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# Multiplet structure in $^{203}$Pb†

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The $^{205}$Pb$(p,t)^{203}$Pb reaction has been studied at 35 MeV bombarding energy using the long-lived radioactive $^{205}$Pb isotope. Tritons were detected in the focal plane of a quadrupole-dipole-dipole-dipole spectrometer by a resistive-wire proportional counter backed by a plastic scintillator. Multiplet structure due to the coupling of the odd $f_{5/2}$ neutron to the $2^+$ vibrational core was observed. Distorted-wave Born approximation calculations reproduced the shape of the angular distributions and allowed determination of $L$ transfers.

[NUCLEAR REACTIONS $^{205}$Pb$(p,t)$, $E=35$ MeV; measured $\sigma(\theta)$ and level energies; DWBA analysis, deduced $L$, $J^\pi$. Resolution 12 keV. Radioactive target.]

## INTRODUCTION

The $(p,t)$ two-neutron transfer reaction is being used in this laboratory to compare the spectroscopic properties of the levels populated by this reaction on an odd-$A$ target with those of immediately adjacent even-even nuclei. If the odd-$A$ target may be described in terms of a spectator nucleon coupled to an even-even core carrying collective degrees of freedom and participating in the $(p,t)$ reaction, then the transfer cross sections observed for the two adjacent targets should be directly related. In the case of well deformed odd-$A$ nuclei the two-nucleon transfer process populates primarily the sequence of rotational states built on the intrinsic Nilsson state corresponding to the ground state of the target nucleus. For more spherical odd-$A$ nuclei where the low-lying core degrees of freedom more closely correspond to those of an isotropic quadrupole vibrator, multiplet level structure is expected from $(p,t)$ spectroscopy. In a weak coupling model, $(p,t)$ cross-section sum rules should obtain between the multiplet in the odd-$A$ nucleus and the corresponding collective state in the even-even parent. Further, the relative cross sections for populating the members of the multiplet in the odd-$A$ nucleus should be related by the statistical factors involving nuclear spin.

In the region of doubly-magic $^{208}$Pb the reaction $^{207}$Pb$(p,t)^{205}$Pb has been studied by Reynolds *et al.*[1] and by Lanford.[2] Here, since the ground state of $^{207}$Pb is primarily the neutron configuration $p_{1/2}^{-1}$ a doublet of states is identified in $^{205}$Pb with spins and parity $\frac{3}{2}^-$ and $\frac{5}{2}^-$ which are related to the $2^+$ first excited level in $^{204}$Pb at 899 keV.

Recently $^{205}$Pb has been prepared at Oak Ridge National Laboratory by neutron irradiation and electromagnetic isotope separation. The ground state of $^{205}$Pb has spin and parity $\frac{5}{2}^-$. The excitation energy of the lowest $2^+$ level in the even lead isotopes decreases with increasing neutron deficiency while the structure becomes more collective. It was of interest to us to search for the expected lowest multiplet of states in $^{203}$Pb corresponding to the core coupling $2^+\otimes\frac{5}{2}^-$ and investigate their properties using the $(p,t)$ reaction.

## EXPERIMENTAL PROCEDURE

Lead carbonate isotopically enriched to 76.8% in the long-lived $^{205}$Pb isotope was reduced in a tantalum boat and the metallic lead was evaporated onto a 25 $\mu$g/cm$^2$ thick carbon foil to form a lead target approximately 45 $\mu$g/cm$^2$ thick. The isotopic abundances of the various lead isotopes in the $^{205}$Pb target and in a $^{204}$Pb target which was used for comparison are listed in Table I.

The $^{205}$Pb$(p,t)^{203}$Pb reaction was investigated with a 34.7 MeV proton beam and the quadrupole-dipole-dipole-dipole (QDDD) magnetic spectrograph at the Princeton University Cyclotron Laboratory. An overall energy resolution of 12 keV was achieved in the

TABLE I. Isotopic abundances of the various lead isotopes in the $^{205}$Pb target, and a $^{204}$Pb target used for comparison.

| Isotope | Isotopic abundance in % $^{205}$Pb target[a] | $^{204}$Pb target[a] |
|---|---|---|
| $^{204}$Pb | 13.70 ± 0.10 | 40.0 ± 0.1 |
| $^{205}$Pb | 78.87 ± 0.20 | ··· |
| $^{206}$Pb | 4.68 ± 0.05 | 26.2 ± 0.1 |
| $^{207}$Pb | 1.22 ± 0.02 | 14.8 ± 0.1 |
| $^{208}$Pb | 1.53 ± 0.04 | 19.0 ± 0.1 |

[a] The isotopic abundance are those given by Oak Ridge National Laboratory for the samples used in this experiment.

triton spectra at a spectrograph solid angle of 12 msr. The position of the tritons in the focal plane was determined with a resistive-wire proportional counter. Particle identification was provided by the specific ionization in the proportional counter and by the signal from a plastic scintillator backing the proportional counter in which the tritons stopped.

Triton spectra were recorded from 7.5 to 60° in the laboratory in 5° steps. Spectra from both the $^{205}$Pb and $^{204}$Pb targets were taken at each angle both for comparison and to facilitate the identification of contaminant peaks in the spectra of interest. The proton flux was monitored using a fixed-angle sodium iodide scintillation counter mounted in the scattering chamber.

