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A study of the ^{113}In(^{3}He, d)^{114}Sn reaction at 37·7 MeV†

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Abstract. The proton particle–hole states of ^{114}Sn have been studied by the ^{113}In(^{3}He,d)^{114}Sn reaction at 37·7 MeV. A ^{113}In(^{3}He,^{3}He)^{113}In elastic scattering experiment provided ^{3}He optical model parameters for the DWBA analysis. The ground state and seven excited states of ^{114}Sn yielded deuteron groups which could be analysed in terms of angular momentum transfers of $l = 2$ or $l = 4$. These transferred protons are believed to occupy $2d_{5/2}$ or $1g_{7/2}$ orbitals and to couple with a $1g_{9/2}$ proton hole. Partial strengths extracted from the angular distributions are consistent with the results obtained on ^{115}In(^{3}He,d)^{116}Sn by Biggerstaff *et al*, but not with those of Shoup *et al*.

1. Introduction

Nuclei at the major closed shells offer the best opportunities for a study of simple particle–hole configurations. For $Z = 50$ and $A = 116$ the reaction ^{115}In(^{3}He,d)^{116}Sn has been investigated by counter telescopes (Conjeaud *et al* 1966 and Biggerstaff *et al* 1967) and by a magnetic spectrograph (Shoup *et al* 1969). Studies of both the ^{113}In(^{3}He,d)^{114}Sn and ^{115}In(^{3}He,d)^{116}Sn reactions are mentioned in a review paper by Bloch *et al* (1969) as having been made by Harar (1968) in his thesis, but no specific results on the ^{113}In(^{3}He,d)^{114}Sn reaction have been published. Proton particle–hole states are best excited by this reaction, although proton as well as neutron particle–hole states and collective states have been observed in inelastic scattering and particle transfer reactions (Kim and Cohen 1966, Schneid *et al* 1967, Yamazaki *et al* 1968, Bjerregaard *et al* 1969 and Betigeri and Morinaga 1967).

The ground state configuration of ^{113}In consists of 49 protons with a $1g_{9/2}$ hole. The addition of a proton to the next empty shell results in configurations involving $2d_{5/2}$, $1g_{7/2}$ and possibly $2d_{3/2}$, $1h_{11/2}$ or $3s_{1/2}$ orbitals. The proton states to be coupled with the $1g_{9/2}$ hole in ^{114}Sn should be those single particle states observed in the Sb isotopes by Bassani *et al* (1967). The excitation energies will be 3·8 MeV or greater. Unfortunately, neutron particle–hole excitations and more complicated configurations are also possible and may confuse the analysis of the simple proton particle–hole configurations. Level spacings in Sn are of the order of a few keV for 4–6 MeV excitations (Allan *et al* 1965), so a resolution better than that available with magnetic spectrographs would be

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needed to resolve all the states. The experiments to be reported employed a counter telescope, and hence average over many levels. However, since the (^{3}He,d) reaction is very sensitive in selecting proton particle–hole states, it is hoped that information can be deduced regarding particle–hole strengths for comparison with the results for ^{116}Sn.

A similar study of the particle–hole states of ^{40}Ca was carried out during this work. The experimental techniques, data analysis and interpretation were quite similar and are reported in somewhat more detail in a paper by the same authors (Cage *et al* 1971).

2. Experimental procedure

^{3}He ions accelerated in the University of Colorado cyclotron to 37·7 MeV were used to bombard enriched targets of ^{113}In(96·36% ^{113}In and 3·64% ^{115}In) supported on 100 μg cm^{-2} carbon foil backings. For the elastic scattering studies a thin target of 360 μg cm^{-2} was used. The counter telescope consisted of a 77 μm thick passing counter and a 4000 μm stopping detector. The resolution for this experiment was 150 keV FWHM. An angular distribution from 12·5° to 90° was obtained in 2·5° to 5·0° steps using a monitor counter, as well as a beam current integrator.

