by using the Myers-Swiatecki-Lysekil[24] mass formula. Transmissions coefficients for particle emission are calculated from standard global optical model parameters, although as an option they can also be read in by the user.

3.2 THE EVAPORATION-RESIDUE. TREATMENT OF THE GAMMA-RAYS

The population distributions calculated following decay from the compound nucleus will look schematically as shown in Fig. 2, where the contour lines define regions of equal population in the E-J plane. We have assumed that the portion of the population which will eventually decay to either the ground or the isomeric states in ^{44}Sc is that which lies under the entry line. As we shall see, this simplification can be safely made in regions where the yrast line is not too steep; in other words, in regions of relatively low angular momentum. This assumption becomes worse for higher values of the spin, particularly in the case of "non-rotational" nuclei.

The population distributions given by the code "ALERT," restricted by the condition imposed by the entry line, are fed into the computer code "GAMMA," which simulates the process of γ-ray decay. "GAMMA" takes the population of each E-J bin and allows it to decay statistically to all other possible bins by assuming that γ-rays can only be

dipole or quadrupole. The code incorporates all low lying discrete energy levels, as well as the higher energy "statistical levels" with average populations. Angular momentum and parity are conserved in the calculation by accounting for the spin and parities of the discrete levels and by assuming that in the statistical region of the level density both parities occur with equal probabilities.

The statistical transition rate from state "i" to state "f" for radiation of multipolarity λ and energy E_γ is given by:[25]

$$T(i \rightarrow f;\sigma\lambda) \propto |M_{if}(\sigma\lambda)|^2 \frac{\rho(E_f - E_\gamma)}{\rho(E_i - E_\gamma)} E_\gamma^{2\lambda+\alpha} \qquad (4)$$

where $\rho(E)$ is given by Equation (3). Here σ represents the nature of the radiation, electric or magnetic, and M_{if} is the reduced transition matrix element. α represents a factor whose value has been theoretically shown to be 2, but whose value has been measured[27] between 1 and 2. In our calculations α has been set equal to 1. In practice, the input parameters used in the calculations are the ratios $R(\sigma\lambda)$ defined as:

$$R(\sigma\lambda) \equiv \frac{|M_{if}(\sigma\lambda)|^2}{|M_{if}(E1)|^2 + |M_{if}(M1)|^2 + |M_{if}(E2)|^2} \qquad (5)$$

M2 probabilities have arbitrarily been set 100 times smaller than corresponding values for E2 transitions.

The yrast line in this part of the calculation is defined according to the following criteria: At low regions of spin, $J \leq 7$, the yrast line consists of the known discrete levels for ^{44}Sc; for higher spins, the former non-uniform low J line joins with the more uniform and smooth line defined by the rotating liquid drop model used in the previous calculation with "ALERT."

4. CALCULATIONS AND DISCUSSION OF RESULTS

One of the main advantages that the "ALERT" code presents is that it requires a minimum set of input parameters in performing the statistical evaporation calculation. The only parameter of importance whose effect was tested in the calculation was the exponential level density parameter "a." No significant changes in the calculated excitation functions were seen for variations in "a" between 4.4 and 10.0. Only slight shifts in the position of the peaks to higher energies are seen with decreasing values of "a."

Fig. 3 shows fits to the isomer ratio values as a function of ^{18}O kinetic energy for different sets of R(E2) values. We have chosen to consider in this calculation only the points between 30 and 80 MeV. Although there is no *a priori* reason for not considering energies above 80 MeV, we are limited by the increasing sensitivity of the calculation to the position of the entry line. The simple assumption that only γ-ray emissions will take place below a line one neutron binding energy above the yrast band begins to fail at 80 MeV and above. In other words, in the higher energy region it becomes increasingly difficult to determine just where in the E-J plane a line defining the onset of significant particle emission should lie for high values of the angular momentum, such as those populated at high energies in this particular heavy ion reaction. This problem is important in this particular mass region (A~40) because the low nuclear moments of inertia are responsible for a steep yrast line which favors particle emission from comparatively lower values of the spin J.

