(^{3}He,n) reaction near and above $Z = 82$

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(Received 15 January 1979)

The two-proton stripping reaction (^{3}He,n) has been studied for targets ^{194,196}Pt, ^{204}Hg, ^{204,206,208}Pb, and ^{232}Th at a beam energy of 33.3 MeV. The neutrons were detected in a time-of-flight spectrometer with a nine meter flight path yielding approximately 500 keV energy resolution. The data near $Z = 82$ are analyzed in terms of a pairing vibrational model with corrections for proton particle-hole and proton-neutron pairing interactions. The results are also used to test several two-proton wave functions for levels in ^{210}Po, and an empirical normalization for the (^{3}He,n) reaction is extracted. The implications of these results to the energy of an "alpha-vibration" state in ^{208}Pb are discussed.

[NUCLEAR REACTIONS ^{204,206,208}Pb, ^{204}Hg, ^{194,196}Pt (^{3}He,n) $E = 33.3$ MeV; measured $\sigma(E,\theta)$, Enriched targets, DWBA analysis.]

I. INTRODUCTION

The concept of an elementary mode of excitation in nuclei produced by the pairing interaction has been shown to be well founded by a large body of nuclear data. Direct two-particle transfer reactions have proved to be a successful method for examining this mode because of the sensitivity of such reactions to the coherent aspects of the pairing force. One particular expression of the pairing mode is the existence of pairing vibrations around closed shells. Within this model one expects pairing phonons to build up a vibrational structure as a function of the number of pairs of particles or holes outside of the vacuum (the closed shell). Such a vibrational picture results in clear predictions for the expected energy positions and intrinsic strengths of the pairing phonons. It also predicts excited multiple phonon states in the various nuclei. The limiting features of such a model are the anharmonic effects due to phonon-phonon interactions, particle-hole interactions, and blocking effects resulting from insufficient degeneracy in the active shell model orbitals. When there are sufficient phonons outside of the vacuum, a vibrational picture will no longer be appropriate. In that case a pairing condensate is formed leading to a superconducting phase. Here all the transition strength lies in the ground states for the two-nucleon transfer reaction and the transition strength remains essentially constant for a fairly wide range of target masses.

The two-neutron transfer reaction has been used extensively to examine the validity of the pairing vibration model near all of the closed neutron shells. The two-proton transfer reaction has, however, been limited primarily to lighter nuclei for the (^{3}He,n) reaction, and only recently have the experimental techniques been sufficient to permit studies at the $Z = 38$ (Ref. 1) and $Z = 50$ (Ref. 2) shell closures. Heavy ion reactions involving the transfer of two protons are difficult to interpret because of the reaction dynamics and indistinguishability of angular momentum transfers, although such a study has been published for the $Z \approx 82$ mass region.[3]

The present results are primarily concerned with the $Z \approx 82$ closed shell and the pairing vibration picture for proton pairing states in this region. Because ^{208}Pb represents a doubly closed shell for protons and neutrons, this nucleus represents an excellent vacuum about which to study the pairing phonons and their residual interactions. There is also a large amount of data concerning the empirical strengths of proton and neutron particle-hole interactions. A preliminary letter on these results has already been reported.[4]

We also discuss here the case of the ^{232}Th(^{3}He,n)^{234}U reaction to illustrate the applicability of the present experimental techniques to the heaviest nuclei.

II. EXPERIMENTAL TECHNIQUES

The experiment was performed at the neutron time-of-flight facility of the University of Colorado cyclotron. This facility[5,6] utilizes a beam swinger to change the angle of the incident beam on the target relative to fixed 5-cm-thick by 20-cm-diameter liquid scintillation neutron detectors.

Three such detectors are located at a distance of about 9.3 m from the target. The neutron time resolution is approximately 1 ns for each detector. The experimental arrangement utilized here was an electromagnet located inside of the scattering chamber to deflect the ^{3}He beam approximately 4° after passing through the target. The beam was then stopped on a tantalum finger which served as a Faraday cup. This finger was shielded from the neutron detectors by the collimator box, thus permitting measurements at 0°. Such a procedure was absolutely necessary to eliminate the direct illumination of the detectors by neutrons from the beam stop.

A solid state monitor detector was located in the scattering chamber at 50° to serve as a target thickness monitor and a beam pulse width monitor. All relative cross section information was provided by this monitor. In addition, a comparison of the ^{3}He elastic scattering using this monitor to optical model predictions[7] provided the thicknesses of the various targets.

