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MIXING OF TWO-PARTICLE TWO-HOLE STATES IN ^{208}Po [#]

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Abstract

States of ^{208}Po up to an excitation energy of 2 MeV have been investigated via the two-neutron pickup reaction $^{210}\text{Po}(p,t)^{208}\text{Po}$. Angular distributions have been extracted for the five observed states of ^{208}Po and $J\pi$ assignments have been made. These states are discussed in terms of the excitation of simple modes observed in ^{206}Pb and ^{210}Po . Matrix elements have been extracted for the interaction between the two-neutron-hole 2^+ excitations and the two-proton-particle 2^+ excitations and compared with simple theoretical estimates.

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A well known feature of the excitation spectra of spherical even-even nuclei is the low energy collective 2^+ state. It is usually the first excited state and is strongly excited in both inelastic scattering and two-nucleon transfer reactions. Its properties have been discussed extensively in the literature¹⁻² both in terms of microscopic wave functions resulting from some residual interactions and also as an elementary excitation mode or "building block" of the nuclear excitation scheme. Both these approaches have been applied successfully in the lead region. In the present paper we address ourselves to the question of what role the neutron-proton force plays in the generation of these states. In the vicinity of a doubly magic nucleus as ^{208}Pb some of the elementary excitations may be characterized as specifically particle-or hole-type as well as neutron-or proton-type, and the question becomes: to what extent are neutron and proton type building blocks independent? Noting that the two-neutron-hole 2^+ state in ^{206}Pb is at 803 keV and the two-proton-particle 2^+ state in ^{210}Po is at 1185 keV, we focus our attention on ^{208}Po where both modes could exist independently but where any coupling between the two modes would cause a mixing of the wave functions with a consequent shift in energies. In the present experiment these shifts have been determined and interpreted in terms of matrix elements connecting these two excitation modes.

The two proton particle-two neutron hole states in ^{208}Po have been studied via the two-neutron pickup reaction $^{210}\text{Po}(p,t)^{208}\text{Po}$ using a 17.8 MeV proton beam from the University of Pittsburgh three-stage Tandem accelerator. The tritons were momentum analyzed and recorded on photographic emulsions placed along the focal plane of the Enge split-pole spectrograph. The overall energy resolution was about 12 keV FWHM. Angular distributions were obtained for states in ^{208}Po for the angular range $10^\circ < \theta < 58^\circ$. The details of the experimental setup and of the fabrication technique for this radioactive target have been given elsewhere.³ Figure 1a shows a triton spectrum at $\theta_{\text{Lab}} = 40^\circ$. Because ^{210}Po (138.4 days) α -decays to ^{206}Pb , the triton groups leading to the ground state and the 1.098 MeV state of ^{204}Pb were also observed (see Fig. 1a). The angular distribution of tritons from the $^{210}\text{Po}(p,t)^{208}\text{Po}$ reaction are shown at the right in Fig. 2. The left column of Fig. 2 shows the angular distribution of tritons from the reaction $^{208}\text{Pb}(p,t)^{206}\text{Pb}$ to the known 0^+ , 2^+ and 4^+ states of ^{206}Pb measured⁴ under identical conditions. The solid curves are the predictions of the distorted wave analyses for the (p,t) reactions on ^{208}Pb and ^{210}Po . The broken lines connect the data points for the $^{208}\text{Pb}(p,t)$ experiment and serve as empirical $\ell=0$, 2 and 4 curves. These curves have been used as templates for the $^{210}\text{Po}(p,t)$ case and by comparison, values of the ℓ -transfer (and hence J^π) for the states of ^{208}Po have been assigned.

The five observed states of ^{208}Po are compared with the levels of ^{206}Pb and ^{210}Po in Fig. 1b. The dotted lines connect states we interpret as having similar character. This is based primarily on the analogy with the two-neutron pickup reaction $^{208}\text{Pb}(p,t)^{206}\text{Pb}$. Thus levels corresponding to the ground state and the first two 2^+ and the first 4^+ states of ^{206}Pb are seen. A level corresponding to the first excited 0^+ state in ^{206}Pb at 1165 keV is not seen in ^{208}Po . The weak level at 1263 keV we identify with the proton correlated 2^+ state of ^{210}Po at 1185 keV. The total absolute intensities of the $\ell=0$ transitions to the ^{206}Pb and ^{208}Po ground states and also the $\ell=2$ transitions to the excited 2^+ states are equal within $\pm 10\%$. The 1584 keV 4^+ state in ^{208}Po has only about 75% of the 1684 keV 4^+ state in ^{208}Pb .

