On the Virtual Excited State of the Be^9 Nucleus*

CONRAD LONGMIRE**
University of Rochester, Rochester, New York
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An attempt has been made, on the basis of a simple model, to understand the energy and width of the virtual level of the Be^9 nucleus, which was found by Davis and Hafner by inelastic scattering of protons from Be^9. The model used for the Be^9 nucleus was that of a neutron moving in a potential well provided by the remainder of the nucleus. There is no striking agreement numerically between the model and experiment, but a loose interpretation by means of the model is possible.

DAVIS and Hafner[1] have found an excited state of the Be^9 nucleus at an energy of 2.41 Mev above the ground state, or 780 kev above the energy of dissociation into Be^8 and a neutron. This virtual level was found through the inelastic scattering of protons from a thin Be^9 target, with magnetic-spectrographic analysis of the scattered protons. The experiment sets an upper limit of about 100 kev for the width of the level.

This letter concerns an attempt to understand the energy and width of the virtual level on the basis of a simple model. The model chosen was that of a neutron (the least bound neutron in the Hartree model of Be^9) moving in a potential well provided by Be^8, the remainder of the nucleus. That such a model might be used successfully in describing low energy processes involving Be^9 was first suggested by Guth,[2] who based his argument on the low binding energy (1.63 Mev) of the one neutron compared with about 8 Mev for the average binding energy per particle. Here the figure 1.63 Mev, the dissociation energy of Be^9, was determined experimentally by Collins, Waldman, and Guth[3] using both electron bombardment and photo-dissociation of Be^9, and also by Skaggs[4] by measuring the energy released in the reaction Be^9 (p, d) Be^8. The neutron-well model has been used with some success by Caldirola[5] to calculate the cross section for disintegration of Be^9 by electrons.

In the ground state, the neutron is in a P-state, since an S-state is ruled out for this particle by the exclusion principle (which must be continually fed into the Hartree model). Assuming the reasonable well-radius 5×10^{-13} cm, a well-depth of 11.96 Mev is required to make the neutron bound by 1.63 Mev. These are the constants used by Caldirola. With these constants there are no other bound states. However, the calculation neglects the spin-orbit coupling for the neutron, so that a bound $P_{\frac{1}{2}}$-state is not ruled out. (The ground state is thought to be a $P_{3/2}$-state.[6,7]

For the purposes of the present calculation, we define a virtual state in the following manner. With the normalization of the neutron wave function maintained in a unit sphere, the coefficient A_i of the Bessel function in the neutron wave function inside the well is calculated as a function of the neutron energy. If $|A_i|^2$ possesses a sharp maximum at some energy, we say there is a virtual state at this energy. That this definition of the state is correct for the inelastic scattering process can be seen by considering that the cross section is proportional to the square of a matrix element from which $|A_i|^2$ can be factored approximately. The remainder of the matrix element will hardly affect the shape of the state if the width of the peak in $|A_i|^2$ is small compared to the well-depth.

With Caldirola's values for the radius and depth of the well, there are no S- or P-states

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** National Research Predoctoral Fellow; now at the Department of Physics, Columbia University, New York.
[1] K. E. Davis and E. M. Hafner, Phys. Rev. **73**, 1473 (1948).
[2] E. Guth, Phys. Rev. **55**, 411 (1939).
[3] Collins, Waldman, and Guth, Phys. Rev. **56**, 876 (1939).
[4] L. S. Skaggs, Phys. Rev. **56**, 24 (1939).
[5] P. Caldirola, Nuovo Cimento, **4**, 39, No. 12 (1947).
[6] E. Feenberg and E. Wigner, Phys. Rev. **51**, 95 (1937).
[7] M. E. Rose and H. A. Bethe, Phys. Rev. **51**, 205 (1937).

near the observed energy. The second radial S-state occurs at 8.3 Mev, and is much too broad. In fact, virtual S-states with low radial quantum numbers have widths of the order of the well-depth, or larger, and can not properly be called levels. Since the first radial P-state is just bound, the second radial P-state is much too high. However, one might argue that the observed state is the lowest $P_{\frac{1}{2}}$-state, with a potential differing from that for the ground state because of the spin-orbit coupling. But even when the well-depth is decreased to bring the lowest P-state to the observed energy, the state is much too broad. The evidence here against a $P_{\frac{1}{2}}$-state is not conclusive, however, for the model may be at fault. Perhaps stronger evidence is the large separation from the ground state, compared to the presumably similar doublets[8, 9] of He^5 and Li^7. It is possible that the $P_{\frac{1}{2}}$-state is so close to the ground state that it was obscured by the elastic scattering in the work of Davis and Hafner.

Again with Caldirola's constants, the lowest D-state is at 3.7 Mev and is much too broad. However, there is not much reason to believe that the effective potential provided for the neutron by Be^8 remains the same for different angular momenta. The D-state is brought down to the observed energy when the well-depth is increased to 17.6 Mev. The width of the level is then about 100 Kev, and this narrowness is due to the angular momentum barrier. The width would be less for a smaller well-radius and a correspondingly greater well-depth; however, the constants required to push the width much below 100 kev seem unreasonable. Thus, if the actual value for the width turns out to be much smaller (100 kev is the width due to the experimental lack of resolution), the neutron-well model would have to be rejected.