The Pt targets were run with average beams of 1–1.5 μA, while 0.2 and 0.6 μA were used for the Hg and Pb targets, respectively, to minimize target deterioration. Target thicknesses for the ^{194,196}Pt were 3.4 and 3.9 mg/cm^2, respectively. The ^{204}Hg target thickness was determined by a comparison to the ^{196}Pt and ^{206}Pb targets using the monitor detector and predicted optical model elastic scattering corrections to be 5.1 mg/cm^2. The ^{204,206,208}Pb targets were of 5.4, 4.6, and 3.5 mg/cm^2 thicknesses, respectively, these being determined either from the monitor results or the use of an α-particle energy loss gauge, or both. The two methods gave equivalent results within the 15% error limit placed on the absolute cross section scale. The thicknesses of the targets were principally chosen to give an adequate counting rate. The ^{232}Th target was approximately 3.5 mg/cm^2 in thickness.

The mercury targets consisted of HgO deposited on an enriched ^{24}Mg foil of 0.35 mg/cm^2 in thickness, and then overlayed with a second ^{24}Mg foil to contain the HgO and reduce loss of the material from beam heating. The use of ^{24}Mg removed the problem of high energy background neutrons produced by the (^{3}He,n) reaction on the ^{13}C content of normal carbon foils. The Pt, Pb, and Th targets were all rolled metallic foils.

Angular distributions for the ^{194,196}Pt, ^{204}Hg, and ^{206}Pb targets were taken in 2° steps from 0 to 22°. More limited angular distributions were taken for the ^{204}Pb and ^{232}Th targets which were observed only at 0°, 8°, and 16°, and 2°, 10°, and 18°, respectively.

III. EXPERIMENTAL RESULTS

Time-of-flight spectra for the ^{194,196}Pt, ^{204}Hg, ^{206,208}Pb, and ^{232}Th targets are shown in Fig. 1. As these figures illustrate, ^{12}C contamination can be of a severe problem in these heavy nuclear targets. The ^{204}Hg(^{3}He,n)^{206}Pb spectrum is also limited in excitation energy by the ^{24}Mg(^{3}He,n)^{26}Si states which begin to interfere near 6 MeV exci-

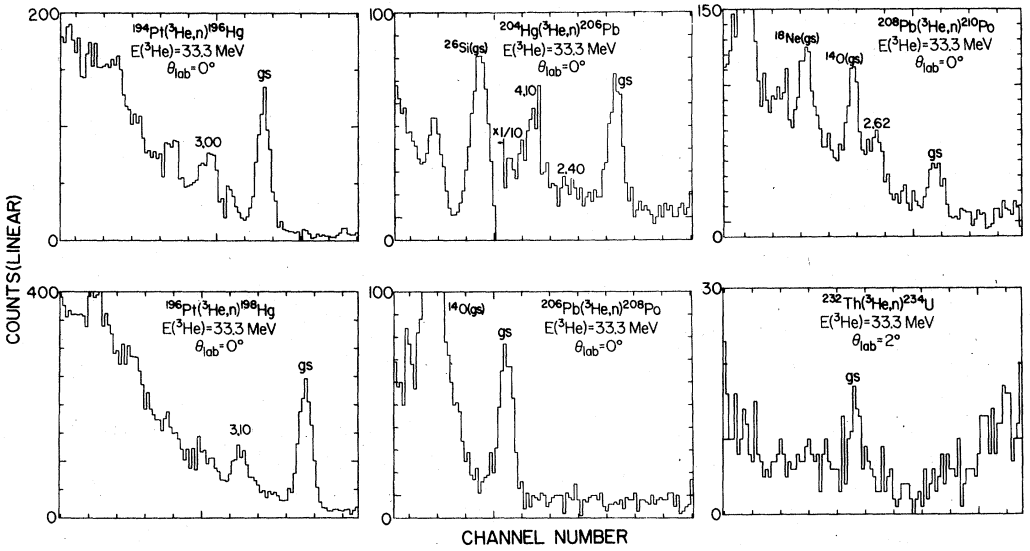

FIG. 1. Typical neutron time-of-flight spectra observed in this work. The time dispersion is 0.17 ns/ch with increasing flight time running from right to left. Excitation energies of prominent peaks are given in MeV.