We interpret the observation of the 1263 keV state in ^{208}Po in this two-neutron pickup reaction as an indication of mixing of the neutron and proton 2^+ excitation modes. In order to extract the matrix element implied by the level shifts, we adopt the obvious notation for the levels in ^{206}Pb and ^{210}Po indicated in Fig. 1b. The unperturbed states in ^{208}Po are denoted: 0_1 as $\nu_0^- \pi_0^+ |0\rangle$, 2_1 as $\nu_2^- \pi_0^+ |0\rangle$, 2_2 as $\nu_0^- \pi_2^+ |0\rangle$, and 2_3 as $\nu_{2_2}^- \pi_0^+ |0\rangle$. Here ν_J^- and π_J^+ refer to neutron hole pairs and proton particle pairs coupled to angular momentum J . In the simplest model where these 2^+ states are independent excitation modes and no mixing of wavefunction occurs, the $^{210}\text{Po}(p,t)$ reaction would only exist two 2^+ states in ^{208}Po , 2_1 and 2_3 , at the unperturbed energies of 803

and 1460 keV respectively. The state 2_2 involves excited proton configurations and should not be excited. Thus the observation of three 2^+ states is an indication of a partial breakdown of this model.

By simple perturbation calculations, we have estimated the matrix elements connecting the unperturbed levels. First, in a model involving only two levels, i.e. ignoring the 1.543 MeV state of ^{208}Po , we obtain from the observed energy shifts a value of $|V_{12}| \approx 217$ keV where V_{12} denotes the matrix element between the two levels. This predicts that the (p,t) reaction should populate the 2_1^+ and 2_2^+ states with relative intensities of 0.83 and 0.17 respectively. The sum of these two intensities should equal the intensity for the 2_1^+ state in ^{206}Pb for the $^{208}\text{Pb}(p,t)^{206}\text{Pb}$ reaction. The experimental results (see Table I) support these predictions.

For the three-level perturbation calculation, we assume there is no interaction between the 2_1^+ and 2_3^+ unperturbed levels, i.e. $V_{13}=0$. This is justified since the locations of the corresponding states in ^{206}Pb , which we are using as the unperturbed energies for the 3-level calculation, already include the effects of such an interaction. Under this constraint the calculation gives

$|V_{12}| \approx 250$ keV and $|V_{23}| \approx 120$ keV. The predicted intensities for the 2^+ levels of ^{208}Po on the basis of both the two-level model as well as the three-level model are summarized in Table I together with

the experimental results. The errors in the predicted intensities are due to the uncertainties of the phases of the wave functions.

It is interesting to estimate the matrix element V_{12} connecting two-neutron-hole and two-proton-particle 2^+ excitation modes. We follow a procedure used⁵⁻⁷ for the interaction of two-neutron-hole and two-neutron-particle 2^+ modes observed in ^{208}Pb . In that case the two ^{208}Pb states are $[^{206}\text{Pb}(2^+) \otimes ^{210}\text{Pb}(0^+)]$ and $[^{206}\text{Pb}(0^+) \otimes ^{210}\text{Pb}(2^+)]$ which in our notation are $v_2^- v_0^+ |0\rangle$ and $v_0^- v_2^+ |0\rangle$ respectively. Here the interaction matrix element, $V_{12}(^{208}\text{Pb})$, extracted from the observed shifts,⁵ is ~ 125 keV. This matrix element has been estimated^{6,7} by using a standard microscopic particle-vibration coupling Hamiltonian, namely $H_C = k_2(r) \sqrt{5} \sum_i (a_2 Y_2(i))_0$. The resulting matrix element is

$$V_{12}(^{208}\text{Pb}) = \frac{\langle k_2 \rangle (b_2(210) b_2(206))^{1/2}}{5 \cdot Z \cdot e_{\text{eff}}(206)}$$

$$\approx 0.012 \langle k_2 \rangle \quad (\text{with } e_{\text{eff}} = 1)$$

$$\text{Here the quantity } b_2(A) = \frac{B(E2, A; 0^+ \rightarrow 2^+)}{B(E2)_{\text{s.p.}}}$$

With a value of $\langle k_2 \rangle = 50$ MeV, $V_{12}(^{208}\text{Pb})$ becomes ~ 600 keV. In order to explain this large overestimate, Broglia et al.⁶ have

introduced a coupling to an isovector quadrupole mode which reduces the above result.

