Energy Levels in Sn^{122}, Sn^{123}, Sn^{124}, and Sn^{125}†

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Studies of the energy levels of Sn^{122}, Sn^{123}, Sn^{124}, and Sn^{125} have been made utilizing the reactions $Sn^{122}(d,p)Sn^{123}$, $Sn^{122}(p,p')Sn^{122}$, $Sn^{124}(d,p)Sn^{125}$, and $Sn^{124}(p,p')Sn^{124}$. Protons resulting from 11- to 12-MeV protons and deuterons incident on separated Sn isotopes were analyzed in a broad range magnetic spectrograph. The Q values of the (d,p) reactions on Sn^{122} and Sn^{124} are 3726±12 keV and 3506±12 keV, respectively. There are considerable differences between the level structure observed in these studies and those of Cohen and Price Sn^{123} and Sn^{125} which result largely from the higher resolution available in this experiment. Probably these differences do not alter drastically the main conclusions in the assignment of single-particle states and in the analysis in terms of the pairing model.

INTRODUCTION

IN the Sn isotopes where the 50-proton closed shell may be assumed to be an inert core, Kisslinger and Sorenson[1] suggest that the ground state corresponds to a diffuse distribution of neutrons in the shell-model states near the Fermi energy. These states for neutron number 50–82 are $2d_{5/2}$, $1g_{7/2}$, $3s_{1/2}$, $1h_{11/2}$, and $2d_{3/2}$. The simple shell model suggests that neutrons have filled the $2d_{5/2}$, $1g_{7/2}$, and $3s_{1/2}$ orbitals and are filling the $1h_{11/2}$ or possibly the $2d_{3/2}$ orbital in pairs, as we go from Sn^{122} to Sn^{124}. Kisslinger and Sorenson have emphasized, on the other hand, the partial filling of all these orbitals because they are all near the Fermi energy.

The energy levels of the odd-mass Sn isotopes are therefore of considerable interest because of the predictions of the theory of Kisslinger and Sorenson. The cross sections for formation of these levels have been analyzed by Cohen and Price[2] in terms of this theory.

In view of the considerably higher resolution available and the importance of these particular experimental data, we felt it advisable to publish these results at this time.

We have been further prompted to publish these results because of their relevance to the recent studies of "analog states." In these studies resonance proton capture on Sn isotopes have given analog states in Sb isotopes which must be compared with the levels resulting from the (d,p) reaction on the same Sn isotope. The actual comparisons between the levels in the Sn isotopes presented here and their analog states in the Sb will be presented in another paper.[3]

Finally, the accurate determination of (d,p) ground-state Q values presented here when coupled with other available information has led to accurate characterization of the mass surface in this mass region.

TABLE I. Enrichments of tin isotopes.

Enriched isotope	Isotopic composition (%) 118	119	120	122	124
Sn^{120}	0.56	0.78	98.14	0.24	0.07
Sn^{122}	0.87	0.75	6.18	88.92	2.05
Sn^{124}	0.5	0.2	1.2	1.2	96.0

EXPERIMENTAL PROCEDURE

Targets of Sn^{122} and Sn^{124} were prepared by vacuum evaporation of the separated isotope (see Table I for isotopic abundances) onto thin carbon backings. They were bombarded with monoenergetic proton and deuteron beams in the F. S. U. tandem Van de Graaff accelerator.[4] The emergent protons from these bombardments were analyzed in a broad range magnetic spectrograph and detected by means of nuclear track emulsion plates. Details of the experimental procedure have been described previously.[5]

The data are plotted in the usual way as number of counts per $\frac{1}{2}$-mm strip versus plate distance. In view of the intricate detail of these spectra and the correspondingly large amount of journal space required for their adequate reproduction, we have decided to present the data as level schemes. A representative proton spectrum for the reaction $Sn^{124}(d,p)Sn^{125}$ is shown in Fig. 1. The incident energy was determined in all of these runs utilizing the well-known Q value (2722.3 keV) for the reaction $C^{12}(d,p)C^{13}$ in the "Q equation" to calculate it.

