$Ce^{140}(d,p)Ce^{141}$ Reaction*

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Eight proton groups were observed, leading to levels in Ce^{141} at excitation energies of 0, 0.65, 1.12, 1.35, 1.47, 1.77, 2.15, and 2.41 Mev. Angular distributions and relative cross sections were used to make the following assignments: $\frac{7}{2}-$ for the ground state, $\frac{3}{2}-$ for the 0.65-Mev state, $\frac{3}{2}-$ for the 1.12-Mev state; $\frac{5}{2}-$ for the 1.77-Mev state, and $\frac{1}{2}-$ for the 2.41-Mev state.

A LARGE amount of experimental information about heavy nuclei has been collected in the region of the doubly closed shell of Pb^{208} [1] and in the region of the deformed nuclei[2] ($A=150-190$ and $A>222$). Quantitative explanations of the data in these regions have been given by the individual-particle model[3] and the unified model.[4] Much less information is available about the energy levels of heavy spherical nuclei that are not near doubly closed shells. Theoretical interest in these nuclei has recently increased with the investigation of a nuclear model that represents a residual two-body interaction by a pairing force plus a long-range force.[5]

The work reported in this paper is an experimental study of the $Ce^{140}(d,p)Ce^{141}$ reaction to give information about the energy levels of $_{58}Ce_{83}{}^{141}$. This nucleus has eight protons outside of the $Z=50$ closed shell and one neutron outside of the $N=82$ closed shell. It is expected to have one of the simpler level structures in this region. In particular, the influence of short-range forces on the neutron levels is small.

The properties of the ground state of Ce^{141} have been determined by several different experiments,[6,7] and information about one excited state has been given by the La^{141} beta decay.[8,9] This decay goes to the Ce^{141} ground state except for a weak inner beta group that is followed by a 1.37-Mev gamma ray. Additional information about the excited states of Ce^{141} is given here.

EXPERIMENTAL PROCEDURES AND RESULTS

Self-supporting evaporated targets of natural cerium (1–7 mg/cm²) were bombarded by the 10.85-Mev deuteron beam from the Indiana University cyclotron. The momenta and intensities of the outgoing proton groups were measured with a double-focusing magnetic spectrometer at a number of laboratory angles between 12.5° and 135°. The experimental arrangement and the handling of the experimental data have been described in earlier papers.[10,11]

Natural cerium is 88% Ce^{140}, 11% Ce^{142}, and the remainder is Ce^{136} and Ce^{138}. All of the intense proton groups were attributed to the $Ce^{140}(d,p)Ce^{141}$ reaction.

Oxygen and carbon contaminants in the targets interfered with the cerium proton groups at forward angles and were subtracted out. The subtractions were made by comparing oxygen and carbon targets with the cerium targets at the angles where the subtractions were necessary and at other angles where the contaminant peaks were not mixed with cerium peaks. A normalization of the targets was made at the latter angles. The oxygen subtraction was particularly troublesome and was responsible for large errors on some of the data.

The energy loss of 8.78-Mev ThC' alpha particles passing through the cerium targets was measured and used in the calculation of the number of target atoms. The energy loss was attributed to the cerium (oxides, carbon, and other impurities affect this assumption by about 5%), and stopping powers were taken from Whaling.[12] The momentum resolution of the spectrometer was 0.32% and the solid angle was 0.004 steradian. Errors on the absolute cross sections are ±40%.

Energy measurements were similar to those described in earlier work.[10,11] The error on the Q values is ±25 kev, except for the 1.06- and 1.8-Mev groups. The error for these groups is ±40 kev.