This treatment (without the isovector quadrupole mode) is directly applicable to the ^{208}Po case. The only difference in the expression for V_{12} is that $b_2(^{210}\text{Pb})$ must be replaced by the $b_2(^{210}\text{Po})$. The two b_2 values have been measured^{3,8} and have both been determined relative to the b_2 of ^{206}Pb . Thus the ratio of the b_2 's is well determined and is:

$$\frac{b_2(^{210}\text{Po})}{b_2(^{210}\text{Pb})} = \frac{1.4}{3.5}.$$

Therefore the predicted matrix element for ^{208}Po becomes

$$V_{12}(^{208}\text{Po}) = \left[\frac{1.4}{3.5} \right]^{1/2} \times V_{12}(^{208}\text{Pb}) \approx 380 \text{ keV}$$

This may be compared with the value of 250 keV derived above from the experimental data. Thus, in the present ^{208}Po case the experimentally determined value is somewhat smaller than the simple estimate, but the discrepancy is not nearly so large as in ^{208}Pb .

It may be concluded from this investigation that there is a coupling between the neutron and proton excitation modes in ^{208}Po which may be represented by a matrix element of approximately 250 keV. The estimate of this matrix element with a simple model

yields a value which is just 50% larger than this experimentally determined value, whereas a similar comparison in ^{208}Pb showed a factor of ~ 5 difference. There is, therefore, no a priori need to introduce the isovector mode in the ^{208}Po case. It is however not clear what the effect of the isovector mode would be in this case, since the coupling is between protons and neutron holes, whereas in ^{208}Pb the coupling is between neutrons and neutron holes. It will be important to determine whether the introduction of the isovector quadrupole mode can explain simultaneously the large deviation from the simple model in ^{208}Pb and the near agreement in ^{208}Po .

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TABLE I

Intensities $\left[\frac{\mu\text{b}}{\text{sr}}\right]$ for the 2^+ States of ^{206}Pb and ^{208}Po
observed in the (p,t) reaction

	$^{208}\text{Pb(p,t)}^{206}\text{Pb}$		$^{210}\text{Po(p,t)}^{208}\text{Po}$		
	$2_1^+(0.803)$	$2_2^+(1.465)$	$2_1^+(0.688)$	$2_2^+(1.263)$	$2_3^+(1.543)$
Observed Intensities	380	29	310	60	22
Calculated Intensities for the 2- level model assuming that the $2_3^+(1.543)$ state of ^{208}Po does not mix. This gives $V_{12}=217$ keV.			315	65	22
Calculated Intensities for the 3- level model but assuming $V_{13} = 0$. This gives $V_{12} = 250$ keV $V_{23} = 120$ keV.			300 ± 10	77 ± 40	33 ± 28

Figure Captions

Figure 1.

- a. The triton spectrum observed for the $^{210}\text{Po}(p,t)^{208}\text{Po}$ reaction at 17.8 MeV proton energy at 40° .
- b. Comparison of the level schemes of ^{206}Pb , ^{208}Po , ^{210}Po . Only natural parity states are shown.

Figure 2.

Angular distributions of tritons from the reactions $^{208}\text{Pb}(p,t)^{206}\text{Pb}$ and $^{210}\text{Po}(p,t)^{208}\text{Po}$ both at 17.8 MeV beam energy. The solid curves are the DWBA predictions; for the $^{208}\text{Pb}(p,t)^{206}\text{Pb}$ reaction, the dotted curves are drawn through the ^{206}Pb data points and serve as the empirical $\ell = 0, 2$ and 4 templates. The Po data is compared with these templates in the right-hand column of the figure.

(a)

(b)

Fig. 1

Fig. 2