s- and p-wave neutrons on ^{30}Si and ^{34}S: Coupled channels optical model

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Recent analysis of ^{30}Si and ^{34}S neutron scattering data in the low energy resonance region has resulted in optical potential parameters having different s- and p-wave well depths. We show that a proper inclusion of the collective excitations of the target nucleus reduces this difference to well within the limits of experimental error and confirms the ability of the neutron resonance reaction to act as a meaningful probe of the bulk properties of target nuclei.

The preceding paper by Carlton *et al.*[1] has presented an interesting analysis of neutron-nucleus scattering data in the low energy resonance region using ^{30}Si and ^{34}S as targets. Although the results confirm the neutron resonance reaction as a powerful probe of the macroscopic influence of the target, they also indicate that the optical parameters are quite different for s and p waves.

The experimental analysis discussed in the preceding paper involves an R-matrix analysis of the high resolution resonance data, an energy averaging, and finally, determination of an average S matrix. This in turn leads to average partial wave shape elastic and compound cross sections. A fit of these cross sections using a standard spherical optical model yields real potential well depths which are 20% larger for p waves than for s waves.[1,2] Similar analyses of ^{206}Pb and ^{40}Ca + n resonance data[3,4] indicate that, for near-closed shell nuclei, the real s- and p-wave well depths are similar in magnitude. Although this apparent anomaly could have several origins, we will concentrate on one obvious limitation of the spherical model analysis in that it neglects the coupling to vibrational or rotational collective modes of the target.

As a preliminary investigation into the reasons for the necessity of a large difference between s- and p-wave potentials, we have examined the influence of the closed channel coupling of low-lying vibrational states of the ^{34}S core and rotational states of the ^{30}Si core on the shape elastic and compound scattering cross sections. The necessity for choosing a different excitation character for ^{34}S and ^{30}Si seems dictated as much by an examination of the spectrum[5] as by previous theoretical work indicating that the sulfur isotopes show a predominance of vibrational excitations,[6] whereas the ^{28}Si and ^{30}Si spectra have strong rotational character.[7] The imaginary component of the potential was introduced to reflect the fact that the macroscopic models used cannot include the more complicated excitations which would be present in a random phase approximation (RPA), doorway state, or continuum shell model calculation.[8]

As in a previous calculation[9] for ^{32}S, we have used the coupled channels code written by Raynal[10] based on methods previously discussed by Tamura.[11] In the case of ^{34}S we coupled the low-lying one-phonon vibrational spectrum [0^+(g.s.)-2^+(2.127 MeV)-3^-(4.622 MeV)] with the deformation parameters $\beta_2=\beta_3=0.26$. The second 2^+ state in ^{34}S occurs at 3.3035 MeV and most likely is not a pure two phonon state.[12] Test calculations coupling it as a one phonon state with $\beta_2=0.08$ (Ref. 13) result in small effects on the cross sections, and we ignore it for the present paper.

The ^{30}Si + n case was treated in two ways: First we coupled the [0^+(g.s.)-2^+(2.24 MeV)-3^-(5.49 MeV)] levels in a one-phonon vibrational model with $\beta_2=\beta_3=0.33$. Next we used a rotational model treatment, coupling the [0^+(g.s.)-2^+(2.24 MeV)-4^+(5.28 MeV)] levels using the values $\beta_2=-0.39$, $\beta_4=+0.30$ which are similar to those previously obtained for ^{28}Si + n at 14.9 MeV by Haouat *et al.*[14] We also used the same fixed geometries as were used for the spherical analysis, and varied only the well depth parameters $V^{l=0}$, $W_D^{l=0}$, $V^{l=1}$, $W_D^{l=1}$, and V_{so}. The coupled channel code ECIS79 was used, which allows for the use of different potentials for different collective target modes. For instance, if the 0^+-2^+-3^- coupling is employed, the target and neutron states which are coupled together for a given channel spin and parity are given in Table I. For each set of potential parameters, two runs were made. For the s wave partial cross sections, we choose the potential parameters appropriate to the channel spin $\frac{1}{2}^+$, which contains as its predominant part the $l=0$ scattering, while for $p_{1/2}$ and $p_{3/2}$ we choose potential parameters appropriate to the channel spin $\frac{1}{2}^-$ and $\frac{3}{2}^-$, respectively. Since only the $l=0$ and $l=1$ data are known, we used in practice positive (negative) parity potentials V^+ (V^-) instead of $V^{l=0}$ ($V^{l=1}$).

