energy and perhaps the correct monopole matrix element with the ground state. It would be interesting to see the same method applied in detail to C^{12}.

ACKNOWLEDGMENTS

We wish to thank Professor L. I. Schiff, who suggested this problem, for his advice and encouragement during its development, and Dr. A. M. Lane for some invaluable correspondence. We also thank Dr. J. P. Elliott and Dr. Ferrell and Dr. Vischer for communication of their result sprior to their publication. One of us (B. F. S.) was sponsored by the Office of Naval Research and the U. S. Naval Postgraduate School while at Stanford University.

PHYSICAL REVIEW VOLUME 103, NUMBER 4 AUGUST 15, 1956

Probable Absence of K Capture in the Decay of Lead-205†

R. H. Herber,* T. T. Sugihara,‡ C. D. Coryell, and W. E. Bennett,§ *Department of Chemistry and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts*

and

J. R. Huizenga, *Argonne National Laboratory, Lemont, Illinois*

(Received May 11, 1956)

A number of experiments designed to detect the K-capture decay of Pb^{205} are discussed. No K x-ray activity which could be ascribed to Pb^{205} was observed in deuteron-bombarded natural lead or neutron-irradiated 25.7% Pb^{204}. From these results, the L-capture half-life of Pb^{205}, and its absence in natural lead, it is concluded that Pb^{205} does not decay by K capture with a half-life in the range 2 seconds $< t_{\frac{1}{2}} < 10^{10}$ years.

In view of the recent determination[1] of the L-capture half-life of Pb^{205}, it seemed appropriate to present evidence for the lack of K capture. These data extend the K-capture half-life limits given in previous communications.[2,3]

The abundance of Pb^{205} occurring naturally has been reported to be less than 0.001%[4] of natural lead. The age of the solid shell of the earth has been estimated to be 4.5×10^9 years.[5] The abundance of Pb^{204} is reported to be $1.45\pm0.007\%$.[6] If it is assumed that the primorbial abundances of Pb^{204} and Pb^{205} were equal, one calculates from the present upper limit of 1 part Pb^{205} per 1450 parts of Pb^{204} that the half-life of Pb^{205} is $\leq 5\times10^8$ years.

A K-capture half-life in the region 5 days to 10^{10} years was excluded on the basis of two experiments. In the first of these, 0.400 g of lead, enriched to 25.7% in Pb^{204},[7] was exposed to an integrated flux of 3×10^{20} thermal neutrons/cm^2 in the Materials Testing Reactor (MTR). If the thermal-neutron capture cross section of Pb^{204} is taken to be 0.9 barns,[8] one calculates that 8.0×10^{16} atoms of Pb^{205} were present at the end of the irradiation if no decay occurred during the irradiation. After suitable radiochemical purification, the sample in the form of $PbSO_4$ was counted on a NaI scintillation spectrometer. The energy scale was calibrated with the 74.7-kev Pb x-ray of 6.4-day Bi^{206}. No activity (<1 count/min) was detected in this energy region (the Tl K x-ray energy is 72.7 kev). Taking 10 disintegrations/min as the upper limit of the Pb^{205} activity, one calculates the K-capture half-life to be longer than 10^{10} years. Since the irradiated sample was counted approximately one month after the irradiation, a K-capture half-life of the order of 5 days would have been detectable.

The second experiment involved the radiochemical separation of bismuth isotopes from a 0.005-in. lead foil bombarded with 1500 microampere-hours of 21-Mev deuterons. Using the same procedure for milking lead from the separated bismuth sample as was used in the L-capture experiment,[1] we found less than 0.2 count/min of activity due to Pb^{205} in the Tl K x-ray region, corresponding to a K-capture half-life longer than 5×10^8 years.

K-capture half-lives in the region of a few seconds to several days were investigated in two separate experiments. In the first of these, two samples of lead, one of natural abundance and the other enriched to 25.7% in Pb^{204}, were irradiated in the thermal flux region of the Brookhaven reactor. The two samples were counted within 4 minutes after the end of the irradiation in a single-channel pulse analyzer—NaI(Tl) arrangement which had been preset to detect Tl x-rays. No activity was observed that satisfied the 1.45 to 25.7 abundance of Pb^{204} in the two samples.

† Supported in part by the U. S. Atomic Energy Commission.
* Now at University of Illinois, Urbana, Illinois.
‡ Now at Clark University, Worcester, Massachusetts.
§ Now at University of Iowa, Iowa City, Iowa.
1 J. R. Huizenga and J. Wing, Phys. Rev. **102**, 926 (1956).
2 Sugihara, Herber, Bennett, and Coryell, Phys. Rev. **95**, 298 (1954).
3 J. R. Huizenga and C. M. Stevens, Phys. Rev. **96**, 548 (1954).
4 White, Collins, and Rourke, Phys. Rev. **101**, 1786 (1956).
5 Patterson, Brown, Tilton, and Inghram, Science **121**, 69 (1955).
6 Farquhar, Palmer, and Aitken, Nature **172**, 860 (1953).
7 Obtained from the Stable Isotopes Division, U. S. Atomic Energy Commission.
8 H. Pomerance, Phys. Rev. **88**, 412 (1952).