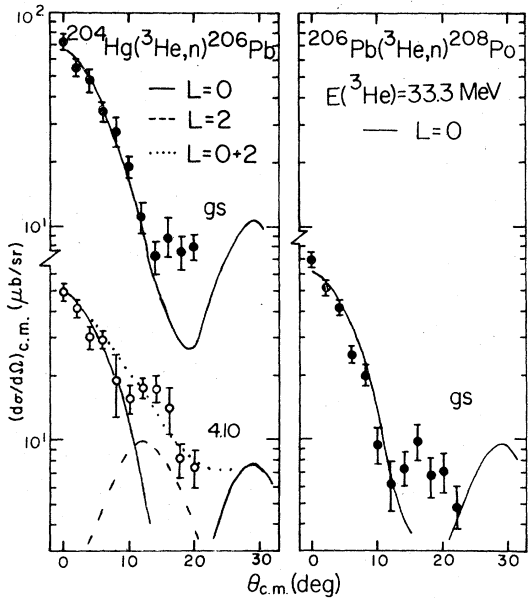

FIG. 2. Angular distributions obtained from the ^{204}Hg(^{3}He,n) ^{206}Pb and ^{206}Pb(^{3}He,n) ^{208}Po reactions. The solid curves are the results of DWBA calculations described in the text.

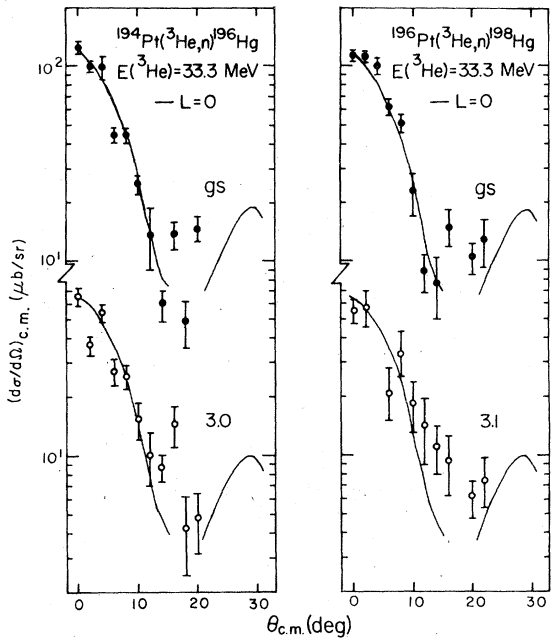

FIG. 4. Angular distributions obtained from the ^{194}Pt(^{3}He,n) ^{196}Hg and ^{196}Pt(^{3}He,n) ^{198}Hg reactions. The solid lines are the results of DWBA calculations described in the text.

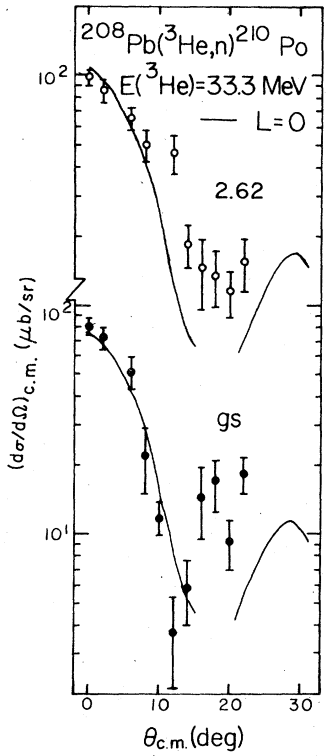

FIG. 3. Angular distributions obtained from the ^{208}Pb(^{3}He,n) ^{210}Po reaction. The solid curves are the results of DWBA calculations described in the text.

tation in ^{206}Pb.

Angular distributions for the ground state and 4.10 MeV state in ^{206}Pb are shown in Fig. 2 along with the ground-state transition leading to ^{208}Po. Those for the ground and 2.62 MeV levels in ^{210}Po are shown in Fig. 3, while those leading to 0^+ states in the Hg isotopes are shown in Fig. 4. Table I contains a list of all of the 0^+ transitions seen in this experiment along with their excitation energies and 0° cross sections, except for the ^{234}U ground-state transition for which the 2° cross section is listed.

TABLE I. 0^+ states with E_x and $\sigma(0°)$.

