Is the Nuclear Spin-Orbit Interaction Changing with Neutron Excess?

J. P. Schiffer,[1] S. J. Freeman,[1,2] J. A. Caggiano,[3] C. Deibel,[3] A. Heinz,[3] C.-L. Jiang,[1] R. Lewis,[3] A. Parikh,[3] P. D. Parker,[3] K. E. Rehm,[1] S. Sinha,[1] and J. S. Thomas[4]

[1]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[2]*University of Manchester, Manchester M13 9PL, United Kingdom*
[3]*Yale University, New Haven, Connecticut 06520, USA*
[4]*Rutgers University, Piscataway, New Jersey 08854, USA*

(Received 17 December 2003; published 20 April 2004)

The difference in the energies of the lowest states corresponding to the two nodeless single-particle orbitals outside the $Z = 50$ closed proton shell, $h_{11/2}$ and $g_{7/2}$, increases with neutron excess. We have measured the Sn(α, t) reaction for all seven stable even Sn isotopes and found that the spectroscopic factors are constant for these two states, confirming their characterization as single-particle states. The trend in energies is consistent with a decrease in the nuclear spin-orbit interaction. A similar trend, also suggesting a decreasing spin-orbit splitting, is seen in the energies of the neutron single-particle states outside the $N = 82$ core, $i_{13/2}$ and $h_{9/2}$.

DOI: 10.1103/PhysRevLett.92.162501 PACS numbers: 21.10.Pc, 25.55.Hp, 27.60.+j

The single-particle character of nuclei underlies much of our understanding of nuclear structure. However, the sequence of single-particle states, especially the magnitude of the spin-orbit splitting, is largely empirical. The spin-orbit splitting in heavier nuclei is responsible for the "magic numbers" of closed shells, formed as the highest angular-momentum state is pushed down by the interaction to energies comparable to that of the next lower oscillator shell. It was the recognition of these features and the *j-j* coupling scheme, which influence nearly every aspect of nuclear structure, that led to the Nobel Prize being awarded to Goeppert-Maier and Jenssen.

While there is not yet a quantitative understanding of the microscopic origins of the spin-orbit term in the nuclear Hamiltonian, it does seem to require three-body forces [1]. It has been suggested [2] that the shell structure may change for nuclei away from stability, for a variety of reasons. Deviations of abundances from the current predictions of the astrophysical *r* process may perhaps be explained by such changes [3].

Experimentally, data exist on spin-orbit doublets with low orbital angular momentum, ℓ [4]. Those with higher ℓ are experimentally inaccessible, since the splitting is so large that both members of the doublet cannot be observed simultaneously in the same nucleus. The spin-orbit splitting may be studied somewhat more indirectly by comparing the energies of the $\ell - \frac{1}{2}$ member of the highest ℓ value in a particular oscillator shell that is pushed up in energy (for example, $g_{7/2}$ or $h_{9/2}$) with those of the $(\ell + 1) + \frac{1}{2}$ state from the next oscillator shell, which is pushed down (for example, $h_{11/2}$ or $i_{13/2}$). A schematic level diagram is shown in Fig. 1 to emphasize this feature.

The largest ranges of stable nuclei with closed shells are at $Z = 50$ and $N = 82$. The Sn isotopes are particularly stable in their structure, with both their first 2^+ and first 3^- states constant in excitation energy to within 5% from ^{112}Sn to ^{124}Sn. The existing data [4] on the lowest lying $11/2^-$ and $7/2^+$ states for $Z = 51$ are summarized in Fig. 1. The binding energy of the last proton is plotted for these two states as a function of neutron excess. Any smooth variation in the potentials, or filling of specific neutron levels, should have very similar effects on these two orbits since the radial overlap integrals are quite similar for these nodeless states. However, their separation in energy changes by over 2 MeV. Taken at face value this could mean a reduction in the spin-orbit interaction by that amount. But, if there were strong mixing with more complicated states and subsequent fragmentation of single-particle strength, the observed change might perhaps be accounted for without requiring such a reduction. The mixing would either have to consist of large admixtures in the $11/2^-$ state in the lighter Sb isotopes (such as to raise the energy centroid by about 2 MeV), or similarly large admixtures for the $7/2^+$ appearing increasingly in the heavy isotopes. In either case the spectroscopic factors for adding a proton would change across the chain of isotopes. Proton-transfer reaction data exist for these states from (^{3}He, d) reactions [7], yet the existing information on spectroscopic factors is not very quantitative for such high angular-momentum transfers.