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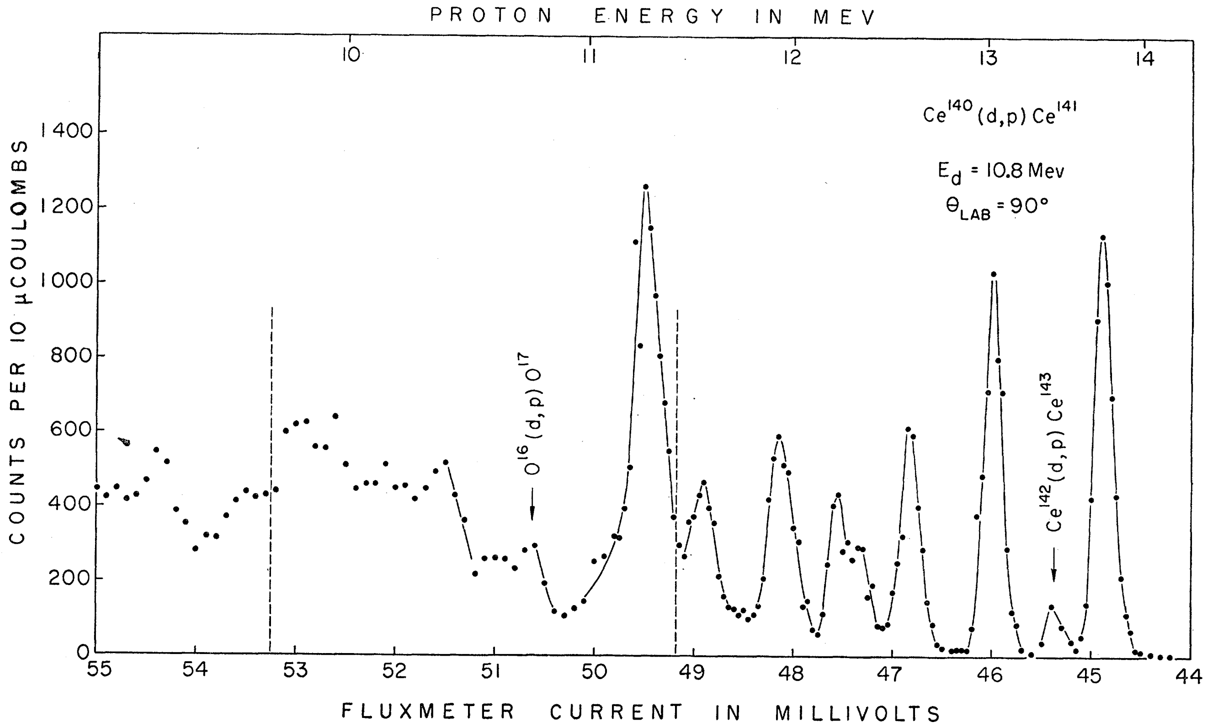

FIG. 1. A proton momentum spectrum for a metallic cerium target. Dotted lines separate the parts of the spectrum that were measured on different runs. The first five proton groups have expected experimental widths and presumably lead to single states in Ce^{141}. Angular distributions were measured for six of the first eight proton groups.

A momentum spectrum of the outgoing protons is shown in Fig. 1. Eight of the proton groups are assigned to the $Ce^{140}(d,p)Ce^{141}$ reaction. The ground-state group for the $Ce^{142}(d,p)Ce^{143}$ reaction is also shown. The first five proton groups have expected experimental widths and lead, presumably, to single states in Ce^{141}. The other groups are somewhat broader, and each may correspond to several closely spaced states in Ce^{141}. Figure 2(a) is a tentative level diagram for Ce^{141}. All of the groups are shown as single states.

