SPIN DETERMINATION FROM COMPOUND NUCLEAR REACTION YIELDS

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[Manuscript received 6 July 1972]

Abstract

The relative population of the 2^+ levels at 243 and 288 keV and the 3^+ levels at 390 and 426 keV in ^{62}Cu via the ^{62}Ni(p, n)^{62}Cu reaction has been compared with the theoretical prediction of the Hauser–Feshbach statistical compound nuclear reaction model. Whereas the yields of the 243, 288, and 426 keV levels are in accord with the Hauser–Feshbach calculations, the observed yield of the 390 keV 3^+ level is anomalously low by a factor of six to seven.

I. Introduction

The technique of determining the spins of nuclear energy levels based on measurements of the relative population of the levels following a compound nuclear reaction has been employed frequently in recent years (Iyengar, Wong, and Neilson 1970; McEllistrem, Jones, and Sheppard 1970; Tepel, Malan, and De Villiers 1970). The theoretical predictions of the relative cross sections are calculated using the statistical compound nuclear reaction model of Hauser and Feshbach (1952). The experimental yields are determined either by using a thick target to produce an energy spread which is large compared with the coherence width of the compound system or by averaging the yields obtained from a thin target over a similarly wide energy region. The energy averaging is intended to ensure that the dominant contribution to the yield may be described by a statistical compound nuclear reaction mechanism. It is hoped that the influence of narrow resonances and Ericsson-type fluctuations of cross sections will be made negligible by the energy averaging procedure.

This technique has enjoyed a fairly high success rate in predicting spins of low-lying excited states, where a comparison with values determined by other techniques, such as measurements of γ-ray angular distributions, could be made. The use of the (p, n) reaction in this regard has, for instance, predicted unique spin values or set limits to them for many excited states of 2p–1f shell nuclei (Bass and Stelson 1970). However, several cases have recently come to light in which the spin value determined from γ-ray angular distributions or β-decay experiments is not in agreement with the value determined from the relative yield measurements. Two such discrepancies are, for example, the 40 keV second excited state in ^{45}Ti ($J = 5/2$ as against 7/2 or 9/2) and the 911 keV level in ^{67}Ga (3/2 as against 5/2 or 7/2).

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The present paper is concerned with the relative yield measurements of the 243 keV (2^+), 288 keV (2^+), 390 keV (3^+), and 426 keV (3^+) levels in ^{62}Cu, following the ^{62}Ni(p, n)^{62}Cu reaction. The spin values for the 243 and 288 keV levels are taken from Hoffman and Sarantites (1969), for the 390 keV level from Sunyar *et al.* (1969), and for the 426 keV level from Davidson *et al.* (1970). A preliminary report of this work has been presented at the International Conference on Statistical Properties of Nuclei (Carlson *et al.* 1971).

II. Experimental Procedure

The relative yield of the excited states of interest was obtained by observing the de-exciting γ-rays in a Ge(Li) detector placed at an angle θ of 55° relative to the beam direction. These yields, together with the known relative efficiency of the Ge(Li) detector and the known decay scheme shown in Figure 1, allow the relative population of the corresponding levels to be calculated. The Ge(Li) detector had a volume of $\sim 40\ \mathrm{cm}^3$ and a resolution of $2\cdot5$ keV for the 1332 keV ^{60}Co γ-ray. The angular distributions of the γ-rays of interest have been shown by Davidson *et al.* (1970) to have an angular dependence which can be described by the Legendre polynominal expansion

$$W(\theta) = I\{1 + a_2 P_2(\cos\theta)\}.$$

Since $P_2(\cos\theta) = 0$ for $\theta = 55°$, $W(55°) = I$, and thus the relative intensities determined with the detector placed at $\theta = 55°$ reflect the total yields of the transitions.

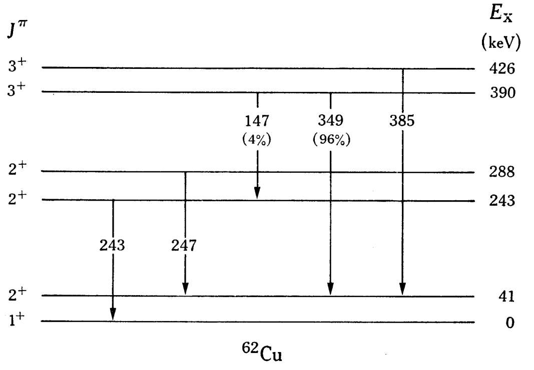

Fig. 1.—Partial decay scheme of ^{62}Cu from Davidson *et al.* (1970).

The γ-transitions studied were those of 243, 247, 349, and 385 keV which arise from the de-excitation of the 243, 288, 390, and 426 keV levels respectively. The proton energies varied between $5\cdot0$ and $5\cdot6$ MeV, allowing excitation of ^{62}Cu states up to energies of 200 and 800 keV respectively. Indirect feeding of the 243, 288, 390, and 426 keV levels by γ-ray decay from higher energy levels, although energetically possible, was not observed in the Ge(Li) γ-spectra.