For the ^{113}In(^{3}He,d)^{114}Sn runs a target of 740 ug cm^{-2} was used with a counter telescope consisting of a 442 μm thick passing counter with a 6000 μm stopping detector. Again, the yield of ^{3}He elastically scattered from the target was monitored. The angular distributions were determined at 2·5° intervals from 15° to 45° and at 50° and 60°. Figure 1 shows a characteristic spectrum of the deuterons with a resolution of 150 keV FWHM. Large peaks arising from ^{12}C and ^{16}O impurities in the target are out of the range of interest.

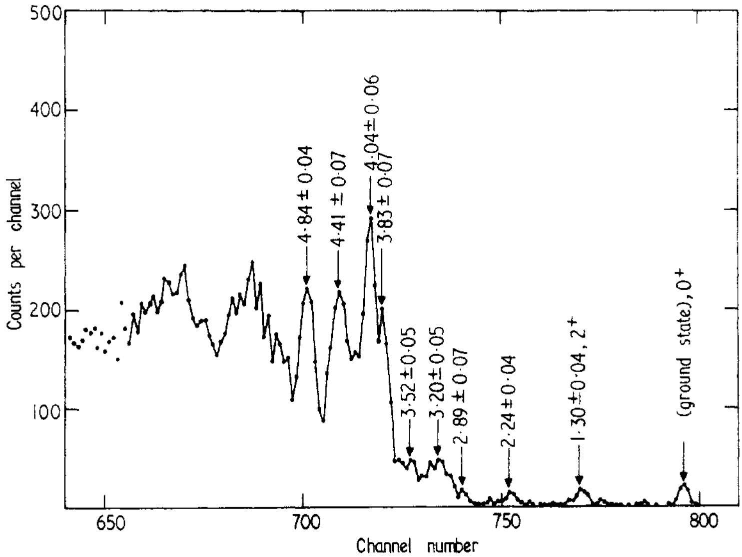

Figure 1. A deuteron energy spectrum of the ^{113}In(^{3}He,d)^{114}Sn reaction obtained at a laboratory scattering angle of 45°. The energy of the incident ^{3}He ions was 37·7 MeV. The values shown on the figure are the excitation energies of ^{114}Sn in MeV.

3. Experimental results and analysis

The excitation energies of previously observed states in ^{114}Sn are listed in table 1. Spin and parity assignments, when known, are listed also. These experiments, employing (d,d′), (d,t), (α,2n), (t,p), and (^{3}He,3nγ) reactions, are expected to excite collective, neutron and pairing-vibrational states in preference to proton particle–hole states. It is evident in figure 1 that the strong peaks correspond to levels above those previously reported.

Table 1. Excitation energy, and spin and parity assignments, with results of the present experiment

Excitation energy† (MeV ± 10 keV all states)	J^{π}‡	E_x§ (MeV ± keV)	l	π	G_2	G_4
(ground state)	0^+	(ground state)	4	+		0·41
1·30	2^+	1·30 ± 40	2	+	0·07	
1·58	0^+					
1·95	0^+					
2·16						
2·19	4^+					
2·28	3^-	2·24 ± 40				
2·42						
2·55						
2·68						
2·82	5^-					
2·86		2·89 ± 70				
2·91						
2·95						
3·02						
3·08						
3·24		3·20 ± 50	2,4	+	0·18	0·18
3·36						
3·57		3·52 ± 50	2,4	+	0·08	0·28
3·64						
		3·83 ± 70	2	+	0·37	
		4·04 ± 60	2	+	1·28	
		4·41 ± 70	4	+		2·22
		4·84 ± 40	2,4	+	0·34	0·91

† Bjerregaard *et al* (1969), Kim and Cohen (1966), Schneid *et al* (1967) and Yamazaki *et al* (1968).

‡ Betigeri and Morinaga (1967), Bjerregaard *et al* (1969), Kim and Cohen (1966), Schneid *et al* (1967) and Yamazaki *et al* (1968).

§ Major observed peaks in present experiment.

Spectra of the type shown in figure 1 were either decomposed by computer or visually, using the systematic behaviour of the spectra at a number of angles to determine the background under the peaks and the yields. The states at 2·24 and 2·89 MeV were too weak to extract reliable angular distributions. Figures 2 and 3 show the angular distributions for all the peaks analysed.