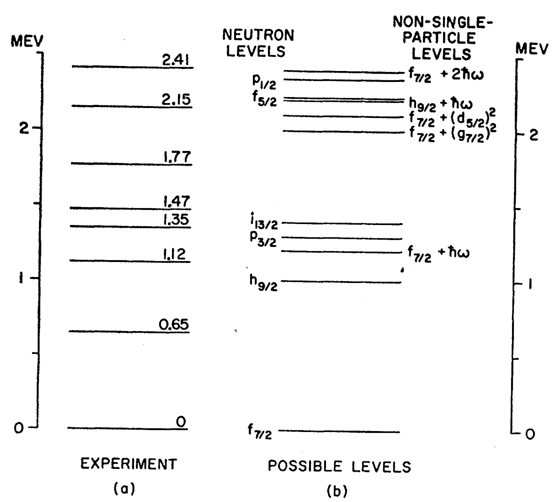

FIG. 2 (a) The experimentally observed Ce^{141} states below 3-Mev excitation. The 1.77-, 2.15-, and 2.41-Mev states are probably complex. (b) Possible zero-order level structure of Ce^{141}. The neutron levels are deduced from the experimental levels of Pb^{207} as described in the text. The non-single-particle levels are shown only as degenerate states. $\hbar\omega$ indicates vibrational and $(l_j)^2$ quasi-particle states. A phonon energy of 1.2 Mev is adopted for Ce^{141} and the quasi-particle energies of Ce^{140} [17] are used.

DISCUSSION

The interpretation of (d,p) reactions in cerium depends upon certain expectations about the nature of the reaction mechanism and about the level structure. There are a large number of possible final states for the compound nucleus reaction mechanism, and its cross section for excitation of any single state is small. The stripping mechanism should be the dominant reaction mechanism for the observed proton groups.

The deuteron bombarding energy of 10.85 Mev is slightly below the Coulomb barrier so that Coulomb and nuclear distortions prevent a comparison of the experimental angular distributions with Butler theory calculations. Nevertheless, the angular distributions should still have distinctive features that are representative of the angular-momentum transfer in the reaction. The experimental results appear to confirm this expectation. Moreover, some unpublished experimental data,[13] as well as distorted-wave calculations,[14]

[13] R. L. Preston, H. J. Martin, and M. B. Sampson, Phys. Rev. **121**, 1741 (1961).

[14] Tobocman's calculations (reference 18) give single-particle

indicate that a comparison of the experimental relative cross sections with Butler theory calculations will have some validity in deciding level assignments.

The stripping mechanism predominantly excites states that can be wholly or partly characterized as a single particle moving in a potential well, the shell model states. Shell model assignments for the neutrons in the $N=82-126$ shell are $2f_{7/2}$, $1h_{9/2}$, $3p_{3/2}$, $1i_{13/2}$, $2f_{5/2}$, and $3p_{1/2}$. These neutron states are expected in Ce^{141} although they may be perturbed by the protons in the unclosed proton shell. A qualitative estimate of possible levels of Ce^{141} is shown in Fig. 2(b). The single-particle levels are taken from the neutron hole states of Pb^{207},[15] and are corrected[16] for the fact that Ce^{141} has a smaller nuclear radius than Pb^{207}. The perturbing levels are vibrational states and proton-excited states from the levels of Ce^{140}.[17] Core excited neutron states are neglected.

The Ground State: $Q=3.21$ Mev

The spin of the ground state has been measured[7] and is 7/2. This is consistent with the shell model assignment of $2f_{7/2}$ for the 83rd neutron.

The ground state angular distribution is shown in Fig. 3. The shell model and the measured spin of the state indicate that this distribution should be representative of f-wave neutron capture in the (d,p) reaction. Tobocman has carried out distorted-wave calculations for this case and his calculations agree with the f-wave assignment.[18]