We have studied the (α, t) reaction on Sn isotopes in the first systematic determination of spectroscopic factors across all seven stable even-A Sn targets. The angular-momentum transfers with $\ell = 4$ and 5 are well matched, and the cross sections are relatively large. The ESTU tandem Van de Graaf accelerator at Yale University delivered a beam of α particles at an energy of 40 MeV. This beam was used to bombard isotopically enriched Sn targets with thicknesses of $\sim 200\ \mu\mathrm{g\,cm^{-2}}$ evaporated onto 40 $\mu\mathrm{g\,cm^{-2}}$ carbon foils. The tritons were momentum analyzed in an Enge split-pole magnetic spectrograph. Since the emphasis in this measurement was to

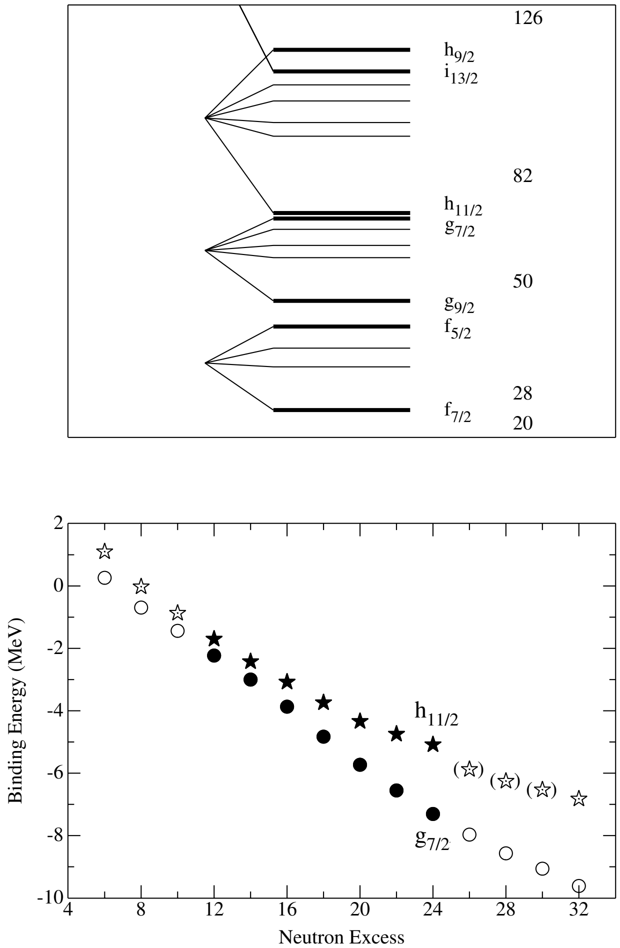

FIG. 1. The upper part of the figure is a schematic level diagram of single-particle states, arising from different oscillator shells. Pairs of states with highest angular momentum in each shell are labeled to emphasize the proximity of a high-j $(\ell + 1) + \frac{1}{2}$ intruder state to the $\ell - \frac{1}{2}$ state from the lower shell. The lower part of the figure shows the neutron-excess dependence of the binding energy of the last proton in $Z = 51$ nuclei. The stars correspond to the $11/2^-$ states and the circles to the $7/2^+$ states. The open symbols designate states where spin assignments have been made but there is no information from transfer reactions about the single-particle character of the states. The points for ^{133}Sb are from [5] and those in parentheses are unpublished [6].

obtain accurate relative cross sections between different targets, a Si detector was used to measure the elastic scattering at 9°, where the scattering should be Rutherford to within 1%. In order to monitor possible small shifts in beam position two additional silicon detectors were used on either side of the beam at 30°, but no significant shifts were seen. Data were obtained at 6, 13, and 25°, and more complete angular distributions were measured for ^{112,118,122}Sn targets.