RESULTS AND COMPARISON TO PREVIOUS STUDIES

The $Sn^{122}(d,p)Sn^{123}$ Reaction

Proton spectra were taken at 25°, 45°, and 65° with a deuteron energy of 12.040, 12.001, and 12.042 MeV, respectively. Since the percentage abundance of Sn^{122} was only 88.9% with 6.18% Sn^{120}, some of the observed groups are states in Sn^{121}. Identification of these peaks

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[1] L. Kisslinger and R. Sorenson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **32**, No. 9 (1960).

[2] B. L. Cohen and R. E. Price, Phys. Rev. **121**, 1441 (1961).

[3] J. A. Becker, C. Nealy, C. F. Moore, D. Robson, and J. D. Fox (to be published).

[4] Operation of the F. S. U. Tandem Accelerator Laboratory is supported in part by the U. S. Air Force Office of Scientific Research.

[5] R. A. Kenefick and R. K. Sheline, Phys. Rev. **133**, B25 (1964).

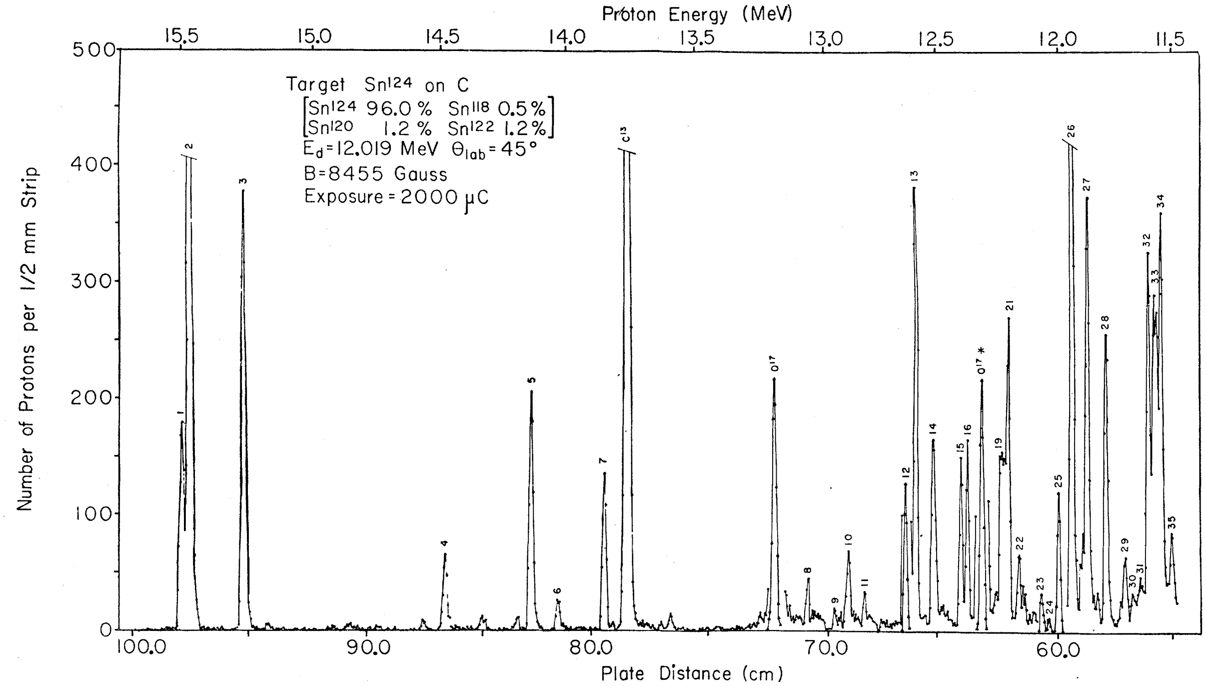

FIG. 1. Typical proton spectrum for the reaction, $Sn^{124}(d,p)Sn^{125}$. Only the numbered peaks are states in Sn^{125}.

was accomplished by making exposures of the reaction $Sn^{120}(d,p)Sn^{121}$, utilizing a Sn^{120} target enriched to 98.14%, at the same incident deuteron energy and same magnetic field setting of the spectrograph.

Only those peaks which are consistent at all angles or are observed at two angles and are covered with a known impurity at the third are assigned as states in Sn^{123}. Table II gives the energy levels and their standard deviation from the average. The standard deviation is the reproducibility and not the absolute error.