Elastic scattering ^{3}He data were taken in order to determine the ^{3}He optical model parameters. A potential of the form

$$V(r) = -U(1+e^{x})^{-1} - iW(1+e^{x'})^{-1} + 4ia_I W_D\left(\frac{d}{dr}\right)(1+e^{x'})^{-1}$$
$$+\left(\frac{\hbar}{m_\pi c}\right)^2 \boldsymbol{\sigma} . \boldsymbol{l} V_S\left(\frac{1}{r}\right)\left(\frac{d}{dr}\right)(1+e^{x})^{-1} + V_C(r) \qquad (1)$$

was employed, where $x = (r - r_R A^{1/3})/a_R$, $x' = (r - r_I A^{1/3})/a_I$ and $V_C(r)$ is a Coulomb potential for a uniformly charged sphere. Two parameter sets were found, one characterized by a real well depth U of 196·2 MeV and the other by a depth of 127·9 MeV. The values of the parameters are listed in table 2.

Table 2. Optical model parameters used in the DWBA calculations for the ^{113}In(^{3}He,d)^{114}Sn reaction

Particle	U (MeV)	r_R (fm)	a_R (fm)	W (MeV)	W_D (MeV)	r_I (fm)	a_I (fm)	r_C (fm)	V_S (MeV)	β (fm)
^{3}He	196·20	1·126	0·643	27·85	0·0	1·459	0·912	1·40	0·0	0·20
^{3}He	127·90	1·171	0·539	16·84	0·0	1·532	0·939	1·40	0·0	0·20
d†	97·84	1·077	0·852	0·0	17·91	1·281	0·778	1·30	0·0	0·54
p	V_p‡	1·250	0·650	0·0	0·0	0·0	0·0	1·25	8·0	0·0

† The deuteron parameters are those of Newman *et al* (1967) for ^{96}Zr at 34·4 MeV.
‡ The well depth is varied to bind the proton.

The deuteron parameter set chosen for DWBA analysis was that found by Newman *et al* (1967) for scattering from ^{96}Zr at 34·4 MeV. The set using no spin–orbit term was chosen since the fits to the ^{113}In(^{3}He,d)^{114}Sn data were insensitive to V_S. This set of parameters is also listed in table 2. The proton potential well parameters are also listed, the depth V_p being adjusted to give the proper proton binding energy.

The DWBA analysis was performed using the program DWUCK (P D Kunz, University of Colorado, unpublished) which calculates a reduced cross section $\sigma_{DW}(\theta)$. The differential cross section can be expressed as

$$\frac{d\sigma}{d\Omega} = 4{\cdot}42\frac{2J+1}{2J_A+1}C^2\sum_l S_l\frac{\sigma_{DW}(\theta)}{2l+1}, \qquad (\text{mb sr}^{-1}) \qquad (2)$$

where l is the transferred angular momentum, J and J_A are the final and initial nuclear spins, C is the isospin Clebsch–Gordan coefficient for the transferred particle and S_l is the spectroscopic factor for transferring the particle into the appropriate orbital. Since for most of the important states populated in the reaction, the spin J is not known, the partial strengths

$$G_l = \frac{2J+1}{2J_A+1}C^2 S_l \qquad (3)$$

are all that can be determined. The sum rule (French and MacFarlane 1961) for stripping a proton into the orbital l, j for $T_<$ final states is given by

$$\sum G_l(T_<) = \langle \text{proton holes} \rangle_j - \frac{\langle \text{neutron holes} \rangle_j}{N-Z+1}, \tag{4}$$

in terms of the number of proton and neutron holes in that orbital of the target and $T_<$, the isospin. For $T_>$ states

$$\sum G_l(T_>) = \frac{\langle \text{neutron holes} \rangle_j}{N-Z+1}. \tag{5}$$

For ^{114}Sn, $T_<$ and $T_>$ are 7 and 8 respectively.