Residual nucleus	E_x (MeV)	$d\sigma/d\Omega$ [a] (μb/sr)
^{210}Po	0	81 ± 7
^{210}Po	2.62 ± 0.1	99 ± 9
^{208}Po	0	70 ± 4
^{206}Po	0	85 ± 11
^{206}Pb	0	73 ± 6
^{206}Pb	4.10 ± 0.1	50 ± 4
^{198}Hg	0	113 ± 7
^{198}Hg	3.1 ± 0.1	55 ± 7
^{196}Hg	0	124 ± 9
^{196}Hg	3.0 ± 0.1	68 ± 6
^{234}U	0	14 ± 5

[a] All cross sections quoted are at 0° with the exception of ^{234}U for which the 2° cross section is given.

TABLE II. Optical model parameters.

	V (MeV)	r_r (fm)	a_r (fm)	W (MeV)	r_i (fm)	a_i (fm)	W_D (MeV)	W_{so} (MeV)	r_{so} (fm)	a_{so} (fm)
^{3}He [a]	175.0	1.14	0.723	17.5	1.6	0.81				
n [b]	40.8	1.17	0.750	5.9	1.26	0.58	2.2	6.2	1.01	0.75
Proton well	c	1.25	0.65					(25)		

[a] From Ref. 7.
[b] From Ref. 8; V, W, and W_D were adjusted with mass and energy according to the formulas therein.
[c] V was adjusted to fit $\frac{1}{2}S_{2p}$, 25 is the value of λ_{so}.

IV. DISTORTED WAVE ANALYSIS

Distorted wave (DW) calculations were carried out to make Q-value and mass corrections to the results so that accurate comparisons between residual nuclei could be made. A variety of optical potentials was examined with similar results. The preferred set is shown in Table II, where the ^{3}He potential is from Ref. 7 and the neutron potential from Ref. 8. The resultant fits to the data are shown in Figs. 2 through 4.

DW calculations also permit a test of two-proton wave functions outside of the ^{208}Pb core. A variety of such wave functions exists in the literature based on shell model, effective interactions, and pairing multipole calculations. The spectroscopic information is obtained from the relation

$$d\sigma/d\Omega_{\rm exp}=N(\tfrac{1}{2}\pi\Delta^2)^{3/2}\,\frac{2J_B+1}{2J_A+1}\,\frac{S_{AB}C^2}{2L+1}\,\epsilon\,\frac{d\sigma}{d\Omega_{\rm DW}}\,, \quad (1)$$

where $d\sigma/d\Omega_{\rm DW}$ is the result of the DWBA calculation, N is an empirical normalization, and Δ is the rms radius of the ^{3}He particle (taken to be 1.7 fm in these calculations). The spins of the initial and final nuclei and the angular momentum transfer are given by J_A, J_B, and L. The spectroscopic amplitude S_{AB} is one for all calculations described here, and the isospin Clebsch-Gordan coefficient C^2 is also taken to be 1. The quantity ϵ is the enhancement factor, which should be close to 1.0 in a realistic calculation.

Unfortunately, there is not yet a systematic survey of targets using realistic wave functions to obtain a value of N. Such a survey has been performed for (t, p) reactions[9] and a value of $N=22$–23 obtained, in agreement with (p, t) results[10]; however, significant dependence on the choice of optical potentials is noted. Analysis of the (^{3}He, n) reaction leading to the closed shell at $N=50$, the tin isotopes, yields ϵ values near 2

TABLE III. Wave functions and ϵ values for proton particle states.

Residual nucleus	E_x (MeV)	Ref.	Configuration $h_{9/2}^2$	$f_{7/2}^2$	$f_{5/2}^2$	$p_{3/2}^2$	$p_{1/2}^2$	$i_{13/2}^2$ [a]	ϵ ($N=22$)	ϵ ($N=30$)
^{208}Po	0	12	0.821	0.367	0.150	0.095	0.053	−0.397	1.15	0.84
^{210}Po	0	12	0.821	0.367	0.150	0.095	0.053	−0.397	1.48	1.09
^{208}Po	0	13	0.885	0.362	0.145	0.110	0.068	−0.335	1.10	0.81
^{210}Po	0	13	0.885	0.362	0.145	0.110	0.068	−0.335	1.42	1.04
^{208}Po	0	14	0.862	0.356	0.171	0.131	0.083	−0.364	1.03	0.76
^{210}Po	0	14	0.862	0.356	0.171	0.131	0.083	−0.364	1.33	0.98
^{208}Po	0	15	0.89	0.20	0.10			−0.39	3.4	2.5
^{210}Po	0	15	0.89	0.20	0.10			−0.39	4.4	3.2
^{208}Po	0		1.0						36.7	27.0
^{210}Po	0		1.0						47.4	34.8
^{210}Po	2.62	12 (2.68)	−0.483	0.845	0.170	0.066	0.039	−0.131	1.74	1.28
^{210}Po	2.62	13 (2.70)	−0.462	0.821	0.096	0.069	0.041	−0.322	1.70	1.25
^{206}Pb	4.10	12 [b]	0.821	0.367	0.150	0.095	0.053	−0.397	1.10	0.81

[a] The negative sign is used because of the $(-1)^l$ phase factor found in the DWBA code DWUCK.
[b] Assumes same wave function as ^{210}Po ground state.