A typical spectrum is shown in Fig. 2 (upper part), along with angular distributions in Fig. 2 (lower part) compared with distorted-wave Born approximation (DWBA) calculations using standard parameters [8,9]. At 6° these angular distributions are at their maximum and relatively flat. The 6° cross sections for the known lowest-energy $7/2^+$ and $11/2^-$ states are given in Table I, along with their ratio, which is found to be constant to

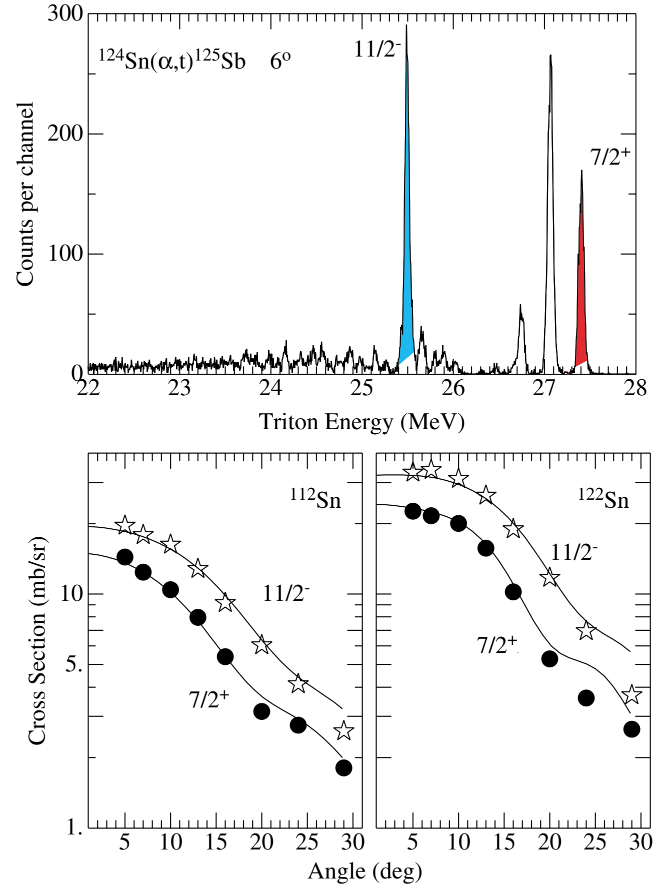

FIG. 2 (color online). The upper part of the figure shows a triton spectrum arising from the (α, t) reaction on a ^{124}Sn target. The two relevant peaks are indicated by shading. The lower part of the figure shows angular distributions for the $7/2^+$ (dots) and $11/2^-$ (stars) states in two Sn isotopes, together with DWBA calculations.

TABLE I. Cross sections (mb/sr) at 6° for the lowest $7/2^+$ and $11/2^-$ states, their ratios, and spectroscopic factors. The uncertainties in the cross sections are estimated at 10% and those in the ratio, at about 5%). The accuracy of the relative spectroscopic factors are estimated at 15%.

Target	$7/2^+$	$11/2^-$	Ratio	$C^2S_{7/2}$	$C^2S_{11/2}$
^{112}Sn	14.6	21.4	1.47	0.99	0.84
^{114}Sn	19.6	27.3	1.39	1.10	0.93
^{116}Sn	19.7	30.9	1.57	0.95	0.97
^{118}Sn	20.4	33.5	1.64	0.88	0.99
^{120}Sn	27.9	39.4	1.41	1.13	1.12
^{122}Sn	24.6	35.5	1.45	0.98	1.00
^{124}Sn	24.7	39.2	1.59	1.00	1.12

about 6%. The association of these cross sections with the full $g_{7/2}$ and $h_{11/2}$ strength is subject to uncertainty arising from the possibility of weak states at higher excitation containing fragments of these configurations. In the current data, the reaction on ^{116}Sn was found to have the most prominent peaks at higher excitation. The separation between the $g_{7/2}$ and $h_{11/2}$ centroids computed by including the higher peaks consistent with $\ell = 4$ or 5 changes the separation by 0.16 MeV. In the reaction on the ^{122}Sn target the $7/2^+$ and $5/2^+$ states are separated by 37 keV and could not be cleanly resolved. Here the energy centroid of this line was used to determine the relative contributions from the two states; this added little to the uncertainty.