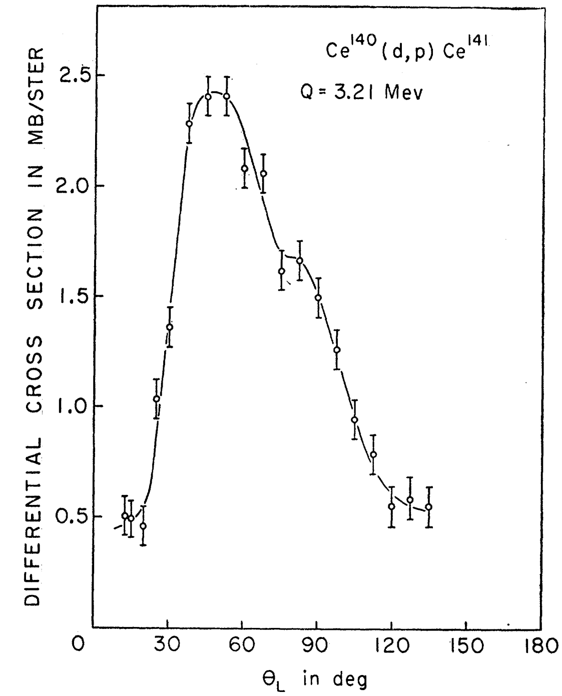

FIG. 3. Angular distribution of protons leading to the ground state of Ce^{141}. This distribution is representative of f-wave neutron capture.

The 0.65-Mev and 1.12-Mev Levels: $Q=2.56$ and 2.09 Mev

The angular distribution for the $Q=2.56$-Mev group is shown in Fig. 4. Tobocman's calculations agree with p-wave neutron capture. A similar distribution was found for the $Q=2.09$-Mev group and is also shown in Fig. 4.

The $3p_{3/2}$ neutron state is expected at about 1 Mev excitation. The first group of perturbing levels is also expected in this region ($f_{7/2}$+one phonon to give states with spins and parities $3/2-$, $5/2-$, $7/2-$, $9/2-$, and $11/2-$). It seems possible that the occurrence of two p states is due to strong mixing of the $3p_{3/2}$ state with the vibrational $3/2-$.

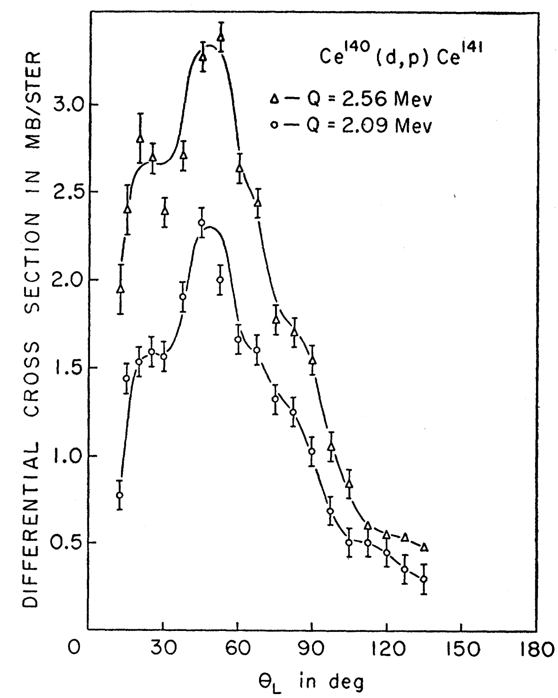

FIG. 4. Angular distributions for the 0.65-Mev and 1.12-Mev Ce^{141} states. These distributions are representative of p-wave neutron capture.

cross sections that are much smaller than the experimentally determined cross sections. However, the ratios of calculated cross sections for different l values are not appreciably different if either the Butler theory or the distorted-wave approximation are used.

[15] D. E. Alburger and A. W. Sunyar, Phys. Rev. **99**, 695 (1955). The $h_{9/2}$ level is assumed to be close to, but at a slightly higher energy than, the $f_{7/2}$ in accordance with B. L. Cohen, S. Mayo, and R. E. Price, Nuclear Phys. **20**, 360 (1960).

[16] Using the $\partial E/\partial R$ obtained by J. Blomqvist and S. Wahlborn, Arkiv Fysik **16**, 545 (1960). These $\partial E/\partial R$ are, of course, only valid within a small range of variation of the nuclear radius R, but actually the variation in R is only about 10% and only a qualitative result is attempted. No attempt is made to estimate pairing energy and collective corrections in Pb^{207}.