The targets of thickness $\sim 1\cdot0\ \mathrm{mg\,cm^{-2}}$ were made by evaporating $99\cdot0\%$ enriched ^{62}NiO onto $0\cdot025$ cm thick tantalum backings. These targets, when placed at 45° to the beam direction, correspond to $\sim$ 55 keV beam energy spread for 5 MeV protons. This thickness is about 10 times the mean level width for $A = 62$ and was considered to give sufficient averaging to allow a comparison with the predictions of the Hauser–Feshbach model.

III. Results

(*a*) *Experimental Results*

The γ-ray yields obtained by summing the relevant full energy peaks after background subtraction are shown in Figure 2. The yields have been normalized to the total charge collected on the target and corrected for the deadtime of the ADC. The measurements between proton energies of 5·2 and 5·4 MeV were repeated and found to be reproduceable. Figure 2(*a*) shows the yields for the 3^+ levels at 390 and 426 keV and Figure 2(*b*) shows the corresponding yields for the 2^+ levels at 243 and 288 keV.

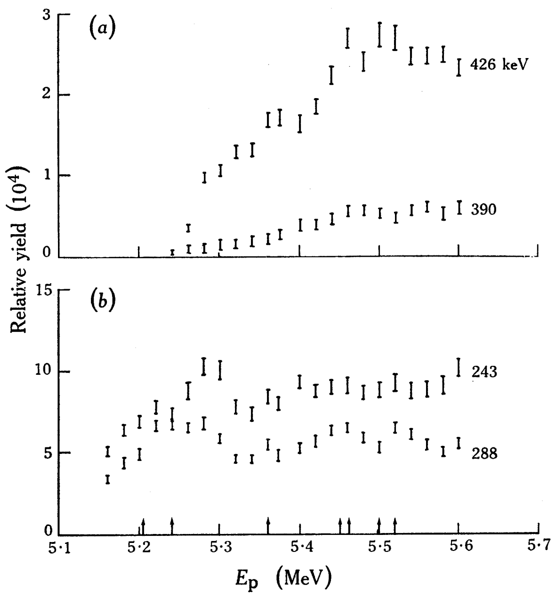

Fig. 2.—Experimental yields for the population of (*a*) the 3^+ levels at 390 and 426 keV, and (*b*) the 2^+ levels at 243 and 288 keV of ^{62}Cu via the $^{62}Ni(p,n)^{62}Cu$ reaction as functions of proton energy E_p between 5·1 and 5·6 MeV.

The broad hump in the yield of the two 2^+ levels between 5·2 and 5·3 MeV proton energy is not understood. It does not appear to be associated directly with the several isobaric analogue resonances known to exist in this energy region; the positions of these resonances taken from the Nuclear Data Sheets (1967) are shown by arrows in Figure 2. The drop in yield at 5·3 MeV proton energy could be related to the opening of the two 3^+ level channels in the decay of the compound nucleus. The Hauser–Feshbach theory predicts a fall of only 4% whereas we observe it to be about 25%.

(*b*) *Theoretical Results*

The calculation of the theoretical cross section was carried out using the computer program HAUSER (Dallimore, Davidson, and Hellström 1969; Dallimore 1971). The calculation follows the statistical compound nuclear reaction theory of Hauser and Feshbach (1952) and includes the effect of fluctuations in the level widths (Moldauer 1967). The proton optical-model parameters of Perey (1963) and the neutron ones of Wilmore and Hodgson (1964) were used in the program HAUSER to calculate the transmission coefficients required for the penetrability term in the expression for the differential cross section. The numerical effect of including this level width term in the calculation is to decrease the yields of all inelastic channels while increasing the yield of the elastic scattering channel. Since all the inelastic channel yields are reduced, the ratios of the various outgoing neutron channel yields are not too sensitive to this effect. The resulting cross sections are presented in Figure 3. It is seen that, as noted in subsection (*a*) above, the opening of the exit channels to the 3^+ levels reduces the yield from the other channels already open.

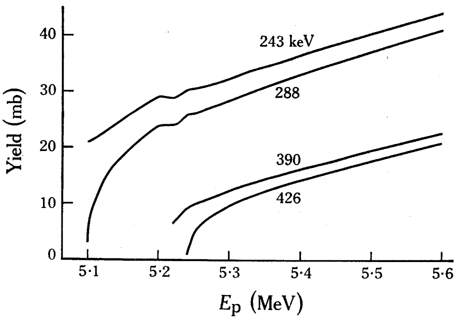

Fig. 3.—Theoretical cross sections for the population of the 2^+ levels at 243 and 288 keV and the 3^+ levels at 390 and 426 keV of ^{62}Cu via the ^{62}Ni(p, n)^{62}Cu reaction as functions of proton energy E_p between 5·1 and 5·6 MeV.