TABLE IV. Wave functions and ϵ values for proton hole states.

Residual nucleus	E_x (MeV)	Ref.	Configuration $s_{1/2}^2$	$d_{3/2}^2$	$d_{5/2}^2$	$h_{11/2}^2$	$g_{7/2}^2$	ϵ ($N=22$)	ϵ ($N=30$)
^{206}Pb	0	12	−0.786	−0.445	−0.257	0.323	−0.119	1.22	0.90
^{206}Pb	0	14	−0.707	−0.552	−0.249	0.410	−0.165	1.16	0.85

when realistic wave functions based on proton pickup reactions are used.[2] Thus, we might expect the normalization N value to lie between 20 and 40 depending upon optical model choices.

Exact agreement with the (t, p) value of N should not be expected for the $(^3\mathrm{He}, n)$ reaction as they are not exact charge exchange analogs of each other. In fact, the present reaction provides an ideal case for an empirical determination of N, for any given set of optical potentials, as there exist numerous wave function sets relative to the doubly closed ^{208}Pb cores. These sets have been shown to reproduce the (t, p) cross sections quite well as, for example, in the case of ^{210}Pb.[11] Tables III and IV summarize the results for various wave functions relative to the ^{208}Pb core for the $(^3\mathrm{He}, n)$ reaction using both a value of $N=22$ and the value $N=30$ which is, as noted later, the average value of N giving $\epsilon=1.0$ for the various theoretical wave functions. These wave functions are based on effective interactions,[12] multipole pairing operators,[13] and generator-coordinate methods.[14] Also shown in the table are the results of an empirical wave function based on the ^{210}Po (t, α) ^{209}Bi reaction[15] and the use of a pure $(h_{9/2})^2$ configuration for the Po isotope and a pure $(s_{1/2})^{-2}$ configuration for the Hg isotopes. Only the Hg → Pb and Pb → Po ground-state transitions were used to determine the empirical value of N. The Pt → Hg results as well as excited 0^+ results are shown in the table. Only the forward-going amplitudes were included in the calculation. In the case of the ^{206}Pb $(^3\mathrm{He}, n)^{208}$Po reaction the wave functions for ^{210}Po were used as these are the only ones available.

V. DISCUSSION

A. Pairing vibration model

The two-proton binding energies for the ground-state final masses and the excited 0^+ states observed here provide a study of the proton-pairing vibration model. This model, unlike the neutron-pairing vibration case, is seriously affected by particle-hole, particle-particle, and hole-hole interactions because of the large Coulomb contribution to these interactions. The neutron interaction is small compared to the phonon energy, being about −126 keV for the two-neutron-hole–two-neutron-particle interaction in the ^{208}Pb-pairing vibration at 4859 keV.[16] On the other hand, the single-proton particle-hole interaction is −324 keV from the ^{209}Bi$(^3\mathrm{He}, d)^{208}$Pb reaction,[17] and this is expected to lower the unperturbed proton-pairing vibration in ^{208}Pb to $(6600 - 4\times 324)$ keV = 5305 keV. This has been suggested by Blomqvist[16] to correspond to a weak 0^+ state seen in the ^{210}Pb$(p, t)^{208}$Pb reaction[18] at 5260 keV. Such shifts in proton-pairing vibration energy centroids have been confirmed in the Cd$(^3\mathrm{He}, n)$Sn reactions[2] when particle-hole corrections are included.[19]