[17] As calculated by L. S. Kisslinger and R. A. Sorenson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **32**, No. 9 (1960). Lower vibrational energies are used since Ce^{141} is a "softer" nucleus than Ce^{140}.

[18] W. Tobocman (private communication).

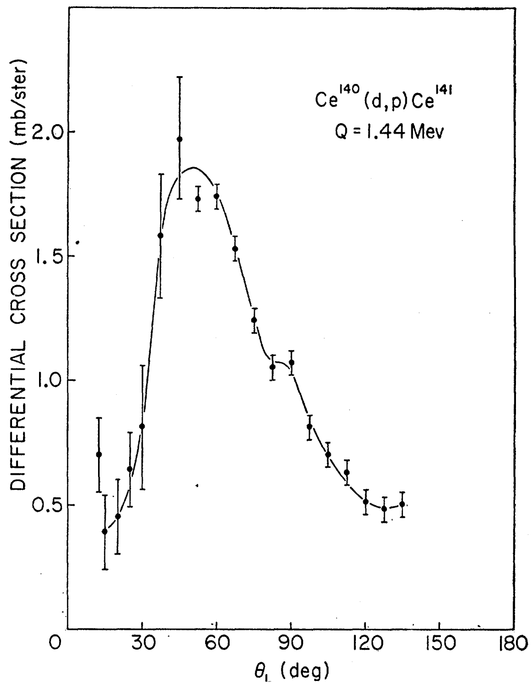

FIG. 5. Angular distribution for excitation of the 1.77-Mev Ce^{141} state. This distribution is similar to the one shown in Fig. 3 and is f wave.

The sum of the cross sections for the two states is 2.3 times larger than the ground-state cross section. This value is not inconsistent with the factor of 3 given by Butler calculations (harmonic-oscillator wave functions are used to calculate neutron reduced widths). Assignments of $3/2-$ are reasonable for the Ce^{141} states at 0.65 and 1.12 Mev excitation.

The 1.35-Mev Level: $Q=1.86$ Mev

The angular distribution for this level was not measured. This level is apparently the same level that is excited in the La^{141} beta decay. The $1h_{9/2}$ and $1i_{13/2}$ single-particle states are expected in this energy region. Mixing of the $f_{7/2}$ or $f_{5/2}$ single-particle states with other nuclear states may also be responsible for this state. ($3p_{3/2}$ states are not considered because the level is fed by beta decay.) The ft value for the beta transition to this state is 7.5 and is consistent with an $h_{9/2}$ assignment (assuming $7/2+$ for La^{141}). The (d,p) cross section is also consistent with an $h_{9/2}$ assignment, but $5/2-$ and $7/2-$ cannot be excluded.

The 1.47-Mev Level: $Q=1.74$ Mev

A complete angular distribution was not obtained for this level, although a partial distribution differed from the partial distribution of the 1.35-Mev level. The possible assignments are the same as those of the 1.35-Mev level, and also include $3/2-$ and $1/2-$. Assignments $5/2-$, $7/2-$, and $9/2-$ seem less likely as the state is not fed by the beta decay.

The 1.77-Mev Level: $Q=1.44$ Mev

The angular distribution for this state is shown in Fig. 5 and is similar to the f-wave ground state distribution. The ratio of this cross section to the ground-state cross section is 0.7 at forward angles. Statistical factors for the $f_{5/2}$ and $f_{7/2}$ shell-model states give a ratio of 0.75. The angular-momentum transfer is high and the Q-value dependence of the Butler calculation is not important. The $3f_{5/2}$ state is expected near 2 Mev excitation, so that a $5/2-$ assignment fits the 1.77-Mev state of Ce^{141}.

This state and the higher states are excited by proton groups that have widths larger than the experimental resolution. This means that the groups no longer lead to single states, probably because of the rapid increase in perturbing levels near 2 Mev excitation. Mixing from these levels is not expected to smear out the single particle levels over a region as large as the shell model spacing. This assumption is supported by experimental evidence.[19,20]

The 2.15-Mev Level: $Q=1.06$ Mev

The angular distribution for the proton group with $Q=1.06$ Mev is shown in Fig. 6. No conclusions can be made about this distribution.

