effects which are different for the two geometries. The value of σ (poor) is low because some products of the $\pi^- - p$ interaction will pass through the last counter. On the other hand, σ (good) is high because a few more mesons are multiply scattered out of the last counter by the CH_2 than by the C attenuator, when the "good" geometry is used. We have assumed that 3 percent of the $\pi^- - p$ interactions give a charged secondary traveling within 6.6° of the beam direction, and 0.3 percent within 2.1°. This corresponds to the condition that all the interactions are elastic scatterings with an isotropic distribution in the center-of-mass system, or to the condition that $\frac{1}{3}$ of the interactions are elastic scatterings with a $\cos^2\theta$ distribution and that the rest send no charged products into the last counter. From a detailed multiple Coulomb scattering calculation it was found that about 9 and 7 percent of the mesons were scattered out of the last counter by the CH_2 and C absorbers, respectively, in the "good" geometry position, while no mesons were so lost in the "poor" geometry position. With these corrections the value of σ for both geometries becomes 47 mb. Thus the total $\pi^- - p$ cross section is 47±5 mb, for a mean energy in the absorber of 840 Mev. The stated error includes an estimate of the uncertainties in the corrections.

We have repeated the above measurements with 500-Mev incident mesons using mainly the 6.6° geometry. With similar corrections, the total $\pi^- - p$ cross section was found to be 27±5 mb for a mean pion energy of 470 Mev. This agrees well with the value of 25±3 mb at 450 Mev found previously at this laboratory.[1]

We find therefore a rise of approximately 20 mb in the total $\pi^- - p$ cross section from 470 to 840 Mev. Since the cross section has been found to be 34±3 mb at 1.5 Bev,[4] and, very recently, 47±4 mb at 1.0 Bev,[4] a second peak in the neighborhood of 900 Mev is indicated. Further study of this energy region has been undertaken by Lindenbaum and Yuan, and Piccioni and Cool.

We should like to thank Dr. George B. Collins and Professor J. Steinberger for their important roles in the initial stages of this experiment, and the many members of the cosmotron group who made it possible.

* This work was performed under the auspices of the U. S. Atomic Energy Commission.

[1] S. J. Lindenbaum and L. C. L. Yuan, Phys. Rev. (to be published).

[2] R. L. Garwin, Rev. Sci. Instr. **21**, 569 (1950).

[3] Leon Madansky (private communication).

[4] Cool, Madansky, and Piccioni (private communication).

Evidence for Subshell at $Z=96$

Glenn T. Seaborg
Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California

(Received September 18, 1953)

THE evidence is decisive that major nuclear shells are completed at 82 protons and 126 neutrons (both represented by the nuclide Pb^{208}) and these, along with major shells at 82 neutrons and certain lower nucleon numbers (N or $Z=20, 28, 50$), are well explained by the strong spin-orbit coupling model of Mayer[1] and Haxel, Jensen, and Suess.[2] This model suggests the filling of quantun states at certain intermediate points, and there is an accumulating amount of evidence that such "subshells" are also discernible, for example, at $Z=58$[3–5] and $Z=64$.[6,7]

The evidence from alpha radioactivity, both (1) the effect of the nuclear radius shrinkage on the relationship between energy and half-life and (2) the discontinuities in the plots of energy *vs* mass number at constant Z, gives a striking indication[8] of the closing of major shells at $Z=82$ and $N=126$. Application of these sensitive criteria as tests for the much smaller "subshell" effects in the regions $Z>82$ and $N>126$ leads to some evidence for such a subshell at $Z=96$ (curium).

Since it has been shown that the Gamow-Gurney-Condon type of formula for alpha decay applies very well to the ground state to ground state transition for even-even alpha emitters,[8] the known[9] alpha energies and partial half-lives were used in the Preston[10] form of the formula to calculate the nuclear radii of a number of even-even nuclides in the range $Z=84$ to 98. Using these radii, a value of r_0 was calculated for each nuclide from the relationship radius$=r_0A^{\frac{1}{3}}$ and the plot in Fig. 1 of the average value of r_0 (r_0 generally decreasing with increasing Z) for each element indicates a just discernible minimum or plateau at $Z=96$. The average value of r_0 for each element was plotted because there is no discernible regular variation of r_0 with A at constant Z.