The ^{206}Hg$(^3\mathrm{He}, n)^{208}$Pb reaction is impractical because of the short half-life of the target, so the ^{204}Hg$(^3\mathrm{He}, n)^{206}$Pb reaction was performed. Prediction of the pairing vibration for protons in this reaction involves corrections for proton particle-neutron-hole and proton-hole-neutron-hole interactions, as well as the proton particle-hole interaction, since both neutrons and protons are unfilled in the excited state. The simplest procedure to account for these corrections is to take $S_{2p}(^{206}\mathrm{Pb}) - S_{2p}(^{208}\mathrm{Po}) - 4\times E_{ph} \approx 5400 - 1300 = 4100$ keV. Here, S_{2p} are the two-proton separation energies and E_{ph} is the proton particle-hole interaction energy mentioned above. Use of the ^{206}Pb and ^{208}Po values automatically takes into account the other interactions. The actual calculation of the proton-pairing vibration energy in ^{206}Pb in terms of all the elementary interactions is as follows. The neutron pair removal energy is obtained from $S_{2p}(^{208}\mathrm{Pb}) - S_{2p}(^{206}\mathrm{Pb}) \approx -1700$ keV, which must be subtracted from the harmonic energy of 6600 keV, obtained from $S_{2p}(^{208}\mathrm{Pb}) - S_{2p}(^{210}\mathrm{Po})$, and yields about 4900 keV. Corrections must then be made for the two-proton-hole—two-neutron-hole interaction using $S_{2n}(^{204}\mathrm{Hg}) - S_{2n}(^{206}\mathrm{Hg}) \approx +1100$ keV and the two-proton-particle—two-neutron-hole interaction using $S_{2n}(^{208}\mathrm{Po}) - S_{2n}(^{210}\mathrm{Po}) \approx -800$ keV. Finally the two-proton particle-hole term of −1300 keV is added, which yields a value of ≈3900 keV for the predicted energy. The observed energy was 4100 ± 100 keV, in reasonable agreement with

both methods. A technique identical to the latter method has been used to calculate the energy of the neutron-pairing vibration in ^{206}Hg with better than 100-keV agreement with a recently observed value.[20] This calculation involves the same proton and neutron residual interactions.

The pairing vibration model also suggests definite relations between the intensities of the state transitions. First of all, the cross sections should be independent of neutron number for a series of isotopes. This may be checked by comparing the ^{206,208,210}Po (ground-state) cross sections. The three Po transitions are essentially equal, as are the two Hg transitions, indicating that the proton-neutron interactions discussed above may be having at most only small effects on the cross sections.

A summary of the present results for the strongest 0^+ states is compared to the pairing vibration model in Table V. The energy agreement is excellent when the appropriate corrections for the particle-hole effects are made. The intensities represented by the σ values in the table are also in reasonable agreement for the one-phonon states and indicative of the trend suggested by the model for two-phonon ground states. The principal deviations lie in the effect of the neutron holes in ^{206}Pb, roughly a 15% effect, and the reduction in strength as compared to predictions for the two-phonon ground-state strengths discussed below. Actually, the enhancement factor for the pairing vibrational state at 4.1 MeV in ^{206}Pb is equal to that of the ground state in ^{208}Po as the model would suggest (see Table III), and it appears that the neutron holes interact with this phonon equally in both cases. The ratio observed here is 0.94 ± 0.1, as compared to the harmonic value of 1.0. This excellent agreement in strength and energy gives credence to the predicted energy of 5.30 MeV in ^{208}Pb for the proton pairing vibration. This prediction would agree with the theoretical estimate of Blomqvist[16] and the observation of a 0^+ state at this energy in the ^{210}Pb$(p,t)^{208}$Pb reaction,[18] as noted previously.

The reduction in strength of the Pt to Hg ground-state transitions from a value of 2.0 σ_r, where σ_r is the strength of the proton-pairing removal phonon represented by the Hg to Pb cross section, may be explained by blocking effects in the microscopic structure of the phonon. The orbital closest to the Fermi surface is the $s_{1/2}$ and, without pairing, this would be empty at Hg. The pairing force smears out the Fermi surface so that it only partially empties at Hg. Because this orbital has significant intrinsic strength in two-nucleon transfer reactions, there is a substantial effect on the transition strength. Identical effects are also noted in the neutron case where the $p_{1/2}$ orbit is blocked as one moves below the closed neutron shell at N=126. The ratio of the transition strengths for the $[(2,0) \rightarrow (1,0)]/[(1,0) \rightarrow (0,0)]$ reactions is 1.7 in that case, quite similar to the present values near 1.5. Thus the proton and neutron situations are very similar at ^{208}Pb with low-degeneracy orbitals below the shell closure having substantial anharmonic effects on the phonons as one goes away from the shell. Above the shell closure there are high degeneracies in the orbitals, and the lowest orbits also have small intrinsic transfer strength. Thus, little blocking effect would be anticipated in reactions involving Po as a target and a ratio closer to 2 would be expected. The analogous effect was indeed observed in the ^{210}Pb$(t,p)^{212}$Pb reaction.[21]

TABLE V. Comparison to pairing vibration model.