DWBA calculations have been carried out using the code DWUCK [10], in both finite- and zero-range versions, as well as the code PTOLEMY [11] and using a range of distorting potentials from the literature. The spectroscopic factors vary depending on the choice of parameters for the potentials and the calculation by as much as a factor of 2. But for a given set of potentials, the spectroscopic factors across all the stable Sn isotopes appear to vary by $\pm 15\%$, with an apparent slight rise for the $11/2^-$ state. The Table I includes spectroscopic factors with the one normalization for both ℓ transfers and the seven targets. The distorting parameters for the DWBA calculations were from Refs. [8,9], and the values given are corrected for the isospin coupling with the occupation of the $T_>$ components obtained from neutron transfer reactions. This latter correction is less than 5%. The lowest $7/2^+$ and $11/2^-$ states in the Sb isotopes seem to have consistent spectroscopic factors, and within the usual constraints of transfer reactions exhibit near-single-particle-like $g_{7/2}$ and $h_{11/2}$ character.

The changing energy separation cannot be readily accounted for by postulating the very substantial admixtures that would be required. The simplest explanation is that the observed energy systematics are a consequence of a decreasing overall spin-orbit splitting, with a suggestion (in Fig. 1) that the effect is primarily in the energy of the intruder $h_{11/2}$ state.

A similar situation occurs in the $N = 83$ nuclei for the separation of the $h_{9/2}$ and $i_{13/2}$ neutron states. The available data on this energy difference [4] are shown in the upper right of Fig. 3, but the information on spectroscopic factors is not very quantitative, similar to the situation for the $Z = 51$ isotopes before the current work. For ^{133}Sn the value of Urban *et al.* is plotted [12], which is inferred from the spectrum of ^{134}Sb. The trend is very similar to that seen for the proton states (upper left in Fig. 3), and suggests that a decreasing spin-orbit interaction with increasing neutron excess is also present for neutrons. There is a hint in both cases that the interaction has a maximum slightly (4 to 7 units in N-Z) below the neutron excess corresponding to beta stability. This is approximately where the proton and neutron Fermi surfaces are equal and where the density distributions the are most similar in terms of the rms radius and diffuseness. Since the spin-orbit interaction, by its nature, is a surface effect it must be especially sensitive to changes in this region of the radial distribution of the core nucleons.

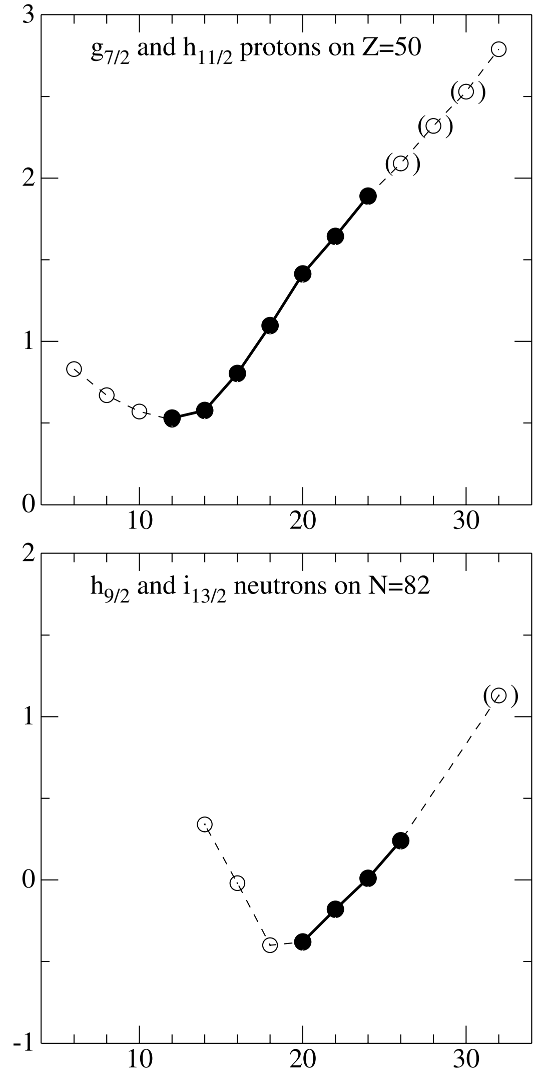

FIG. 3. Comparison of energy differences between pairs of high-j single-particle states for single nucleons outside the $Z = 50$ or $N = 82$ shells as a function of the neutron excess of the core. In the upper part the energy differences for proton single-particle states are shown that are the subject of the present work. Below are the available data on neutron single-particle states. The solid dots indicate that information is available from transfer reactions; the open circles represent cases where these configurations have been assigned using methods which are less sensitive to the single-particle nature. The parentheses indicate less certain or indirect assignments. The pronounced minimum in the two curves is near the neutron excess corresponding to maximum stability.