A level scheme is shown in Fig. 2 along with a comparison of the results of Cohen and Price[2] over the energy range of these measurements. The resolution available to Cohen and Price did not permit the separation of the ground state and first excited state doublet which differ in energy by 24 keV. Under these conditions of resolution, the apparent Q value will vary depending on the angle of observation and hence relative amounts of the two unresolved states in the apparent ground state. Comparisons of the low-energy excitation spectra (Fig. 2) show a better agreement if the ground state of Cohen and Price is assigned as the first excited state. Thus, it would seem that the ground state as assigned by Cohen and Price is primarily due to the first excited state. Also one additional state at 1.158 MeV and many others at higher excitation energies have been resolved. States at 1.79, 1.94 and 2.42 MeV are not observed in this work. It seems probable that these are not states in Sn^{123} but arise from impurities since their intensities are in most cases greater than the 0.91-MeV state observed in both studies (see Table III). It seems unlikely that a change in deuteron bombarding energy from 12 to 15 MeV would produce such a drastic change in the cross section.

The $Sn^{124}(d,p)Sn^{125}$ Reaction

Proton spectra were taken at 25°, 45°, and 65° with an incident deuteron energy of 12.047, 12.019, and 12.045 MeV, respectively. The excitation energies obtained from these spectra are given in Table II.

A level scheme along with a comparison of the work of Cohen and Price[2] is shown in Fig. 3. As in the case of Sn^{123}, it appears as though the ground state as assigned by Cohen and Price is due primarily to the first excited state. One additional state is resolved at 1.362 MeV along with many additional states at higher excitation energies. Cohen and Price observe states at 1.64, 1.90, and 2.10 MeV which are not observed in this work. They do not give the intensity of the two states at 1.64 and 1.90 but the intensity of the 2.10 state compared to the 0.91-MeV state is 0.64. It seems probable, from the analogy with Sn^{123}, that the observation of these cannot be accounted for on the basis of more integrated beams and again it does not seem likely that the cross section would change so drastically with an increase in bombarding energy from 12 to 15 MeV. Therefore, we believe they result from impurities.

The $Sn^{122}(p,p')Sn^{122}$ Reaction

Proton spectra were taken at 115°, 122.5°, and 133° with a respective incident proton energy of 12.026,

TABLE II. Energies of levels observed in odd Sn isotopes from (d,p) reactions on even isotopes and their standard deviation.

Sn^{123} E(keV)	σ	Sn^{125} E(keV)	σ
0		0	
24	2	26	2
151	3	210	9
932	3	936	6
1158	4	1257	13
1199	1	1362	9
1494	2	1540	9
2274	2	2358	1
2677	1	2462	10
2724	7	2519	4
2758	4	2592	9
2826	3	2759	6
3050	1	2801	12
3071	4	2877	6
3112	2	2995	7
3150	1	3024	5
3182	2	3081	6
3215	1	3109	3
3263	2	3150	2
3316	3	3178	8
3354	2	3195	7
3395	2	3245	4
3432	2	3338	3
3454	3	3375	6
3526	5	3414	6
3549	3	3469	7
3627	1	3537	8
3640	4	3623	7
3666	5	3703	10
3713	3	3738	7
3727	6	3774	14
3761	3	3810	6
3805	4	3845	11
3842	4	3863	6
3903	4	3913	4
3952	7		
3999	5		
4043	3		
4097	2		

TABLE III. Relative intensities of the states in the work of Cohen and Price on Sn^{123} compared to the state at 0.91 MeV which is observed in both studies.

Level (MeV)	Relative intensity
0.91	1
1.79	0.54
1.94	1.13
2.42	1.54

12.006, and 12.026 MeV. Since the abundance of Sn^{122} was only 88.9% with 6.18 Sn^{120}, it was necessary to obtain proton spectra of $Sn^{120}(p,p')Sn^{120}$ using a target enriched to 98.14% in order to assign peaks in these spectra to the correct Sn isotopes.