The fits to the experimental points shown in Fig. 3 are for different combinations of the reduced transition probabilities R(E1,M1) and R(E2), where R(E1,M1) is defined as the sum of R(E1) and R(M1). The proportions of R(E1) and R(M1) in R(E1,M1) are not important in our

calculations. Our tests show that isomer ratios are not sensitive to such proportions as long as the dipole fraction R(E1,M1) remains constant. The best fit of the calculations to the experimental data is for a strength ratio:

$$\frac{R(E2)}{R(E1,M1)} = \frac{|M_{if}(E2)|^2}{|M_{if}(E1)|^2 + |M_{if}(M1)|^2} = \frac{3}{97} \qquad (6)$$

Isomer ratios seem to be quite sensitive to the values of the gamma-ray strength ratios, particularly at the higher energy points. An increase in the quadrupole/dipole strength ratio decreases the isomer ratio. We can expect "stretched" E2 transitions to have a better chance of reaching those levels closer to the ground state than dipole transitions, thus increasing the probability of it being populated.

We would now like to address the question as to how the ratios of the reduced transition probabilities $|M_{if}(E2)|^2/|M_{if}(E1,M1)|^2$ extracted from this work compare with other experimental findings. For this purpose, we find it convenient to refer to the tables of gamma-ray strengths published by Endt.[28] The transition strengths are given in Weisskopf units[29] (W.u.) for the mass region in question; recommended upper limits and our estimated averages are listed in Table III. The average strength ratio is given as

$$\frac{|M_{if}(E2)|^2}{|M_{if}(E1,M1)|^2} \sim 0.02 \qquad (7)$$

This number is reasonably consistent with an equivalent ratio of about 0.03 estimated from the isomer ratio data. The ratio calculated from the upper limits is about 2.5×10^{-4}, which is clearly unreasonable as should be expected.

An interesting comparison can also be made with the results obtained by Saranties and Hoffman[30] for ^{61}Cu and ^{60}Ni. They proceeded to fit experimental cross sections for populating different levels in the two nuclides through the reactions ^{58}Ni(α,pγ) and ^{58}Ni(α,2pγ) by varying the rate of approach to rigidity of the moment of inertia with excitation energy along with the enhancement and retardation factors over single particle estimates for dipole and quadrupole γ-ray emission. The fraction of R(E2) in the γ-ray de-excitation process which they were able to extract corresponds to about 11%. Despite the fact that both systems are essentially statistical, as is the case of ^{44}Sc, we expect lower values of the quadrupole fraction in Sc because dipole strengths decrease significantly with increasing mass number, while non-collective quadrupole strengths tend to remain relatively constant with A. As the mass number increases and nuclei begin to be deformed, much larger values of the quadrupole strengths are needed in order to fit the experimental data in similar type statistical model calculations. A quadrupole strength of about 50 W.u. is already needed, for example, in the case of ^{72}Se formed in the ^{58}Ni(^{18}O,2p) reaction.[31]

A corollary of the results that we have so far described is that, for the range of energies studied, reduced transition matrix elements do not seem to vary with the energy of the transition. Although admittedly our calculated results are model dependent, it is nevertheless illustrative to show graphically how the quadrupole portion of the gamma-ray spectrum affects the decay process in the evaporation residue ^{44}Sc. Fig. 4 is a diagram of the calculated preferential gamma-ray decay paths in the region between the yrast and entry lines. As can be seen from the graph, the decay from any particular higher energy region to the yrast line would seem to be, on the average, a one or two step process. Once the yrast line is reached, decay goes parallel to it, preferentially

in quadrupole steps. It seems obvious that at spins somewhat higher than that of the isomer, most of the population will gather at the yrast line. The appropriate quadrupole contribution has the effect of preventing the population in question from overfeeding the isomeric state.

We now finally address the question of the importance of accounting for the discrete levels in the ^{44}Sc evaporation residue when calculating the isomer ratio. As has been the case of other authors[8] treating different systems, our results show that proper accounting of such levels is of vital importance in determining isomer ratios. Fig. 5 shows the behavior of the calculated isomer ratio in ^{44}Sc when the discrete levels of ^{44}Sc are neglected in the calculation. These results were obtained using the original set of quadrupole to dipole gamma-ray ratios of reduced transition probabilities. Neglecting levels other than the yrast line causes the isomer ratio to increase very rapidly with energy. The basic reason behind this result is that the additional levels between the isomeric and ground states act as "liaisons," and contribute to "pass" populations from high to low angular momentum regions. An absence of such levels results in a blocking effect which makes high spin populations finally decay overwhelmingly into the isomeric state, thereby increasing the isomer ratio.