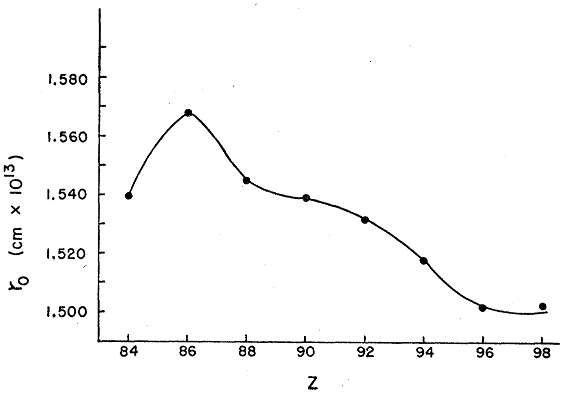

FIG. 1. Plot of average values of r_0 *vs* Z. The following isotopes are included: Po^{212}, Po^{214}, Po^{216}, Po^{218} for Po; Em^{220}, Em^{222} for Em; Ra^{222}, Ra^{224}, Ra^{226} for Ra; Th^{226}, Th^{228}, Th^{230}, Th^{232} for Th; U^{230}, U^{232}, U^{234}, U^{236}, U^{238} for U; Pu^{236}, Pu^{238}, Pu^{240}, Pu^{242} for Pu; Cm^{242}, Cm^{244} for Cm; Cf^{246}, Cf^{248} for Cf.

The stable shell of 82 protons is attained upon completion of the $h_{11/2}$ level and the spin of Bi^{209} (9/2) indicates that the 83rd proton begins the filling of the $h_{9/2}$ level as might be expected. However, if the $h_{9/2}$ level is raised in energy as more protons are added, so that the $f_{7/2}$ and $f_{5/2}$ are filled before the $h_{9/2}$ levels, one might expect subshell effects at $Z=90$ and 96. If the quantum states are filled in this order, the variation of r_0 with Z should perhaps also indicate an effect $Z=90$. A careful consideration of the values of r_0 in the region on both sides of $Z=90$ points to a barely discernible plateau in the variation of r_0 with Z at this atomic number.

In the case of $Z=96$ there is an additional argument which points to the completion of a subshell here. The known odd-even isotopes of berkelium, Bk^{243} and Bk^{245}, are highly "hindered"[8] in their most prominent modes of alpha decay, i.e., they decay much slower than the simple formula would indicate. This exceptional degree of hindrance is not observed for similar (odd-even) isotopes of any other odd Z alpha-particle emitter with the exception of bismuth ($Z=83$) where the slowed rates of decay are presumably to be associated with the closed proton shell (and consequent shrunken radius) at $Z=82$.

There are other lines of evidence which may also point to the filling of the $f_{7/2}$ and $f_{5/2}$ before the $h_{9/2}$ proton states. The spins of Np^{237}[11] and Am^{241}[12] are both 5/2 as expected on this basis. On the other hand, the spins of Ac^{227}[13] and Pa^{231}[14] have both been reported as 3/2, indicating perhaps that the odd proton occupies the $p_{3/2}$ state, whereas spins of 7/2 and 5/2 corresponding to $f_{7/2}$ and $f_{5/2}$ states, respectively, would be expected. Whether or not this indicates a breakdown of the single-particle model, it does seem to indicate that arguments based on spin values cannot be conclusive here. It is interesting to add that a consideration of the systematics of beta radioactivity in this region also leads to the assignment of spectroscopic states in agreement with the suggested higher position of the $h_{9/2}$ level energetically.

It is interesting to note that arguments based on spin values[15] indicate that in the case of neutrons the $f_{7/2}$ level fills before the $h_{9/2}$ level just after the completion of the major shell at 82 neutrons. Thus, the situation is analogous to that postulated for protons although the evidence is not clear on the relative position of the $f_{5/2}$ and $h_{9/2}$ neutron levels.

It seems likely that in the region following the major closed shell at 126 neutrons, which is completed with the filling of the $i_{13/2}$ states, the $i_{11/2}$ level is not occupied until the $g_{9/2}$ and possibly also the $g_{7/2}$ and $d_{5/2}$, etc., states are filled. Attempts to apply the aforementioned criteria of alpha-decay data do not lead to any discernible evidence for subshells up to $N=148$. Successful application of these criteria here probably awaits both a larger quantity of and more accurate alpha-decay data in this region. There is only one spin value known in this region, that of U^{235}, which has been reported as 5/2 or 7/2 with the former value the more probable.[16] Since U^{235} has 143 neutrons, either spin value would fit nicely with the view that the $i_{11/2}$ level lies above the $g_{9/2}$, $g_{7/2}$, and $d_{5/2}$ levels.