The energy levels observed from these spectra are listed in Table IV and a level scheme with a comparison of the levels obtained by Cohen and Price[6] from (d,d')

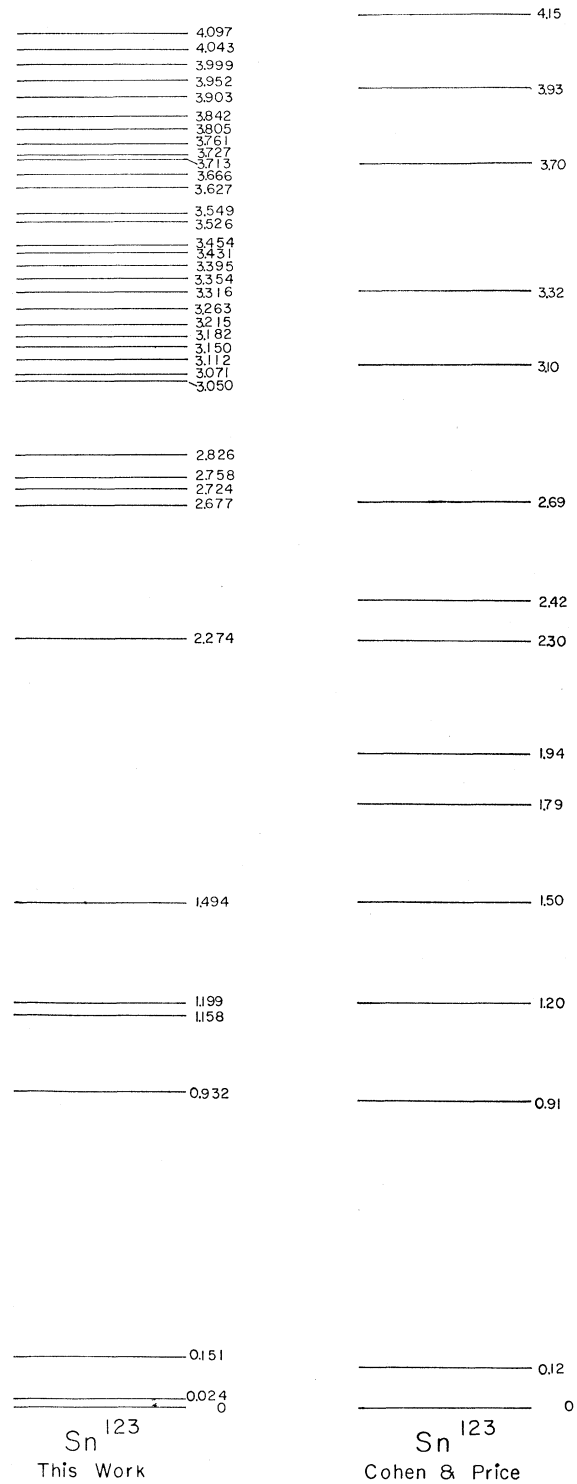

FIG. 2. Level scheme comparison of Sn^{123} with that obtained by Cohen and Price.

[6] B. L. Cohen and R. E. Price, Phys. Rev. **123**, 283 (1961).