5. CONCLUSIONS

From the preceding analysis of the ^{29}Si(^{18}O,p2n)^{44}Sc^{m},^{44}Sc^{g} reaction, it can be concluded that the statistical theory is most suitable for a detailed representation of the process involved.

We have been able to reproduce substantially well the isomer ratio dependence on energy with a minimum of parameterization. Basically, the only parameter varied in the calculation has been the ratio

of quadrupole to dipole γ-ray strengths. Such a parameter was left constant for all energies considered. The value obtained for this parameter agrees remarkably well with the corresponding one extracted from gamma-ray strength tables in the literature and does not seem to be either energy or spin dependent within the range of energies considered.

For the system in question, the isomer ratio is very sensitive to the amount of quadrupole admixture, particularly when bombarding energies are high and regions of high spin are populated in the reaction. Increasing the ratio of quadrupole to dipole reduced transition probabilities results in decreasing values of the isomer ratio.

Finally, the isomer ratio calculated using the formalism described here is very sensitive to the presence of discrete levels other than the ones which conform to the yrast line. The inclusion of other levels with spins between that of the isomer and that of the ground state contribute to decreasing the isomer ratio.

6. ACKNOWLEDGEMENTS

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TABLE I

Isomer Ratios in the Reaction $^{29}Si(^{18}O,p2n)^{44}Sc^{m},^{44}Sc^{g}$

^{18}O energy (MeV)	$\sigma_{isomer}/\sigma_{ground\ state}$
30	0.97 ± 0.02
40	2.44 ± 0.04
50	3.91 ± 0.05
58.5	4.66 ± 0.13
70	5.33 ± 0.15
80	5.32 ± 0.44
87	5.23 ± 0.22
99	3.61 ± 0.43

TABLE II

Definition of Symbols Used

T_ℓ, $T_\ell(\varepsilon)$, $T_\ell^\nu(\varepsilon)$	Transmission coefficient; for channel energy ε for particle type ν and orbital angular momentum $\ell\,\hbar$.
$P_\nu(\varepsilon,I)d\varepsilon$	Probability of emitting particle type ν with channel energy ε to $\varepsilon + d\varepsilon$ from compound nucleus of angular momentum I.
s_ν	Intrinsic spin of particle ν.
E	Residual nucleus excitation.
J	Residual nucleus angular momentum.
ℓ	Orbital angular momentum of captured or emitted particle.
$\rho(E,J)$	Level density of nucleus at excitation energy E and angular momentum J.
a	Level density paramater; value used in this work is $A/8\ MeV^{-1}$

TABLE III

Gamma-Ray Strengths for T-allowed Transitions

in Weisskopf Units (W.u.)

Transition Type	Average Strength	Recommended Upper Limit
E1	0.0002	0.1
M1	0.1	10
E2	8	100

Figure Captions

Fig. 1. Isomer ratios as a function of ^{18}O laboratory energy for the reaction $^{29}Si(^{18}O,p2n)^{44}Sc^{m},^{44}Sc^{g}$. Error bars are not indicated at points where they are smaller than circle size. (XBL 818-11293)

Fig. 2. Schematic diagram illustrating typical population distributions in the E-J plane for a nuclide near the yrast line, prior to most of the gamma ray emission. Contours represent lines joining points of equal populations. (XBL 818-11299)

Fig. 3. Calculated fits to the experimental isomer ratios for the reaction $^{29}Si(^{18}O,p2n)^{44}Sc^{m},^{44}Sc^{g}$, using different values of the ratios R(E1,M1); R(E2). (XBL 818-11296)

Fig. 4. Average preferential gamma ray decay paths in the E-J plane for different points under the entry line, as calculated for ^{44}Sc.* (XBL 818-11353)

Fig. 5. Fits to the isomer ratio dependence on ^{18}O energy for the reaction $^{29}Si(^{18}O,p2n)^{44}Sc^{m},^{44}Sc^{g}$, in which the effect of an accounting for all discrete levels is illustrated. The solid line represents the calculation that includes no discrete levels except for the yrast. The dashed line includes all known discrete levels. (XBL 818-11292).