The generous help of F. Asaro and D. C. Dunlavey in making numerous calculations is gratefully acknowledged.

[1] M. G. Mayer, Phys. Rev. **75**, 1969 (1949); **78**, 16, 22 (1950).
[2] Haxel, Jensen, and Suess, Phys. Rev. **75**, 1766 (1949); Z. Physik **128**, 295 (1950).
[3] H. E. Duckworth and R. S. Preston, Phys. Rev. **82**, 468 (1951).
[4] Duckworth, Kegley, Olson, and Stanford, Phys. Rev. **83**, 1114 (1941).
[5] G. P. Dube and S. Jha, Phys. Rev. **85**, 1042 (1952).
[6] Coryell, Brightsen, and Pappas, Phys. Rev. **85**, 732 (1952); C. D. Coryell, Ann. Rev. Nuc. Sci. **2**, 305 (1953).
[7] Rasmussen, Thompson, and Ghiorso, Phys. Rev. **89**, 33 (1953).
[8] Perlman, Ghiorso, and Seaborg, Phys. Rev. **77**, 26 (1950).
[9] Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953); additional data: Cf^{248}—partial half-life 260 days, energy 6.26 Mev [E. K. Hulet, Ph.D. thesis, University of California Report UCRL-2283, August, 1953 (unpublished)]; U^{230}—energy 5.886 Mev, Th^{226}—energy 6.342 Mev, Ra^{222}—energy 6.567 Mev, U^{232}—energy 5.318 Mev [F. Asaro (private communication)]; U^{238}—energy 4.187 Mev, Th^{232}—energy 3.998 Mev [B. G. Harvey (private communication)]; Cf^{246}—partial half-life 40.6 hr [D. C. Dunlavey (private communication)].
[10] M. Preston, Phys. Rev. **71**, 865 (1947).
[11] F. S. Tompkins and M. Fred, J. Opt. Soc. Am. **39**, 357 (1949).
[12] M. Fred and F. S. Tompkins, Phys. Rev. **89**, 318 (1953).
[13] Tompkins, Fred, and Meggers, Phys. Rev. **84**, 168 (1951).
[14] J. E. Mack, Revs. Modern Phys. **22**, 64 (1950).
[15] P. F. A. Klinkenberg, Revs. Modern Phys. **24**, 63 (1952).
[16] G. L. Stukenbroeker and J. R. McNally, J. Opt. Soc. Am. **40**, 336 (1950).

Possible 0→0 (no) β Transitions in $4n+2$ Nuclei

O. Kofoed-Hansen
Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark

(Received October 1, 1953)

The 0→0 (no) β transitions so far identified take place between the $T=1$ states of nuclei of mass number $4n+2$, n being an integer. The cases are $C^{10}\rightarrow B^{10**}$,[1] $O^{14}\rightarrow N^{14*}$, and $Cl^{34}\rightarrow S^{34}$.[2] These transitions occur because the β^+ energy is large and because the energy difference between the $T=1$ and $T=0$ states is relatively small for these nuclei. The value of $E_{T=1}-E_{T=0}$ can be estimated by comparing Q values or $E_\beta{}^{\max}$ data for the $T_z=1$, $T_z=0$ partners or similar data for the $T_z=0$, $T_z=-1$ partners with correction for the neutron-proton mass difference and the Coulomb energy difference $(0.62/A^{\frac{1}{3}})\cdot(Z-1)Z$, or directly when the $T=1$ state is observed in a $T_z=0$ nucleus (Li^6, B^{10}, N^{14}, and Cl^{34}). Such an analysis leads to the curve shown in Fig. 1. The trend of the curve agrees with the observation made by Arber and Stähelin[2] that in Cl^{34} the $T=1$ state lies below the $T=0$ state. The closed shell 2×8 shows up as a peak in the curve.

The nuclear matrix element for the 0→0 ($\Delta T=0$, no) transition is independent of nuclear models. It just depends on the assumption of charge independence of nuclear forces,[3] and one finds

$$\left|\int 1\right|^2=T(T+1)-T_{z1}T_{z2}=2$$

for $T=1$ transitions.

So long as T is a "good quantum number" one would therefore expect ft to be constant for these transitions, and an experimental investigation of this constancy of ft would be a very valuable method for checking the validity of the charge independence of nuclear forces. High precision in the ft values is of course needed.