In the second experiment, the bismuth activities resulting from the Pb(d,xn)Bi reactions produced by 15-Mev deuterons in the MIT cyclotron were adsorbed on Dowex-1 anion resin and the lead was quickly eluted to look for a very short half-life. The eluate flowed rapidly into the well of a NaI scintillation counter. An increase in counting rate was observed, but the activity had a relatively long half-life ($t_{\frac{1}{2}}$ ~several hours) and could be attributed to the equilibrium concentration of Bi activities in the eluate. A half-life as short as 2 seconds could have been detected. No Pb activity, the initial concentration of which fell with the 14-day half-life of the Bi^{205} parent, could be observed in washings of the Dowex-1 column which would have removed any Pb decay daughters.[9–11]

[9] E. C. Campbell and F. Nelson, Phys. Rev. **91**, 499 (1953).
[10] F. Nelson and K. A. Kraus, J. Am. Chem. Soc. **76**, 5916 (1954).
[11] *Note added in proof*.—From the negative results of this experiment, nothing can be concluded regarding the existence of a short-lived Pb^{205} isomer, except that Bi^{205} electron capture does not heavily populate the $i_{13/2}$ level in Pb^{205}. In the analogous Bi^{207} decay, 87% of the e.c. (electron capture) transitions go to the $i_{13/2}$ state of the 0.8 sec Pb^{207m}. The half-life of this $h_{9/2}$ to $i_{13/2}$ transition is 9.2 years (8 y/0.87) and the competing $h_{9/2}$ to $f_{7/2}$ transition in B^{207} has an energy of only 50±40 kev. In the decay of Bi^{205}, this latter transition probably has considerably more energy, and may be the transition most influencing the half-life. The $h_{9/2}$ to $i_{13/2}$ decay may be roughly estimated by the ratio 14d to 9 years or 0.004, and this low rate of population of the $i_{13/2}$ level of Pb^{205m} may well be the reason that we do not observe this isomer.

These data indicate that Pb^{205} does not decay by K capture with a half-life in the range of 2 sec to 10^{10} years. A partial K-capture half-life of less than 2 sec can be ruled out on the basis of the observed[1] L-capture half-life of 5×10^7 years. Hence it is concluded that if Pb^{205} decays by K capture at all the half-life for this decay mode must be greater than 10^{10} years.

It is a pleasure to acknowledge the helpful chemical advice of Professor J. W. Irvine, Jr., and the assistance of the MIT and Argonne cyclotron crews.

PHYSICAL REVIEW VOLUME 103, NUMBER 4 AUGUST 15, 1956

Nucleon-Hole Interaction in *jj* Coupling*

SUDHIR P. PANDYA
Physics Department, University of Rochester, Rochester, New York
(Received May 9, 1956)

A theorem connecting the energy levels in jj coupling of a nucleon-nucleon and nucleon-hole system is derived, and applied in particular to Cl^{38} and K^{40}.

THE interaction of a nucleon with a hole in a closed shell has been considered by Racah and others[1] by an application of tensor algebraic methods. An alternate approach, independent of the nature of the two-nucleon interaction, is possible for the jj-coupling case. It is based on the property that the coefficients of fractional parentage (c.f.p.) connecting the states of one- and two-hole systems have a particularly simple analytical form.[2] This approach yields a theorem which gives the energy levels of a nucleon-hole system directly in terms of the energy levels of the corresponding nucleon-nucleon system.

Consider a proton (or a neutron) hole in shell j, and a neutron (or a proton) in shell j' coupled to a resultant spin J. The $2j$ protons are antisymmetrized with respect to each other, but not with respect to the neutron. (Note, however, that if, as we assume, all the lower-lying proton and neutron subshells are filled, this state does have a specified isotopic spin.) The interaction Hamiltonian for the system, $\sum_{i<j}H_{ij}$, may then be written as a sum of two parts: (i) The interactions among the identical nucleons giving the energy of the hole, $E[j^{-1}]$, independent of J, and (ii) the neutron-proton interactions. To evaluate the second part, c.f.p. are used to write the state of the hole $<j^{-1}|$ in terms of $2j-1$ antisymmetrized protons coupled to a single proton; then the neutron and the proton are recoupled by means of a Racah coefficient. Now, using the explicit analytical form for the c.f.p., the sum over the parent states of the hole can easily be carried out, leaving only a sum over the states J_0, of a proton in shell j coupled to a neutron in shell j'. Finally, we obtain for the relative energies $E_J[j^{-1}j']$ of the neutron-proton hole configuration,[3]

$$E_J[j^{-1}j'] = -\sum_{J_0} (2J_0+1)W(jj'j'j;JJ_0)E_{J_0}[jj'], \quad (1)$$

and the reciprocal relation,

$$E_J[jj'] = -\sum_{J_0} (2J_0+1)W(jj'j'j;JJ_0)E_{J_0}[j^{-1}j']. \quad (1')$$

* This work was supported in part by the U. S. Atomic Energy Commission.
[1] G. Racah, Phys. Rev. **62**, 438 (1942); Marty, Nataf, and Prentki, J. phys. radium **15**, 134 (1954).
[2] G. Racah, Phys. Rev. **63**, 367 (1943), Eq. (19); C. Schwartz and A. de-Shalit, Phys. Rev. **94**, 1257 (1954).
[3] For detailed derivation of (1) and (1′) see S. P. Pandya, U. S. Atomic Energy Commission Report NYO-7590 (unpublished), Appendix.