The angular distributions for the ^{113}In(^{3}He,d)^{114}Sn reaction were calculated using the two ^{3}He optical model potential sets and the deuteron potential set. Nonlocal and finite range corrections (Bassel 1966) were included. The nonlocal correction made no essential change in the magnitude or shape of the calculated angular distributions; the zero-range correction increased the magnitude by 10%.

In the simple shell model the configuration for a proton transferred to form the ground state of ^{114}Sn is a $1g_{9/2}$ orbital. The angular distribution should be characterized by an $l = 4$ transfer only. The two calculated curves shown in figure 2 for the ground

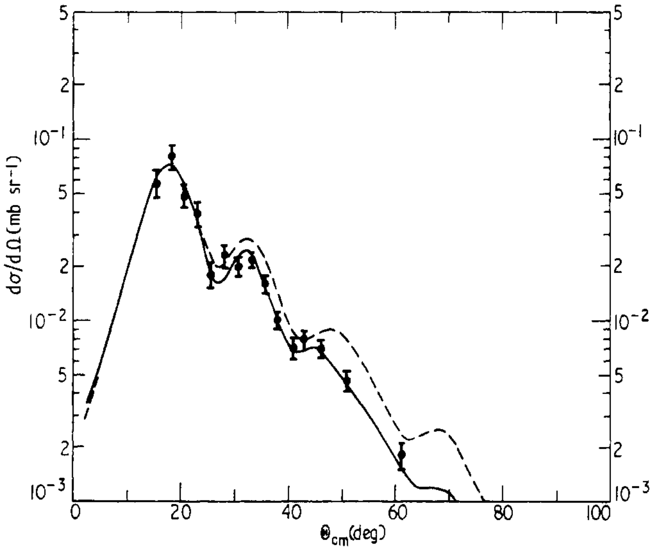

Figure 2. Angular distribution of the deuteron group corresponding to the ground state of ^{114}Sn. DWBA predictions using the two ^{3}He optical model parameter sets and the deuteron set listed in table 2 are shown fitted to the data. The full curve is for $U = 196{\cdot}2$ MeV; the broken curve is for $U = 127{\cdot}9$ MeV. Energy of incident ^{3}He ions was 37·7 MeV; $G_4 = 0{\cdot}41$, $l = 4$.

state transition indicate the effect of changing the ^{3}He optical model parameter set. The set using the deeper real central well provides a better fit for the ground state transition and for the excited state transitions as well, which are shown in figure 3. Orbital angular momenta assigned to the distributions are $l = 2$ and $l = 4$, hence it is assumed that the proton is captured into the $1g_{9/2}$ orbital to form the ground state, or into $2d_{5/2}$ or $1g_{7/2}$ orbitals respectively. In table 1 the values of the excitation energy of the states, the