A further theoretical estimate of the ^{62}Ni(p, n)^{62}Cu cross section to the 3^+ levels, assuming a direct interaction mechanism, has been carried out using the computer program DWUCK (Kunz 1969; Dallimore and Davis 1971). This calculation used the same optical-model parameters as did the Hauser–Feshbach calculation mentioned above. Configurations of

$$\text{(i)}\quad \Pi\,|\,p_{3/2}\rangle\,\nu\,|(p_{3/2})^{-1}(f_{5/2})^2\rangle \qquad \text{and} \qquad \text{(ii)}\quad \Pi\,|\,p_{3/2}\rangle\,\nu\,|(p_{3/2})^4(f_{5/2})^1\rangle$$

were assumed for the two 3^+ states of ^{62}Cu, that is, the proton and neutron shells are filled through the $f_{7/2}$ states with the last proton in the $p_{3/2}$ orbital and the remaining five neutrons in the $p_{3/2}$ and $f_{5/2}$ orbitals. The orbital angular momentum L transferred to the nucleus can have the values 2 or 4. The resulting calculated cross sections for $E_p = 5 \cdot 5$ MeV are given below.

Configuration (i) of ^{62}Cu 3^+ state	σ (mb sr^{-1}) $L = 2$	4	Configuration (ii) of ^{62}Cu 3^+ state	σ (mb sr^{-1}) $L = 2$	4
$\Pi\,|\,p_{3/2}\rangle\,\nu\,|(p_{3/2})^{-1}(f_{5/2})^2\rangle$	1·944	0·481	$\Pi\,|\,p_{3/2}\rangle\,\nu\,|(p_{3/2})^4(f_{5/2})^1\rangle$	0·019	0·002

For $E_p = 5 \cdot 5$ MeV, this calculation estimates the ratio of the contributions to the population of the ^{62}Cu spin 3 state from the direct and statistical compound nuclear reactions to be $< 0 \cdot 1$ for configuration (i) and $< 0 \cdot 001$ for configuration (ii). Since the direct reaction calculation entails a detailed knowledge of the wavefunctions of the two spin 3^+ states, this contribution has been neglected relative to that of the compound nucleus.

Davidson *et al.* (1970) have postulated that the 426 keV 3^+ level is dominated by configuration (i) while the 390 keV 3^+ level is dominated by configuration (ii). This hypothesis is supported by the g factor measurement of Sunyar *et al.* (1969) for the 390 keV level.

IV. Discussion

To obtain a numerical comparison between experiment and theory we have summed both the experimental yields (corrected for detector efficiency and decay scheme branching ratios) and the theoretical Hauser–Feshbach cross sections between $5 \cdot 3$ and $5 \cdot 6$ MeV proton energy. This large region of energy averaging should make the effect of nonstatistical processes negligible. The resulting ratio of the yield Y_{243} to the 243 keV 2^+ level relative to the yield $Y_{\rm L}$ to each level is presented below.

Level (keV)	$J\pi$	$Y_{243}/Y_{\rm L}$ Exp.	$Y_{243}/Y_{\rm L}$ Theor.	Level (keV)	$J\pi$	$Y_{243}/Y_{\rm L}$ Exp.	$Y_{243}/Y_{\rm L}$ Theor.
243	2^+	$1 \cdot 00$	$1 \cdot 00$	390	3^+	$13 \cdot 3 \pm 1 \cdot 3$	$1 \cdot 99$
288	2^+	$1 \cdot 55 \pm 0 \cdot 15$	$1 \cdot 10$		$[4^+]$	—	$[7 \cdot 1]$
426	3^+	$2 \cdot 55 \pm 0 \cdot 25$	$2 \cdot 45$		$[5^+]$	—	$[22 \cdot 0]$

It is seen that the ratios differ by a factor of six to seven for the 390 keV 3^+ level, while those for the other levels agree to within 40%. The theoretical and experimental ratios should be identical if the reaction proceeds as described by the statistical compound nucleus theory.

Theoretical ratios for a fictitious level at 390 keV with spin and parity values of 4^+ and 5^+ have also been included (in square brackets) above. The predicted ratios of ~ 7 and ~ 22 bracket the experimentally determined value of $13 \cdot 3 \pm 1 \cdot 3$. Thus in this case an anomalously low yield could lead to an erroneous spin assignment of 4^+ or 5^+ for a 3^+ level. This result emphasises that one should not rely on yield determinations alone in the assignment of spin values.

V. Acknowledgment

One of us (L.E.C.) would like to acknowledge the financial assistance of an Australian Institute of Nuclear Science and Engineering Fellowship.

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