Moreover, this ft value would help in the determination of the amount of Fermi interaction present in β decay. For $g_F=g_{GT}$,[4] the expected ft value would be 2650, in general agreement with the uncertain values for C^{10}:$ft=6000\pm3000$ and O^{14}:$ft=3300\pm900$ and in close agreement with the more accurate value for Cl^{34}:$ft=2700\pm200$.

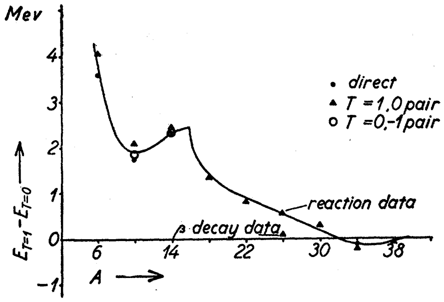

FIG. 1. The $E_{T=1}-E_{T=0}$ value as a function of A for $A=4n+2$ nuclei.

For $A>18$, the entire series of $4n+2$ nuclei should exhibit two 0→0 transitions per mass number. It happens, however, in cases where $E_{T=1}-E_{T=0}>0$ and the odd-odd isobar has a low-spin ground state or excited state below the $T=1$ state, that the latter state may decay preferably by a γ transition. In Table I a list is given of the states in question of mass number $18\leqslant A\leqslant 58$. The $T_z=0$ state can be obtained by (p,n) reactions and the $T_z=-1$ state by $(He^3,3n)$ reactions although many other reactions are also available. A systematic search for these transitions seems very promising. It is of interest to note that the value[5] $E_\beta{}^{\max}=3.1$ Mev for the Al^{26} decay disagrees with the mass determination from the reactions $Mg^{25}(d,n)Al^{26}$:$Q=5.58$,[6] and $Mg^{25}(d,p)Mg^{26}$:$Q=8.88$,[7] which give $\Delta Mc^2=2.52$ Mev. The latter point fits into the curve in Fig. 1, whereas the $E_\beta{}^{\max}$ value suggests that the transition actually observed is the 0→0 ($\Delta T=0$, no) transition. In agreement with this suggestion the observed values $E_\beta{}^{\max}=3.1$ and $t=6.6$ sec leads to $ft=2700$.

TABLE I. Expected values of $E_\beta{}^{\max}$ and half-life t for possible 0→0 (no) β transition of mass number $A=4n+2$, $18\leq A\leq 58$.[a] In those cases where experimental data already exist these data are given in brackets.

A	Element	Expected $E_\beta{}^{\max}$ (Mev)	Expected t (sec)[b]	Element	Expected $E_\beta{}^{\max}$ (Mev)	Expected t (sec)[b]
18	Ne	2.46	17	F	γ unstable	
22	Mg	3.06	7	Na	γ unstable	
26	Si	3.64	3.4	Al	3.22 (3.1)	6 (6.7)
30	S	4.19	1.8	P	γ unstable	
34	A	4.71	1	Cl	4.33 (4.45)	1.5 (1.45)
38	Ca	5.21	0.7	K	4.84	0.9
42	Ti	5.69	0.4	Sc	5.34	0.6
46	Co	6.16	0.3	V	5.81	0.39 (0.40)
50	Fe	6.61	0.2	Mn	6.28	0.27 (0.28)
54	Ni	7.06	0.16	Co	6.73	0.20 (0.18)
58	Zn	7.50	0.12	Ca	7.17	0.15

[a] The uncertainty in the expected $E_\beta{}^{\max}$ arises from the uncertainty in the Coulomb correction, and the uncertainty in the expected half-lives t arises from the uncertainties in $E_\beta{}^{\max}$ and in $ft=2650$. The Fermi integral has been calculated by the method of Moszkowski. (See reference 5.)
[b] The expected half-lives are the partial half-lives only; β-decay branching may reduce these values. This will occur especially in Ne^{18} and S^{30}.

Further observed cases of short-lived states in the $4n+2$ family are 0.40-sec V^{46}, 0.28-sec Mn^{50} and 0.18-sec Co^{54}.[8] If the Coulomb energy difference minus the proton-neutron mass difference is used for a calculation of $E_\beta{}^{\max}$ under the assumption of a 0→0 ($\Delta T=0$, no) transition, ft values of ~2700 result for these decays.

The A^{34} decay would be extremely interesting in connection with β-recoil experiments, since it is a monatomic gas and decays by pure Fermi interaction.

The present considerations are results of discussions with Mr.