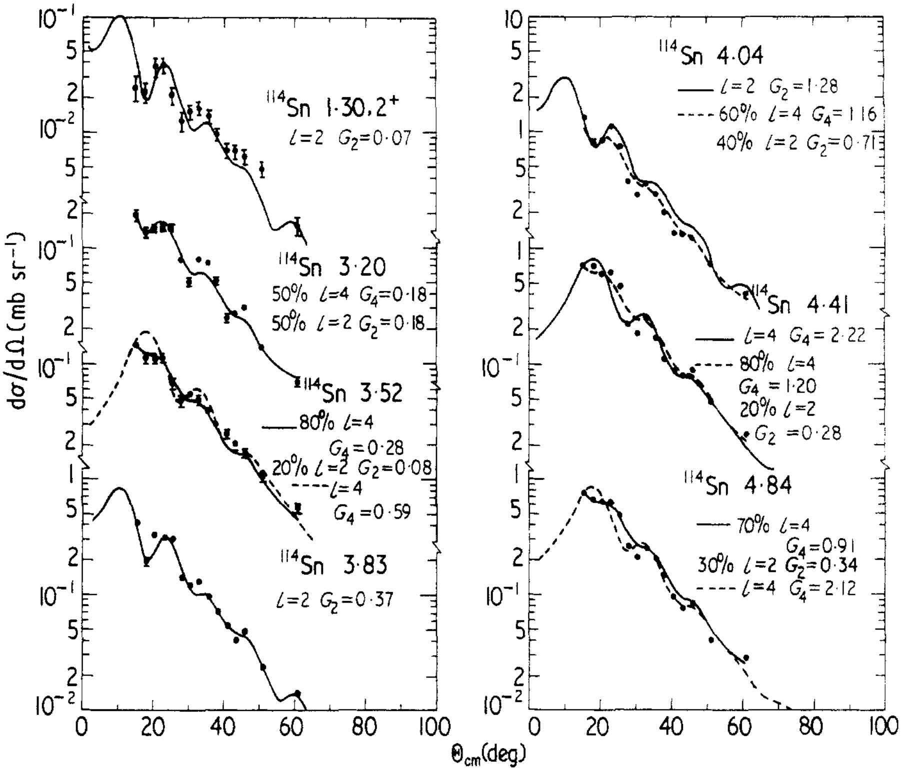

Figure 3. Angular distributions of deuteron groups corresponding to the excitation peaks of ^{114}Sn, and the DWBA predictions.

orbital angular momentum transfer and the values of G_l are presented. The angular distributions were fitted over the full angular range, but in several cases mixtures of $l = 2$ and $l = 4$ distributions are required to achieve best fits. Since low l angular momentum transfers may have a considerable effect on the angular distribution, and since $3s_{1/2}$ and $2p_{1/2}$ orbitals are available in this mass region, attempts were made to include an $l = 0$ or $l = 1$ component, but without success.

The large increase in cross section for peaks at 3·83 MeV and above probably represents population of $2d_{5/2}$ and $1g_{7/2}$ orbitals. The strong similarity between the (^{3}He,d) spectra from ^{113}In and ^{115}In suggests such an interpretation (Bloch *et al* 1969). There are many states excited that even the high resolution experiment of Shoup *et al* (1969) on the ^{115}In(^{3}He,d)^{116}Sn reaction could not resolve.

The summed partial strengths for the assigned $l = 2$ and $l = 4$ transitions to excited states and values of the centroid energies, calculated from the relation

$$\bar{E} = \Sigma(E_x G_l)/\Sigma G_l, \tag{6}$$

are given in table 3. Values determined by the sum rules (equations (4) and (5)) are given for the $(1g_{9/2}^{-1}\, 1g_{7/2})$ and $(1g_{9/2}^{-1}\, 2d_{5/2})$ configurations assuming the limiting cases of completely full or empty corresponding neutron orbitals. If the $1g_{7/2}$ and $2d_{5/2}$ neutron orbitals were completely filled only $T = 7$ configurations would contribute and the upper bound on the sum rule would apply. If the neutron orbitals were empty the

Table 3. The sum rules and centroid energies of ^{114}Sn configurations

Configurations	ΣG_l exp	ΣG_l theor†	$\bar{E} = \Sigma(E_x G_l)/\Sigma G_l$ (MeV)
$(1g_{9/2}^{-1}1g_{7/2})_{T = 7+(8)}^{J = 1, 2 \ldots, 8}$	3·59‡	7·5–8·0	4·37‡
$(1g_{9/2}^{-1}2d_{5/2})_{T = 7+(8)}^{J = 2, 3 \ldots, 7}$	2·32‡	5·6–6·0	3·96‡

† The range in summed partial strength for the $T = 7$ configurations corresponds to completely empty or filled $1g_{7/2}$ and $2d_{5/2}$ neutron orbitals, with the upper limits being the most probable.
‡ Unresolved states at higher excitation energies may also contribute.

lower bound would apply for the sum rule on $T = 7$ states. Experimentally no distinction between $T = 7$ or $T = 8$ states is possible. The strength of the $T = 8$ states is only $\frac{1}{16}$ that of the $T = 7$ states, and the mean energy should be considerably above that for the $T = 7$ states. Only 4 states resulting from $l = 4$ particle transfer comprise the sum while a minimum of 8 should occur. For the $l = 2$ transfer 6 states contribute. The observed fullness of the $g_{7/2}$ and $d_{5/2}$ neutron orbitals (Schneid *et al* 1967) in ^{114}Sn indicates that little error is made by assuming them to be entirely full.