Residual nucleus	Phonon transfer	Harmonic pred.[a] ($E_{x-n}E_{ph}$) MeV	n	Observed E_x (MeV)	σ (Harmonic)[c]	σ (Observed)
^{210}Po	(0,0)→(0,1)	g.s.	0	g.s.	$1.0\sigma_a$	$1.0\sigma_a$[b]
^{208}Po	(0,0)→(0,1)	g.s.	0	g.s	$1.0\sigma_a$	$(0.86 \pm 0.1)\sigma_a$
^{206}Pb	(1,0)→(0,0)	g.s.	0	g.s	$1.0\sigma_r$	$1.0\sigma_r$[b]
^{206}Pb	(1,0)→(1,1)	4.11	4	4.10	$1.0\sigma_a$	$(0.94 \pm 0.1)\sigma_a$
^{198}Hg	(2,0)→(1,0)	g.s.	0	g.s	$2.0\sigma_r$	$(1.5 \pm 0.2)\sigma_r$
^{198}Hg	(2,0)→(2,1)	2.81	8	3.1	$1.0\sigma_a$	$(0.9 \pm 0.1)\sigma_a$
^{196}Hg	(2,0)→(1,0)	g.s.	0	g.s.	$2.0\sigma_r$	$(1.6 \pm 0.2)\sigma_r$
^{196}Hg	(2,0)→(2,1)	2.81	8	3.0	$1.0\sigma_a$	$(1.0 \pm 0.1)\sigma_a$
^{208}Pb	(1,0)→(1,1)	5.30	4			

[a] Using E_{ph}=−324 from (d,^{3}He) results.
[b] Set equal to 1.0.
[c] σ_a is addition phonon strength, σ_r is removal phonon strength.

B. Theoretical wave functions

The present data serve as a test of a variety of models and other experimental results. Tables III and IV contain the two-nucleon amplitudes and the ϵ values obtained by using these values in the code DWUCK4. As discussed earlier, the value of N is somewhat uncertain in Eq. (1); however, we note that the various theoretical results, Refs. 12, 13, and 14, give a remarkably consistent result for ϵ for both the two-particle case of ^{210}Po and similarly for the two-hole case of ^{204}Hg leading to ^{206}Pb. We have arbitrarily chosen these cases to find an average value of $\epsilon=1$ which yields $N=30$. With this result we note that the three theoretical wave functions, the shell model approach of Kuo and Herling,[12] the pairing multipole theory of Bortignon and Broglia,[13] and the generator-coordinate method of Faessler *et al.*[14] all agree within 20%. However, the experimental coefficients determined by the ^{210}Po(t, α) results disagree by a factor of 3. We attribute this to a lack of $(f_{7/2})^2$ strength in their results. The two-nucleon transfer reaction is very sensitive to the $(f_{7/2})^2$ component because of the large structure factor associated with that orbital.

Table III illustrates the large coherence which the pairing force brings into play in the particle states. The lowest orbital making up the ground state of ^{210}Po is the $h_{9/2}$; it has an amplitude exceeding 0.8 in all of the calculations. However, Table III indicates that the ϵ factor is ≈ 35 for this orbital alone, and thus it contributes little strength to the transition. The Kuo-Herling wave functions predict a state at 2.68 MeV based primarily on the $f_{7/2}$ orbital. This wave function, which is orthogonal to the ground-state wave function, has the $h_{9/2}$ orbital mixing with destructive interference. However, the $f_{7/2}$ intrinsic strength is sufficient to overcome this and yields a state of amplitude nearly equal to the ground state. The ϵ value of 1.28 indicates that the Kuo-Herling wave function satisfactorily reproduces the observed strength as does the Bortignon-Broglia wave function and energy. The hole states are also well reproduced and here the lowest orbital, the $s_{1/2}$, does dominate the cross section.