In Fig. 1(a) we plot the $s_{1/2}$ shape elastic cross section for the ^{30}Si + n reaction at $E_n=500$ keV as a function of V^+, the real positive parity potential well depth (whose predominant component for the $J^\pi=\frac{1}{2}^+$ channel is $l=0$). The $p_{3/2}$ cross section [Fig. 1(b)] is plotted as a function of V^-, the real negative parity potential well depth. Because of a lack of experimental $\frac{1}{2}^-$ resonance data, the $p_{1/2}$ cross section is not given. Carlton *et al.*[1] assumed a reasonable value of $V_{so}=6$ MeV for their spherical

TABLE I. The target and neutron states which are coupled together for each given channel spin and parity for 0^+-2^+-3^- coupling.

Channel spin J^π	Target state	Neutron state l	Neutron state J	Parity of optical potential used
$\frac{1}{2}^+$	0^+	0	$\frac{1}{2}$	+
	3^-	3	$\frac{5}{2}$	−
	3^-	3	$\frac{7}{2}$	−
	2^+	2	$\frac{3}{2}$	+
	2^+	2	$\frac{5}{2}$	+
$\frac{1}{2}^-$	0^+	1	$\frac{1}{2}$	−
	3^-	2	$\frac{5}{2}$	+
	3^-	4	$\frac{7}{2}$	+
	2^+	1	$\frac{3}{2}$	−
	2^+	3	$\frac{5}{2}$	−

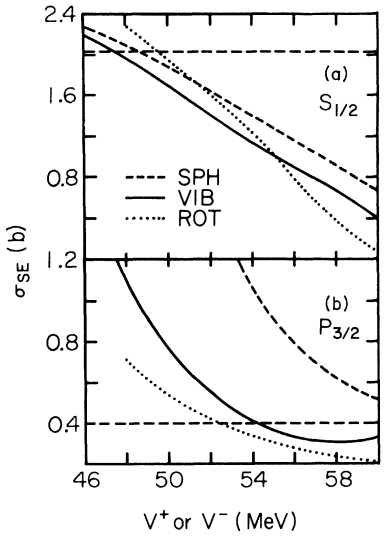

FIG. 1. Shape elastic cross sections versus real well depth V for n+^{30}Si at $E_n=500$ keV. (a) and (b) give $s_{1/2}$ and $p_{3/2}$ cross sections vs V^+ and V^-, respectively, for spherical (dashed curve), vibrational (solid curve), and rotational (dotted curve) models. The horizontal dashed lines indicate the "experimental" values given by Carlton *et al.* (Ref. 1).

analysis. The horizontal lines represent the "experimental" values described in the preceding paper. The potential parameters other than the one varied were kept the same (at values close to the final values chosen) for the spherical, vibrational, and rotational schemes. It can be seen that for s waves, the best values for V^+ are 48.5, 47.5, and 49.5 MeV for spherical, vibrational, and rotational models, respectively. Therefore the effect of coupling on s-wave scattering is small. However, for $p_{3/2}$, the best values for V^- are 62, 54, and 52 MeV, respectively. Therefore the difference in the V^+ and V^- well depths is about 13 MeV for the spherical model, 6.5 MeV for the vibrational model, and 2 MeV for the rotational model. Both types of coupling drastically reduce the l or parity dependence of the real well depths, an effect which shows up also for ^{34}S. Although ^{30}Si has a rotational character, the potential parameters other than V^+ and V^- were still obtained by a vibrational model fit to the six partial wave cross sections versus energy. Thus the 2 MeV difference between V^+ and V^- could possibly be further reduced. If we assume that the unknown $p_{1/2}$ cross sections are reasonably fit by the same potential parameters as $p_{3/2}$, we obtain for the $p_{1/2}$ shape elastic cross section, $\sigma_{SE}=0.20$ b with $V^-=58.5$ MeV in a spherical optical model calculation. This cross section is also well fit using $V^-=52$ MeV in a rotational model coupled channels model.