The partial strength of the $l = 4$ transition to the ground state is 0·41, rather than 1·0, the result expected from the simple shell model. The observed summed partial strength for the $(1g_{9/2}^{-1}\,1g_{7/2})$ configuration is 45% of the maximum total strength while that for $(1g_{9/2}^{-1}\,2d_{5/2})$ is 39%. Some coupling of a $2d_{3/2}$ state could be included in the strength associated with the $2d_{5/2}$ particle state. Configuration mixing is expected to occur for the ground state and for the $(1g_{9/2}^{-1}\,1g_{7/2})$ and $(1g_{9/2}^{-1}\,2d_{5/2})$ configurations, so that the dilution of strength is comparable for all three states.

A brief study of the ^{115}In(^{3}He,d)^{116}Sn reaction at 37·7 MeV with a resolution comparable to that of the ^{115}In(^{3}He,d)^{116}Sn experiments of Conjeaud *et al* (1966) and Biggerstaff *et al* (1967) yielded spectra strikingly similar to that shown in figure 1 (see also figure 8 in Bloch *et al* 1969). The excitation energies of the states observed agreed well with those reported. Biggerstaff *et al* (1967) find that all the G_4 strength is concentrated in one state at 4·28 MeV. Shoup *et al* (1969) extracted 16 states between 3·7 and 4·9 MeV in their data and assign pure $l = 2$, or 90% $l = 2$ mixtures with 10% $l = 0$, but with no $l = 4$ contribution. They only used data forward of 35° to determine spectroscopic factors because the large angles could not be fitted by DWBA analysis. However, the low energy used for their study (25 MeV) causes the small l values to dominate the angular distributions. At small angles a small admixture of $l = 0$ would have a marked effect on the angular distribution.

All observers note that above 5 MeV excitation in ^{114}Sn and ^{116}Sn there are very strong unresolved groups of states which could not be analysed.

The data presented are for the ^{114}Sn final states. Figure 8 of the paper by Bloch *et al* (1969) shows representative spectra for 18 MeV bombarding energy in the reactions ^{115}In(^{3}He,d)^{116}Sn and ^{113}In(^{3}He,d)^{114}Sn. There is a marked similarity in location and intensity of the states observed, which is also consistent with the data presented in this paper. No other published work on ^{114}Sn was available for comparison. The results of Shoup *et al* (1969) on ^{116}Sn done with high resolution (35 keV FWHM), but at 25 MeV, consistently disagree with the results presented here for ^{114}Sn and also with those of

Biggerstaff *et al* (1967). Shoup *et al* (1969) could not fit their angular distributions by DWBA calculations beyond 35°, and the observed cross sections at 60° were consistently higher than predicted. At the low energy employed the results of a DWBA calculation can be questioned.

A serious criticism of this work, as well as that of Conjeaud *et al* (1966) and Biggerstaff *et al* (1967), is that the resolution was not adequate to properly resolve the particle groups. The effect of unresolved groups of states is to increase the cross sections at 60° where the intensity has fallen to a low level. The data presented consistently show that the DWBA calculations follow the experimental data out to 60°, the largest angle observed. On the other hand, the effect of admixtures is strong only at small angles. Attempts to include $l = 0$ or $l = 1$ admixtures were not successful. Only the $l = 4$ with $l = 2$ mixtures gave best fits to the data; this agrees with the observations of Biggerstaff *et al* (1967). The much higher bombarding energy of 37·7 MeV and the nature of the fits with the DWBA predictions suggests that the conclusions leading to assigment of $(1g_{9/2}^{-1}\, 2d_{5/2})$ and $(1g_{9/2}^{-1}\, 1g_{7/2})$ configurations for the low-lying particle–hole states in ^{114}Sn are justified. To improve on this work will require a very high resolution experiment, with angular data taken down to 5° or less.

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