The author also calculated the angular distribution of the inelastically scattered protons from the virtual level of Be^9, using the method of distorted waves, for 7-Mev incident protons. Although the crudeness of the model would not permit one to believe the fine details of such a calculation, it was felt that the general predictions, if any, might provide a test for the model. One such prediction is that the sum of forward plus backward scattering should predominate over scattering at right angles, provided the force between the incident proton and the neutron outside Be^8 in the Be^9 nucleus is of the ordinary (non-exchange) type. This is a consequence of the facts: (a) the incident protons have no angular momentum about their direction of motion; (b) protons with angular momentum up to $4\hbar$ or $5\hbar$ are scattered; (c) most of the scattering occurs with a change in the proton angular momentum by a vector of length zero or $1\hbar$ (other matrix elements are small). Therefore, the protons after scattering have mostly small components of angular momentum about the incident direction. The spatial distribution of such states is predominantly in the forward and backward directions, and is symmetric. However, the result of interference between the states is that only the average of forward and backward scattering predominates over that at right angles. The statements made here were borne out by the calculation; the average predominance of forward and backward compared to 90° scattering turned out to be about 3:1.

If the neutron-proton force is completely of the exchange type, then, by similar reasoning, the distribution of inelastically scattered protons should be approximately spherically symmetric. For an exchange force, the effective initial proton state is the actual initial state of the neutron, for which the angular momentum is uniformly distributed in direction. After scattering, the uniformity should still hold approximately. The scattering would then be in principle spherically symmetric, but there could be quite large "accidental" variations. However, calculation to check this conclusion was not carried through.

Experiments by Davis on the angular distribution are in progress. Preliminary indications[10] are that the scattering is approximately spherically symmetric. If this is borne out, it would suggest an exchange force for the neutron-proton interaction. However, this evidence is certainly not strong, for either exchange forces or the validity of the neutron-well model.

Assuming that the scattering is spherically symmetric, and using the experimental value of

[8] H. Staub and H. Tatel, Phys. Rev. **58**, 820 (1940).
[9] D. R. Inglis, Phys. Rev. **50**, 783 (1936).
[10] K. E. Davis, private communication.

the differential cross section at 37°, the total cross section for inelastic scattering from the virtual state is $(5.0\pm1.0)\times10^{-26}$ cm^2. The calculation, with ordinary forces, gave 4.5×10^{-26} cm^2, and it is not likely that the value for exchange forces would be widely different. It appears, therefore, that the neutron-well model gives approximately the correct value for the product of width times height of the state, as defined by $|A_i|^2$.

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Tc^{92} and Tc^{93} by Relative Cross-Section Measurements

D. N. KUNDU* AND M. L. POOL
Ohio State University, Columbus, Ohio

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Under 5-Mev proton and 10-Mev deuteron bombardments on natural Mo and on electromagnetically enriched Mo isotopes, activities of 2.7-hour, 47-minute, and 4.5-minute half-lives are found to be produced from Mo^{92}. The relative cross sections for the production of these activities are 25:127:1, respectively. On comparing these figures with those for the $(p, n):(p, \gamma)$ reactions from Mo^{95}, the 47-minute activity is assigned to Tc^{92}, and the 2.7-hour and the 4.5-minute activities to Tc^{93}. Tc^{92} decays by K-capture only attended with 1.5-Mev γ-rays. For the 2.7-hour Tc^{93}, the decay is 93 percent by K-capture and 7 percent by emission of positrons of maximum energy 0.83 Mev. There are also γ-rays of energy 2.0 Mev associated with this activity.

I. INTRODUCTION

A NUMBER of technicium activities are known to which no definite mass numbers have been assigned. The situation has remained inconclusive in spite of the recent use of electromagnetically enriched isotopes of Mo as target materials. The reason is that the usual method of assigning mass numbers to artificially produced radioisotopes by production through appropriate cross reactions from neighboring elements is not immediately available for deciding the issue due to the lack of suitable stable target isotopes. Relative cross-section measurements may be expected to be of use in such cases. In a previous paper,[1] enriched Mo isotopes were used to obtain the relative cross sections for (p, n) to (p, γ) reactions of Mo^{95}. These results have been utilized to assign mass numbers to three technicium activities of half-lives 2.7 hours, 47 minutes, and 4.5 minutes.

* Research Fellow of the National Institute of Health, Bethesda, Maryland.

[1] D. N. Kundu and M. L. Pool, Phys. Rev. **74**, 1574 (1948).

II. REVIEW OF Tc ACTIVITIES

2.7 Hours.—A technicium activity with a provisional value of a 2-hour half-life was reported[2] as a result of deuteron bombardments of Mo. This activity was later[3] shown to be a 2.7-hour positron emitter obtained by bombarding Mo with protons. To correlate these facts with the observations by others[4] that a similar activity is produced by alpha-bombardments of columbium, the 2.7-hour period was assigned[5] to Tc^{96}. Recently, by using a deuteron beam on enriched Mo^{92}, it has been shown[6] that the 2.7-hour activity is produced from Mo^{92}. However, no definite assignment of the activity to Tc^{92} or Tc^{93} could be made. The decay is claimed to take place by emission of positrons of maximum energy 1.2 ± 0.2 Mev and a hard γ-ray of 2.4 ±0.5 Mev.

[2] G. T. Seaborg and E. Segrè, Phys. Rev. **55**, 808 (1939).

[3] L. A. Delsasso, L. N. Ridenour, R. Sherr, and M. G. White, Phys. Rev. **55**, 113 (1939).

[4] L. D. P. King, W. J. Henderson, and J. R. Risser, Phys. Rev. **55**, 1118 (1939).

[5] G. T. Seaborg, Rev. Mod. Phys. **16**, 1 (1944).

[6] E. E. Motta and G. E. Boyd, Phys. Rev. **73**, 1470 (1948).