Unfortunately there are no other obvious regions of nuclei in which such data are available. The available data on hole states in $Z = 50$ or $N = 82$ nuclei indicate considerable fragmentation and will need more quantitative systematic studies. Elsewhere, for $Z = 28$ or 82, and $N = 126$ or 50, the existing data are much more limited. When beams of radioactive nuclei become available with sufficient intensity these trends can be explored further. In particular, it is interesting to note that the tentatively assigned $h_{11/2}$ proton state [5] in ^{133}Sb and the inferred energy of the $i_{13/2}$ state in ^{133}Sn [12] would suggest that the spin-orbit interaction for the unoccupied orbits has diminished to something on the order of half its normal value. A recent analysis of states around the ^{132}Sn core using a modified oscillator potential has also indicated the weakening of the spin-orbit strength [13]. Whether it is the spin-orbit interaction or some other effect that changes the energy of the intruder single-particle state, such a trend implies that for very neutron-rich nuclei the shell structure could be radically different from that in the stable region.

We wish to acknowledge helpful discussions with J. Cizewski, R. V. F. Janssens, C. J. Lister, A. H. Wuosmaa, and are indebted to W. Walters for sharing his results before publication and for helpful information. This research was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. W-31-109-ENG-38 and Grant No. DE-FG02-91ERRR-40609.

[1] S. C. Pieper and V. R. Pandharipande, Phys. Rev. Lett. **70**, 2541 (1993).

[2] F. Tondeur, Z. Phys. A **288**, 97 (1978); P. Haensel and J. L. Zdunik, Astron. Astrophys. **222**, 353 (1989); J. Dobaczewski, I. Hamamoto, W. Nazarewicz, and J. A. Sheikh, Phys. Rev. Lett. **72**, 981 (1994); J. M. Pearson, R. C. Nayak, and S. Goriely, Phys. Lett. B **387**, 455 (1996); G. A. Lalazissis, D. Vretenar, W. Pöschl, and P. Ring, Phys. Lett. B **418**, 7 (1998).

[3] B. Chen, J. Dobaczewski, K.-L. Kratz, K. Langanke, B. Pfeiffer, F.-K. Thielemann, and P. Vogel, Phys. Lett. B **355**, 37 (1995).

[4] Richard B. Firestone, *Table of Isotopes*, edited by Virginia S. Shirley (Wiley, New York, 1996).

[5] K. Sistemich, W.-D. Lauppe, T. A. Khan, H. Lawin, H. A. Selic, J. P. Bocquet, E. Monnand, and F. Schussler, Z. Phys. A **285**, 305 (1978); M. Sanchez-Vega, B. Fogelberg, H. Mach, R. B. E. Taylor, A. Lindroth, and J. Blomquist, Phys. Rev. Lett. **80**, 5504 (1998); M. Sanchez-Vega, B. Fogelberg, H. Mach, R. B. E. Taylor, A. Lindroth, J. Blomqvist, A. Covello, and A. Gargano, Phys. Rev. C **60**, 024303 (1999).

[6] W. B. Walters (private communication, based on the thesis research of C. Stone).

[7] For example, M. Conjeaud, S. Harar, and Y. Cassagnou, Nucl. Phys. **A117**, 449 (1968); T. Ishimatsu, K. Yagi, H. Ohmura, Y. Nakajima, T. Nakagawa, and H. Orihara, Nucl. Phys. **A104**, 481 (1967).

[8] G. Bassani and J. Picard, Nucl. Phys. **A131**, 653 (1969).

[9] G. R. Satchler, W. C. Parkinson, and D. L. Hendrie, Phys. Rev. **187**, 1491 (1969).

[10] P. D. Kunz, University of Colorado (unpublished).

[11] M. H. Macfarlane and S. C. Pieper, Argonne National Laboratory Report No. ANL-76-11, 1976 (unpublished).

[12] W. Urban *et al.*, Eur. Phys. J. A **5**, 239 (1999).

[13] Jing-ye Zhang, Yang Sun, Mike Guidry, L. L. Riedinger, and G. A. Lalazissis, Phys. Rev. C **58**, R2663 (1998).