Communications

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Gamow-state analysis of ^{54}Fe(d, n) to proton resonances in ^{55}Co

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Distorted-wave Born-approximation (DWBA) calculations are performed for ^{54}Fe(d,n) angular distributions at 10 MeV populating five proton resonances in ^{55}Co, at 5.17, 5.54, 5.74, 5.86, and 6.07 MeV excitation, using Gamow states as form factors. Results of the calculations are compared with previous DWBA analyses in which bound-state functions were used.

[NUCLEAR REACTIONS ^{54}Fe(d,n), E=10.0 MeV; calculated $\sigma(\theta)$; deduced proton-unbound ^{55}Co levels, J, π.]

The f-p shell nuclei have been extensively studied using direct nuclear reactions; the proton-rich nuclei have been reached usually via (^{3}He,d) and (d,n) reactions. The reactions ^{54}Fe(d,n)^{55}Co and ^{54}Fe(^{3}He,d)^{55}Co have been the object of several investigations.[1-5] All levels in ^{55}Co above 5.05 MeV excitation are proton-unbound, and extraction of spectroscopic information from the angular distributions for these levels has invariably been done using the usual zero-range distorted-wave Born approximation (DWBA) with form factors appropriate to weakly bound levels.[1-5]

It was thought worthwhile to repeat at least one such analysis, that of the ^{54}Fe(d,n)^{55}Co data of Couch *et al.*,[1] with complex energy-resonance eigenstates, or Gamow states, as form factors.[6] Couch *et al.* observed five proton-resonance states in ^{55}Co at 5.170, 5.541, 5.743, 5.860, and 6.066 MeV. Four of these states, excluding the 5.860-MeV state, have also been observed via (^{3}He,d).[3-5] They are not seen in (p,γ)[7-9] or (p,p)[10] studies. Indeed, from considerations of Coulomb-plus-centrifugal barrier penetrability, the single-particle width of an f-p proton resonance at such excitations can be estimated at ~10^{-10} MeV, so that the approximation of a weakly bound state should be a good one in this case, if it is ever good. Thus the calculations also serve to test the Gamow-state description of single-particle resonances.[6]

Gamow states were computed for all five resonances using the program GAMOV[6] which, for a given optical potential, finds the complex energy at which the single-particle wave function asymptotically approaches a purely outgoing Coulomb wave of complex argument. Details of the method of calculation have been given elsewhere.[6,11] The small widths involved in the present calculations required extremely accurate numerical construction of Coulomb functions of complex ρ and η. The program COUCAM[12] written by H. H. Wolter, was used for this purpose as a subroutine of GAMOV. Results of the calculations are given in the table. The geometrical parameters used in the program GAMOV were $r=r_{s.o.}=1.19$ fm, $a=a_{s.o.}=0.65$ fm, $V_{s.o.}=5.8$ MeV. The well depth V_p was searched,

TABLE I. Results of the calculations using the codes GAMOW and VENUS.

E_x (MeV)	l_j	C^2S_{GS}	C^2S_{bs} [a]	Γ_{spr} (MeV)	V_p (MeV)
5.170	$p_{1/2}$	0.147	0.13	$<10^{-16}$	58.31
···	$p_{3/2}$	0.070	···	$<10^{-16}$	55.54
5.541	$p_{1/2}$	0.056	0.055	1.1×10^{-11}	57.60
···	$p_{3/2}$	0.027	···	1.1×10^{-11}	54.82
5.743	$f_{5/2}$	0.19	0.22	4.9×10^{-11}	57.27
5.860	$d_{5/2}$	0.008	0.010	2.4×10^{-8}	73.35
6.066	$g_{9/2}$	0.19	0.18	4.5×10^{-10}	67.28

[a] Reference 1 (Couch *et al.*).