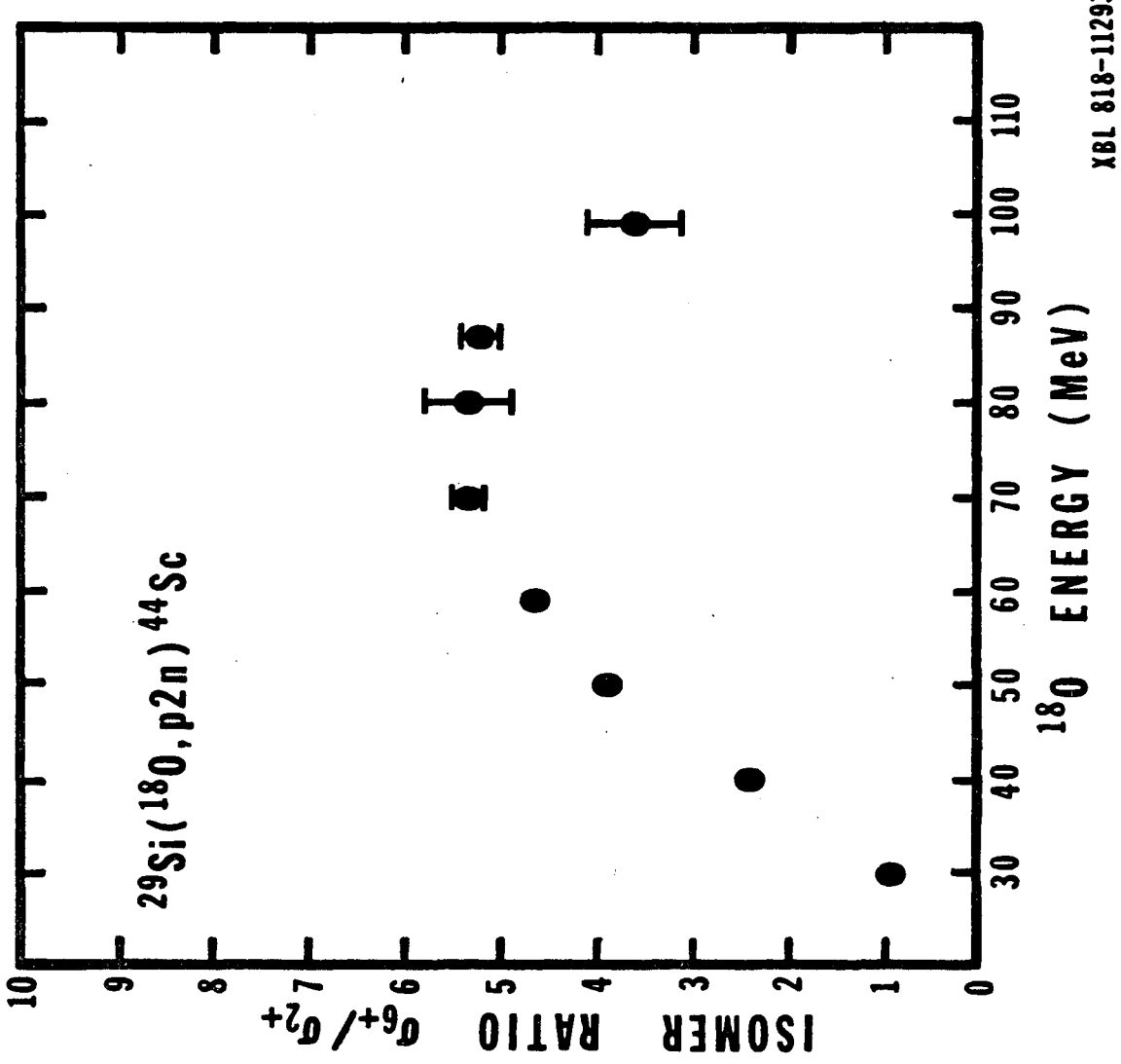
$^{29}Si(^{18}O,p2n)^{44}Sc$
ISOMER RATIO σ_{6+}/σ_{2+}
^{18}O ENERGY (MeV)
XBL 818-11293