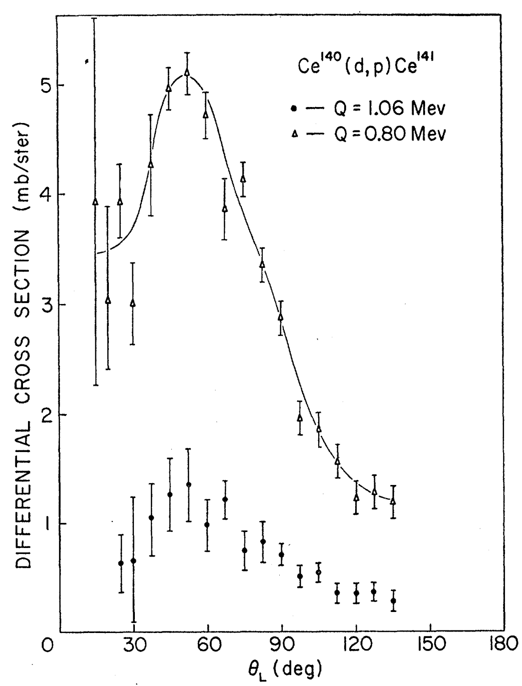

FIG. 6. Angular distributions for the 2.15-Mev Ce^{141} state and the 2.41-Mev Ce^{141} state.

[19] J. P. Schiffer, L. L. Lee, and B. Zeidman, Phys. Rev. **115**, 427 (1959).

[20] B. L. Cohen and R. E. Price, Nuclear Phys. **17**, 129 (1960).

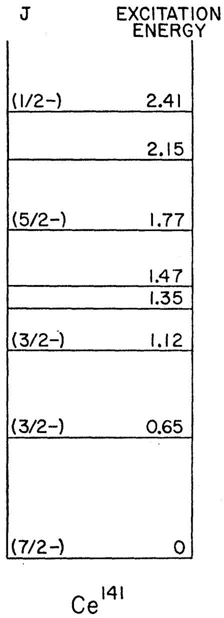

FIG. 7. Ce^{141} levels that were excited in this (d,p) work. The spin assignments for the different states are discussed in the text. Energies are in Mev.

The 2.41-Mev Level: $Q=0.80$ Mev

The angular distribution of the proton group with $Q=0.80$ Mev is also shown in Fig. 6. This distribution is similar to that of the $Q=2.56$ Mev and $Q=2.09$ Mev groups.

The $3p_{1/2}$ state is expected near this energy. Butler calculations for p waves vary markedly with Q and give a $p_{1/2}$ cross section at this Q that is 0.9 times the total $p_{3/2}$ cross section. The experimental cross section is 0.9 times the total $p_{3/2}$ cross section. A $3p_{1/2}$ assignment fits the Ce^{141} states near 2.41-Mev excitation energy.

Levels at Higher Excitation

An energy gap of about 3 Mev is expected between the $3p_{1/2}$ state and the next highest single-particle state $(2g_{9/2})$. A group of unresolved levels beginning at about 3 Mev excitation is shown in Fig. 1. The appearance of this group of states indicates, if the general features of the earlier interpretations are correct, that noticeable mixing can take place over rather large distances in Ce^{141}.

CONCLUSIONS

Figure 7 shows the energy levels of Ce^{141} and the spin and parity assignments that have been made in the preceding discussion. The experimental data indicate that mixing of the neutron levels with the perturbing levels is limited at excitation energies of less than 2 Mev. The number of "extra" levels found in the study of the (d,p) reaction is small. A comparison of the experimental neutron level structure with the level structure deduced from Pb^{207} shows qualitative agreement and encourages the possibility of a more quantitative fit.

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