The well depth parameters obtained for the best fit to the ^{30}Si and ^{34}S data using the coupling schemes described above are given in Table II along with the corresponding spherical parameters. The coupled channels V_{so} well depths are smaller than the spherical values but remain about the same for $A=30$ and 34. The values of W_D are also reduced in the coupled channels model, but the ratio W_{D+}/W_{D-} remains about the same as for the spherical model.

In conclusion, we have demonstrated that the ability of the neutron resonance reaction to act as a reliable probe of the macroscopic effects of the target can be increased by a dynamical treatment of the target-nucleus coupling. We have specifically shown that in the case of the ^{30}Si and ^{34}S + n reactions a proper treatment of the deformed nature of the target nucleus reduces the difference in s- and p-wave real well depths to at most 2 MeV. Since this difference is within the limits of experimental error, the need for the introduction of an l dependence is not press-

TABLE II. Well depth parameters and corresponding spherical parameters obtained for the best fit to the ^{30}Si and ^{34}S data using coupling schemes described in the text.

		V (MeV)		W_D (MeV)		V_{so} (MeV)	
Target	l	sph	CC	sph	CC	sph	CC
^{30}Si	0	48	49.5	2	1		
	1	62	51.5	4.2	2	7	3.3
^{34}S	0	51.5	50.5	3	2.5		
	1	58.5	51	2.5	2.5	6	3.5

ing. However, this argument would not be conclusive without some mention of the possible effects of nonlocality on l dependence. Of course, the coupling of the ground state to different collective states produces a form of nonlocality when studied in a single channel spherical model. We have just shown that the effect of coupling on the real well depth is large in the resonance region. Previous calculations[15] of equivalent single channel potentials due to coupling effects for 8 MeV neutrons on ^{76}Se and ^{82}Se have led to small surface effects on the real potential well, and larger ($\sim$30%) effects on the imaginary potential well which exhibit a pronounced parity dependence. Other studies employing different local approximations to several real nonlocal potentials derived from microscopic theories show a large decrease with l in the well depth at small distances, with this effect moving to larger radii for larger l values. Recent calculations[16] employing two different equivalent local potential approximations to the Perey-Buck nonlocal potential for n-^{40}Ca scattering at 24 MeV show this interior damping of the $l=0$ potential compared to the $l=2$ potential inside $r\approx 1.5$ fm. The question arises as to whether this difference will affect scattering at energies below 1 MeV. As a test in collaboration with Johnson, we have fitted the experimental partial wave cross sections for the ^{32}S + n reaction in the energy region 100—1000 keV using the Perey-Buck nonlocal potential with the nonlocality parameter $\beta=0.85$. The fit, which was as good as the spherical local potential model fit, was obtained with the Perey-Buck parameters $V^{l=0}=72$ MeV, $V^{l=1}=90$ MeV, $W^{l=0}=7$ MeV, $W^{l=1}=5$ MeV, and $V_{so}=13$ MeV. The result is that the same 20% increase in p-wave over s-wave real potential well depth was required as for the spherical case. Therefore, in this case we attribute a major fraction of this 20% difference to the vibrational character of ^{32}S. This justifies to some extent the priority we have given to the coupled channel technique in analyzing the results of the neutron resonance reaction.

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