Fig. 1

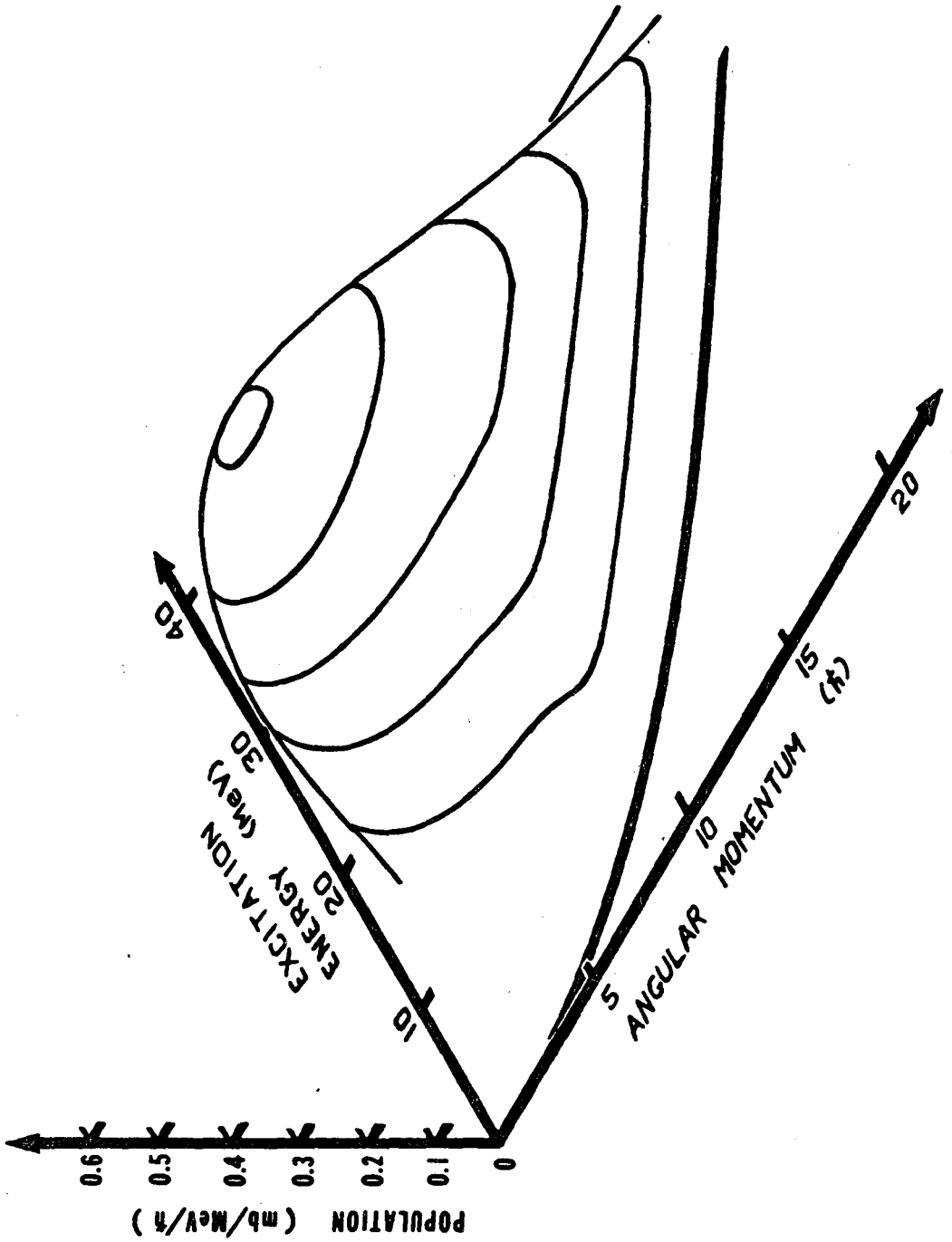
80 MeV $^{18}O + ^{29}Si$ transient ^{44}Sc population
EXCITATION ENERGY (MeV)
ANGULAR MOMENTUM (ħ)
POPULATION (mb/MeV/ħ)
0
0.1
0.2
0.3
0.4
0.5
0.6
10
20
30
40
5
10
15
20
XBL 818-11299