Two-proton transfer studies with the (^{16}O, ^{14}C) and (^{12}C, ^{10}Be) reactions have also been published for a ^{208}Pb target.[3] In that work enhancement factors, defined as the ratio of the DWBA cross sections to the experimentally measured cross sections, were calculated. For the ground-state transition, assuming an $(h_{9/2})^2$ configuration, the enhancement factors range from about 2 to about 9, depending on the projectile and DWBA normalization used. In the present work similar ground-state enhancements were calculated to be 35 (see Table III). When the Kuo-Herling wave functions were used, enhancements of about 1 were obtained in this work, while the calculations tended to substantially overpredict the cross sections for the heavy ion reactions. Direct comparisons cannot be made for the 0^+ excited state seen in this work at 2.6 MeV. In Ref. 3 the 0^+ state was assumed to be a level at 2.27 MeV, although a level at 2.55 MeV was weakly excited. The calculations of Ma and True[22] predict this level to lie at 2.3 MeV, while those of Kuo and Herling[12] as well as Broglia and Bortignon[13] predict 2.68 MeV, in very good agreement with the present measurements.

The success of the Kuo-Herling[12] and Broglia-Bortignon[13] wave functions in describing both 0^+ states seen in ^{210}Po indicates that they may be used as input to DWBA calculations, and that the ^{208}Pb$\rightarrow^{210}$Po (g.s.) transition studied in heavy ion reactions may be used in order to select among various assumptions for the reaction mechanism and for assessing the various approaches used to calculate the product form factor. Only one note of caution must be introduced. The (^{3}He, n) reaction is sensitive primarily to the amplitude of the $(f_{7/2})^2$ component, while the $(h_{9/2})^2$ and $(i_{13/2})^2$ components are less well determined.

C. Implications for "alpha-vibration" states

Given the success of the pairing vibration model for two-neutron and two-proton configurations in the lead region, it seems reasonable to envision a four-particle–four-hole "α-vibration" state which can be expressed symbolically as

$$|^{208}\mathrm{Pb}(\alpha\ \mathrm{vib})\rangle = |^{204}\mathrm{Hg}(\mathrm{g.s.}) \otimes {}^{212}\mathrm{Po}(\mathrm{g.s.})\rangle\ .$$

Such a state has been calculated by Broglia and Bortignon[23] to lie at $E_x[^{208}\mathrm{Pb}(\alpha\ \mathrm{vib})] \approx 7.2$ MeV and would be expected to be populated in an α-stripping reaction on a ^{204}Hg target. The expected strength can be deduced from the α-stripping transition $^{208}\mathrm{Pb}\rightarrow{}^{212}\mathrm{Po}$.

Recently, the ^{208}Pb(^{16}O, ^{12}C)^{212}Po reaction was measured[24] and compared to the corresponding α-decay data. Subsequent data[25] for the ^{204}Hg(^{16}O, ^{12}C)^{208}Pb reaction indicated that the expected strength was not observed near the predicted excitation energy (≈ 7.2 MeV). However, a state was observed at $E_x=9.3$ MeV with the expected strength.

Our data for the ^{204}Hg(^{3}He, n)^{206}Pb reaction

allow us to verify[16] that the $E_x=5.26$ MeV level in ^{208}Pb is the proton-pairing state. We may use this (and related) information to calculate the particle-hole corrections to the harmonic energy (8.44 MeV) of the α-vibration state in ^{208}Pb. Specifically, the two-proton particle-hole interaction comes out at -1.34 MeV, while the two-neutron particle-hole interaction yields -0.11 MeV. The two-neutron-hole-two-proton-hole interaction was computed earlier as $+1.10$ MeV, while we obtain -0.80 MeV for the two-proton-particle–two-neutron-hole term. The two-neutron-particle–two-proton-particle interaction can be obtained from $S_{2p}(^{212}\mathrm{Po}) - S_{2p}(^{210}\mathrm{Po}) \cong -1.44$ MeV. Unfortunately, the two-neutron-particle–two-proton-hole interaction is not easily calculated because the mass of ^{208}Hg is unknown. However, an estimate can be made by taking

$$4\times ME[(^{208}\mathrm{Tl} - {}^{208}\mathrm{Pb}) - S_n(^{209}\mathrm{Pb}) + S_p(^{208}\mathrm{Pb})] \approx +0.54 \text{ MeV}.$$

This yields a predicted energy for ^{208}Pb(α vib) of $E_x \cong 6.39$ MeV which is below the value obtained by Broglia and Bortignon[23] of 7.2 MeV, which presumably includes higher order corrections. In any case, these values rule out the $E_x=9.3$ MeV level in ^{208}Pb as the α-vibration state. We conclude that the simple α vibration is not a mode which is strong and well localized in excitation energy in the region of the periodic table where other elementary modes of nuclear excitation remain pure.

This work was performed under the auspices of the U. S. Department of Energy.

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