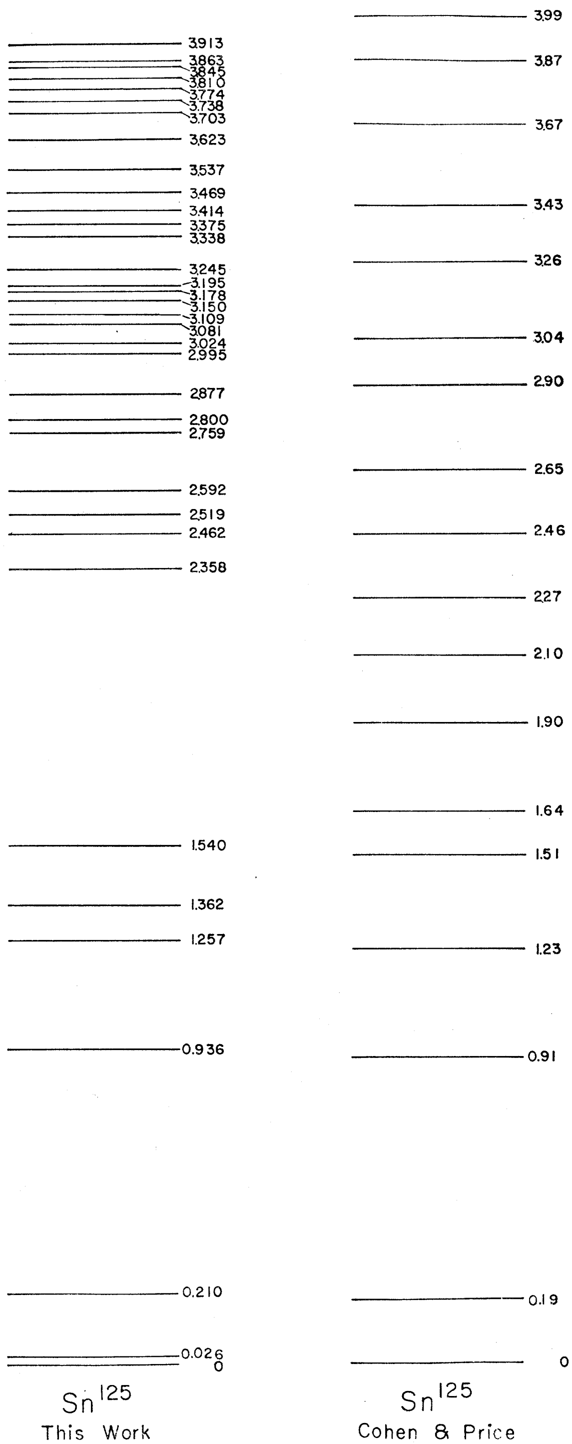

FIG. 3. Level scheme comparison of Sn^{125} with that obtained by Cohen and Price.

using 15-MeV deuterons produced with a cyclotron is shown in Fig. 4. Their resolution was approximately 80 keV. Within the excitation energy of this work, two additional states at 2.247 and 2.414 MeV are observed.

TABLE IV. Energies of levels in even isotopes of tin from proton scattering and their standard deviation.

E(keV)	Sn^{122} σ	E(keV)	Sn^{124} σ
0		0	
1141	2	1131	5
2147	1	2101	4
2247	3	2200	5
2414	3	2428	4
2494	1	2605	5

The $Sn^{124}(p,p')Sn^{124}$ Reaction

Proton spectra were taken at 90°, 122.4°, and 133° with a respective proton energy of 12.002, 11.200, and 11.00 MeV. The energy levels obtained are listed in Table IV and a level scheme with a comparison with the (d,d') results of Cohen and Price,[6] in the energy region of this work, is shown in Fig. 4. All of the levels

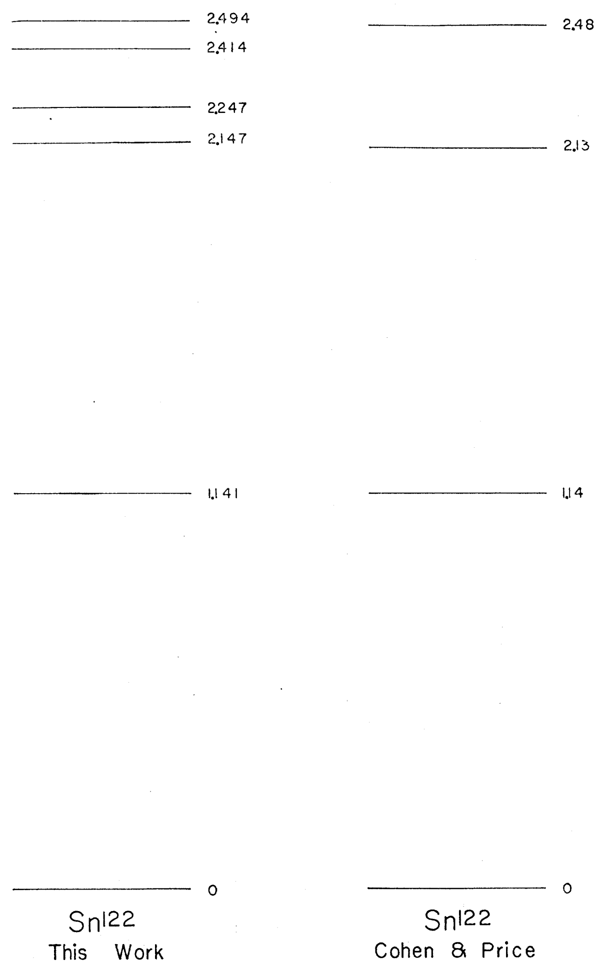

FIG. 4. Level scheme comparison of Sn^{122} with that obtained by Cohen and Price.

which are observed by Cohen and Price are observed in this work.