Fig. 2

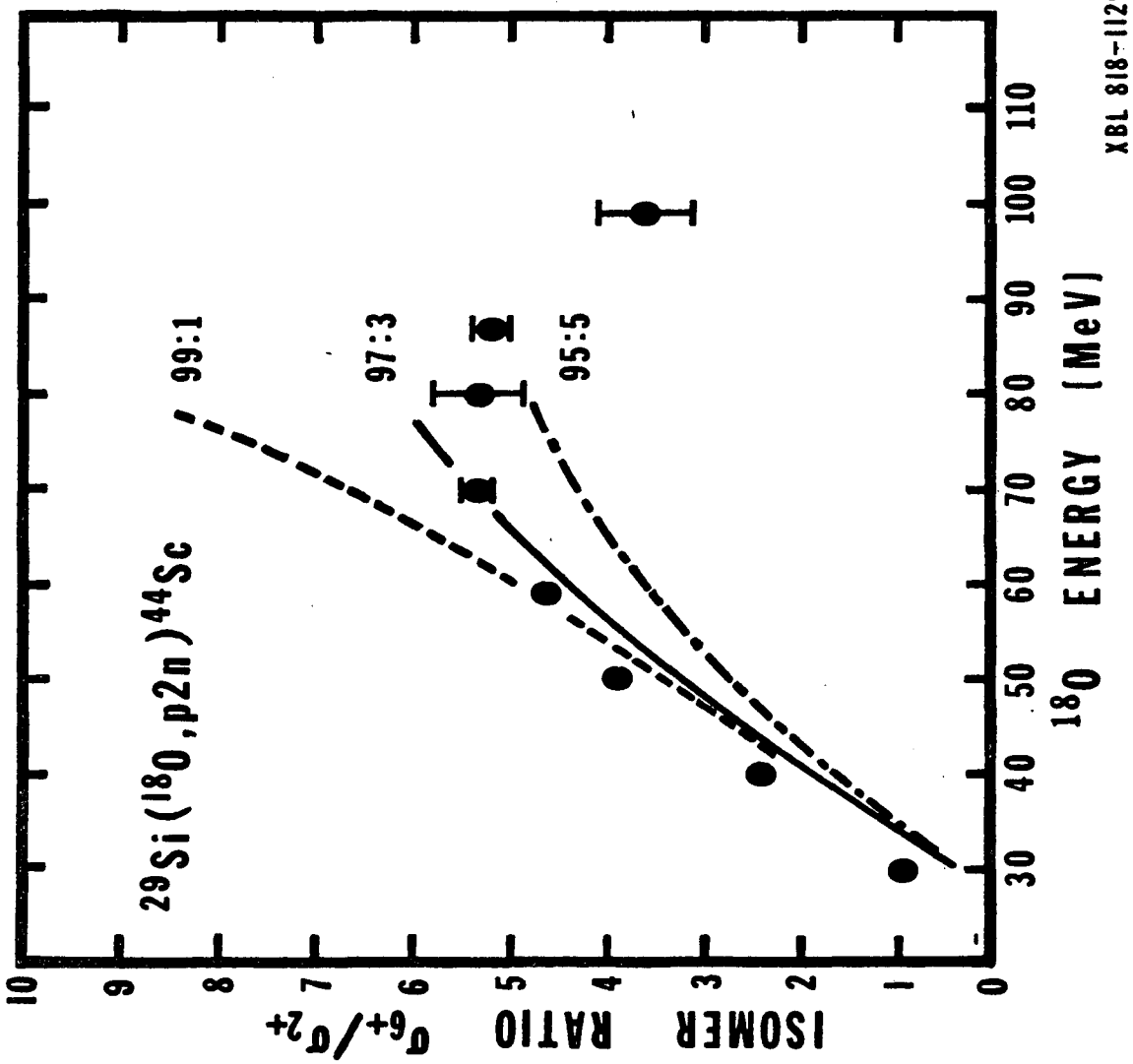

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Fig. 3