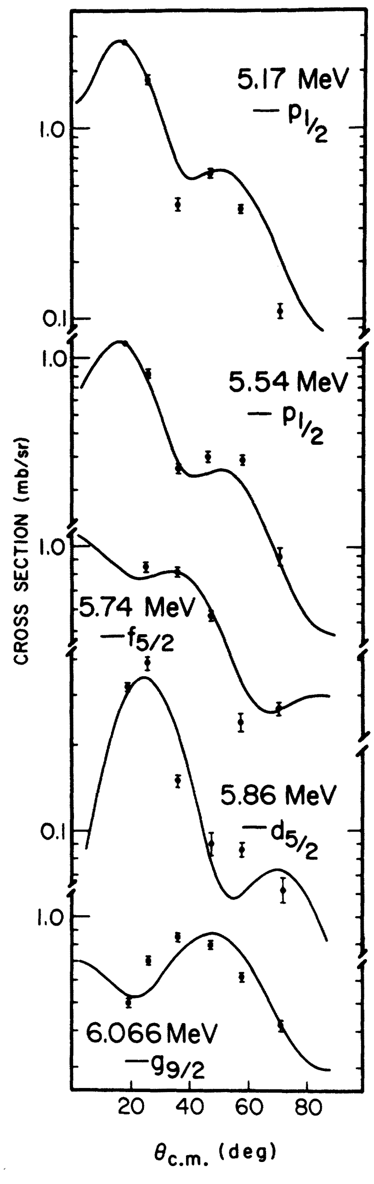

FIG. 1. Experimental data and DWBA predictions for ^{54}Fe(d,n)^{55}Co to proton resonances at 5.17, 5.54, 5.74, 5.86, and 6.07 MeV in excitation. The incident deuteron energy was 10.0 MeV. The data are those of Couch *et al.* (Ref. 1), while the DWBA calculations are those described in the text, using Gamow states as form factors.

for each resonance, and the resulting value is given in the last column of the table. The Gamow state corresponding to the 5.170-MeV level is for all practical purposes indistinguishable from a bound-proton state of negligible separation energy, having a single-particle width of less than 10^{-10} eV. The calculated widths of the other states are given in the fifth column of the table, as Γ_{spr}.

The DWBA calculations, with the Gamow states as form factors, were performed just as outlined earlier, using the Abel method of regularization.[6] The deuteron optical potential was taken from the survey by Lohr and Haeberli,[13] while the neutron potential is due to Perey.[14] In a standard notation (V, W, W_D, $V_{s.o.}$, r, a, r', a', $r_{s.o.}$, $a_{s.o.}$, r_c) the deuteron parameters are 106.26, 17.14, 0.0, and 7.0 MeV, 1.05, 0.86, 1.41, 0.70, 0.75, 0.50, and 1.29 fm while the neutron parameters are 45.0, 0.0, 11.0, and 7.5 MeV, 1.25, 0.65, 1.25, 0.47, 1.25, 0.65, and 1.25 fm. The (d,n) zero-range strength was taken as 1.58×10^4 MeV^2 fm^3. The DWBA program VENUS was used.[15]

Results of the calculations are shown in Fig. 1, together with the data of Couch *et al.*[1] The extracted spectroscopic factors C^2S are given in the table. Some peculiarities of the data are worth mentioning. The two states at 5.17 and 5.54 MeV are clearly both $l=1$, but their angular distributions are rather different. The differences are not due to j dependence; DWBA calculations with deuteron potentials which describe tensor polarization, such as used here,[13] are capable of describing the usual Lee-Schiffer j dependence,[16] but the calculations for $p_{1/2}$ and $p_{3/2}$ are nevertheless essentially the same from 0 to 70°, the range covered by the present data. The calculated curves for these two states, shown in Fig. 1, are for $p_{1/2}$. Thus the reason for the difference, which was also apparent in the DWBA analysis of Couch *et al.*,[1] is unknown. Finally, the data for the $l=4$ transition at 6.066 MeV show an angular shift in peak of nearly 10° relative to the calculations, an effect also seen in the analysis of Couch *et al.* Considering the low cross sections for the $l=4$ and $l=2$ states, and their considerable distance from the single-particle strengths for $g_{9/2}$ and $d_{5/2}$, important contributions to the observed cross sections from processes other than simple stripping are a strong possibility.

For comparison with the C^2S values we have extracted, we include in the table the C^2S values resulting from the analysis of Couch *et al.*[1] The agreement in absolute magnitude is fortuitous, since Couch *et al.* used different optical potentials, a different form factor and form-factor geometry, and a different zero-range strength. But the relative agreement in C^2S from state to state between the two analyses is remarkable, and serves as a mutual check both on the weakly bound state and Gamow state calculations.

We may conclude that for such low-lying proton resonances, the approximation of a weakly bound state is excellent for spectroscopic purposes, and earlier spectroscopic studies using that approximation have not produced misleading results.

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