Ground-State Spin of Sn^{123} and Sn^{125}

The spins assigned as a result of β- and γ-ray work[7–10] for the ground state and first excited state are $11/2-$ and $3/2+$. The determination of the β-ray energies was not accurate enough to determine which was the ground state, but it was suggested in the case of Sn^{125} that the $11/2-$ state is the ground state. Although angular distributions were not done in this work, the three exposures taken at different angles indicate that the $11/2-$ state is the ground state. This is based mainly on the fact that the intensity of the ground state is way down compared to the first excited state at 25° while at 65° it is almost equal in intensity to it. This is approximately what is observed in the angular distributions of the corresponding two states in Sn^{117}.[1]

Ground-State Q Values

The ground-state Q values for the (d,p) reactions on Sn^{122} and Sn^{124} are 3726 ± 12 keV and 3506 ± 12 keV, respectively. The error quoted is the estimated error in absolute magnitude.[5] These values are in agreement with determinations by other instruments of similar precision as evidenced by the agreement of the neutron separation energy of Sn^{123}(5951 ± 12 keV) with that obtained by Duckworth[10] (5949 ± 14 keV).

DISCUSSION

Since the resolution in the work by Cohen and Price was not sufficient to resolve a large number of the states in the odd Sn isotopes it is of interest to see how this increased resolution affects their calculations and conclusions.

The first most obvious effect is in the angular distributions of higher energy states. They observed that these angular distributions were all essentially alike and lacked detail. From these facts they suggest that there is some anomaly associated with them. It seems more likely that the composite nature of these "states" results in these apparent anomalies.

However, these angular distributions are only a minor part of their work and do not seriously affect the assignment of single-particle states in the region of lower energy excitation. Except for the ground and first excited states, their resolution was sufficient to resolve these low-lying states. They were aware that they did not resolve these two states and therefore estimated the contribution from the 11/2 state. Since most of their work was at forward angles, where this state is low in intensity, this seems a reasonable assumption. We therefore do not expect it to drastically change their calculations. The calculated "V's" using the corrected energies changes them only a percent or so.

The important work done on the odd Sn isotopes by Cohen and Price was hampered by moderate resolution which makes necessary drastic changes in the level spectra. Probably these changes do not alter drastically their main conclusions.

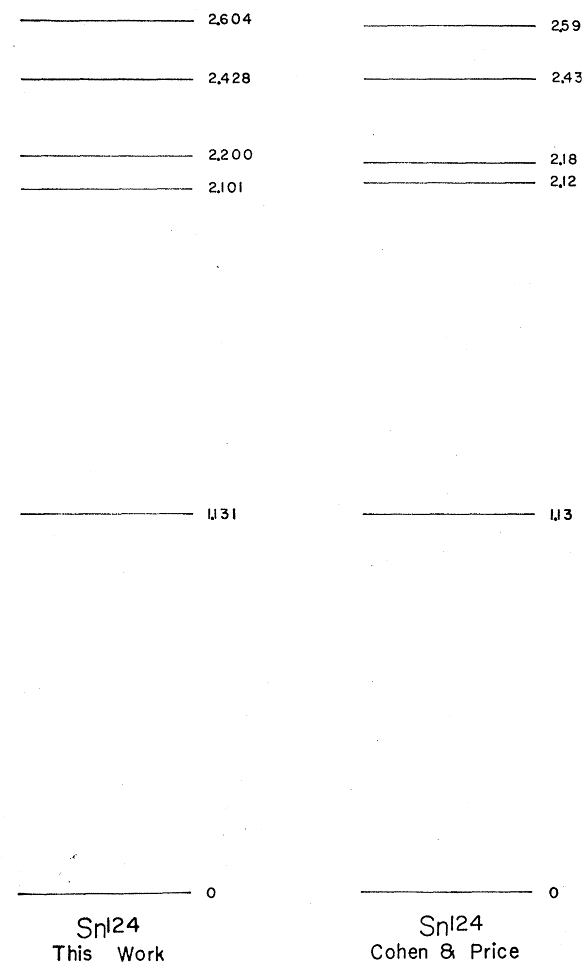

FIG. 5. Level scheme comparison of Sn^{124} with that obtained by Cohen and Price.

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