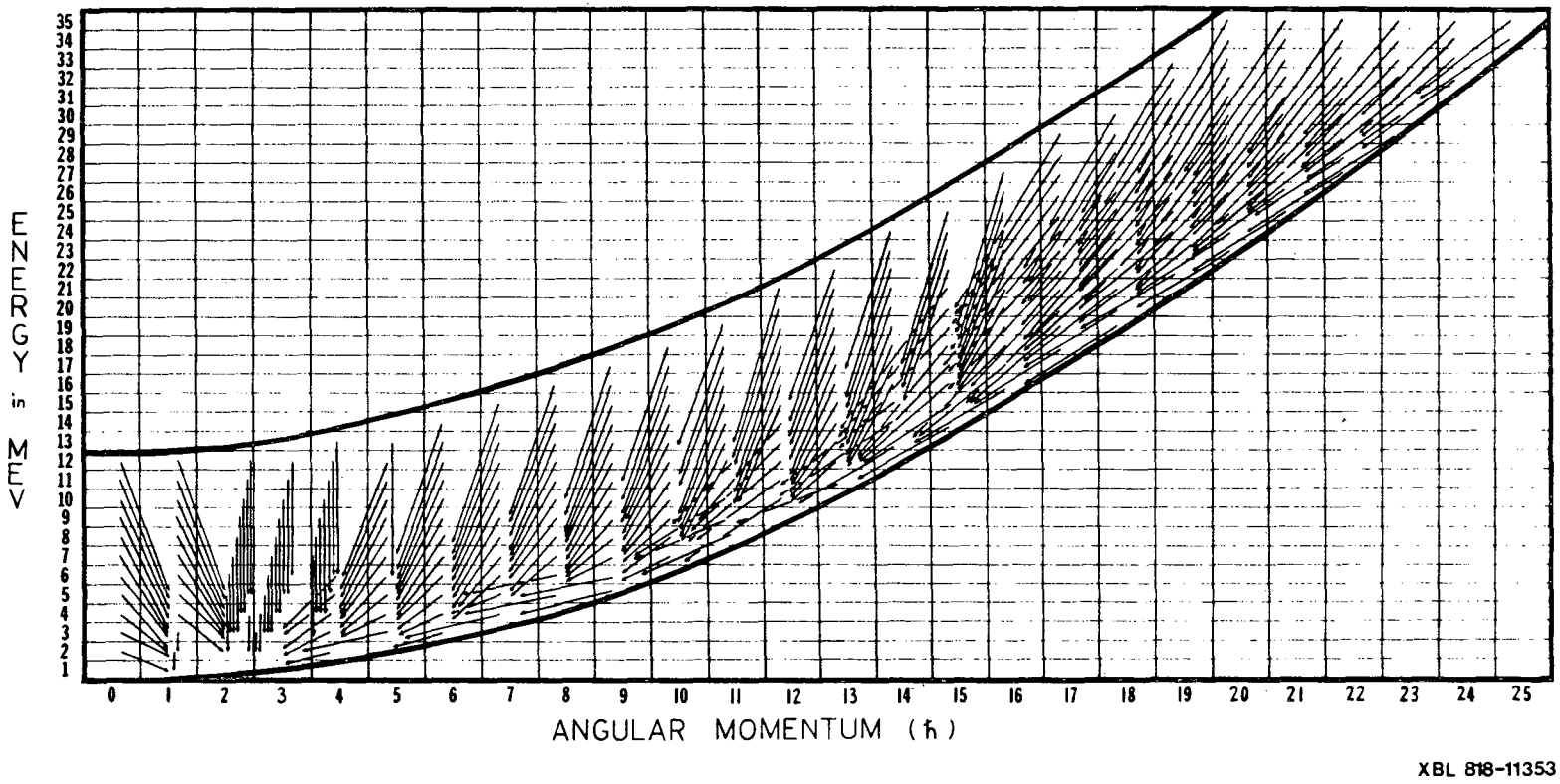

Fig. 4

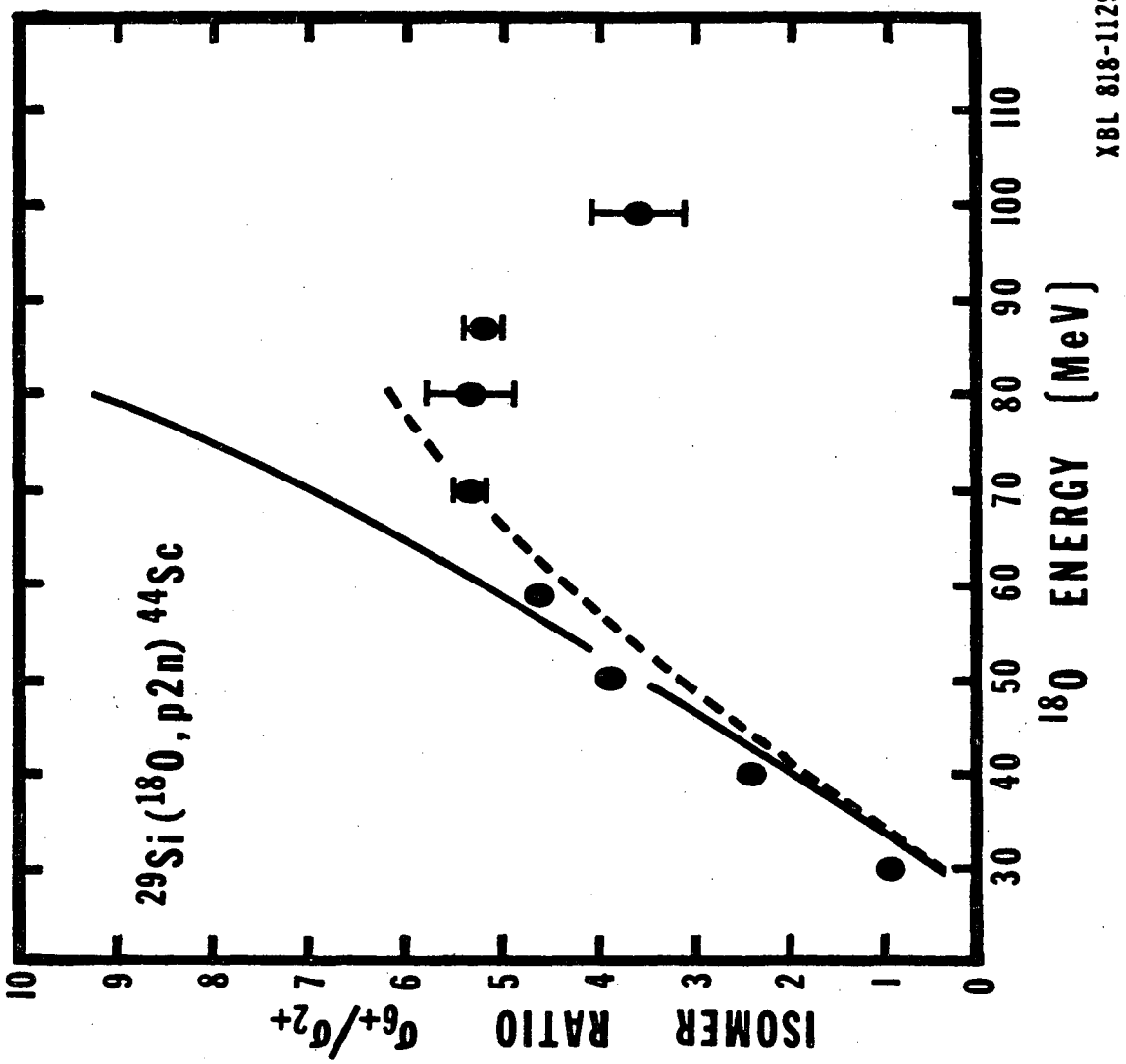

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Fig. 5

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720