## RESULTS

Figure 1 shows the triton spectra recorded at 10°. Besides the states attributed to $^{203}$Pb, levels in $^{202}$Pb, $^{204}$Pb, $^{205}$Pb, and $^{206}$Pb are present from $(p,t)$ reactions on other stable lead isotopes present in the target. Comparison of the spectra from the $^{205}$Pb target with those obtained from the low enrichment $^{204}$Pb target and with those of Lanford[2] on the stable lead isotopes indicates that the expected contaminant peaks from the lead

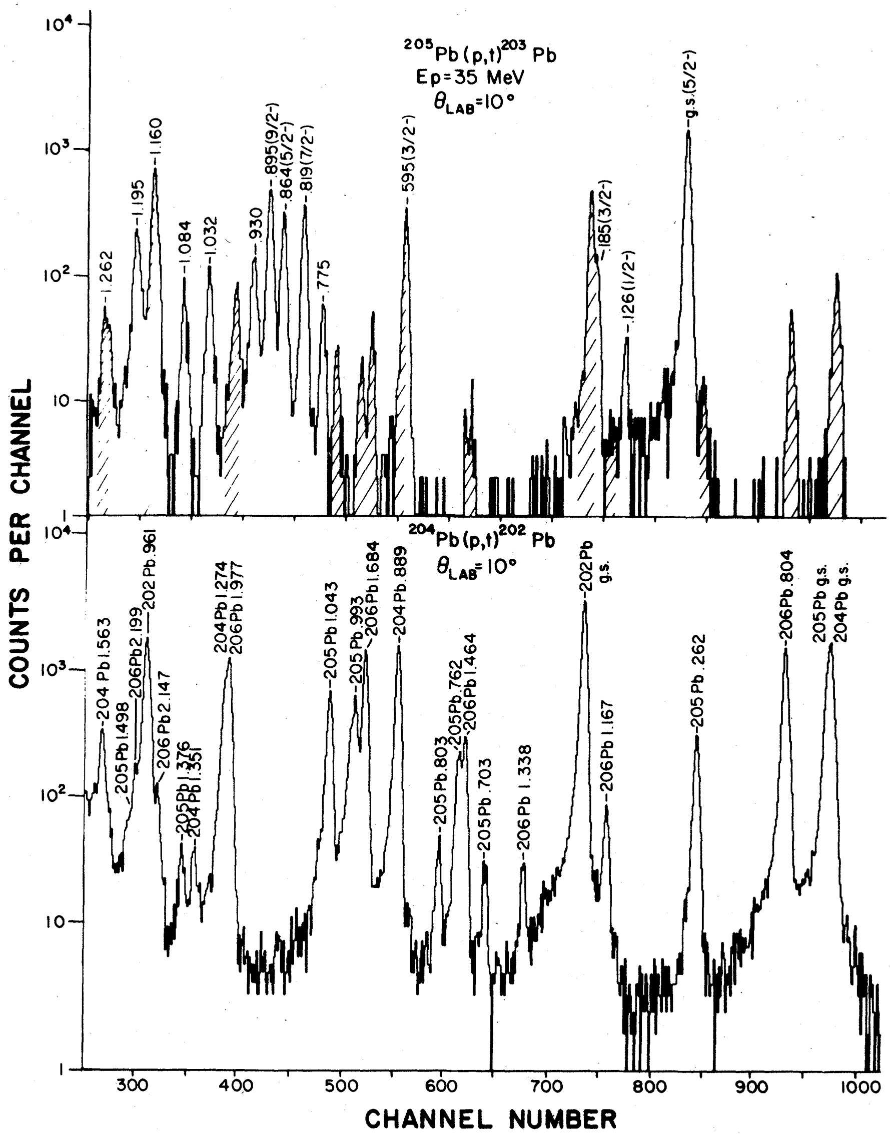


FIG. 1. Comparison of the triton spectra from the $^{205}$Pb and $^{204}$Pb targets used in this work. The spin and parity assignments indicated are those discussed in the text.

isotopes have been properly identified. The most prominent peak in the $^{205}Pb(p,t)^{203}Pb$ spectrum is due to the $L=0$ transition to the $J^{\pi}=\frac{5}{2}^{-}$ ground state of $^{203}Pb$. Figure 2 compares the angular distribution of this level with a distorted-wave Born approximation (DWBA) calculation made using the computer program DWUCK (Ref. 3) and the proton and triton optical model parameters of Greenlees *et al.*[4] and Flynn *et al.*,[5] respectively. The DWBA calculation predicts the first minimum at about 23° while the minimum is located experimentally at about 20°. The trend of the experimental minima to occur at a lower scattering angle than the DWBA calculation continues for the higher minima and is similar to the observations of Lanford and McGrory[6] who used the same optical model parameters.

The two levels at 126 and 185 keV in the $^{203}Pb$ spectrum are populated weakly by the $(p,t)$ reaction and are known to have $J^{\pi}=\frac{1}{2}^{-}$ and $\frac{3}{2}^{-}$, respectively. These two levels were also seen in a $^{204}Pb(p,d)^{203}Pb$ spectrum taken for calibration purposes. The prominence of these levels in the $(p,d)$ reaction and their lack of strength in the $(p,t)$ reaction supports the interpretation of these levels as single quasiparticle states. Further Richel *et al.*[7] point out that the positions of these levels are in good agreement with one-quasiparticle calculations. The angular distribution of the $\frac{1}{2}^{-}$ level is shown in Fig. 3. Since the 185 keV level was obscured by the $^{204}Pb(p,t)^{202}Pb$ ground state transition, its angular distribution is not shown.

Next there are five levels at 595, 775, 819, 864, and 895 keV that exhibit $L=2$ angular distributions. Richel *et al.*[7] have made the following spin and parity assignments based on $\gamma$-ray transitions involving these states, $\frac{3}{2}^{-}$, not seen, $\frac{7}{2}^{-}$, $\frac{5}{2}^{-}$, and $\frac{9}{2}^{-}$ in order of increasing excitation. The shapes of

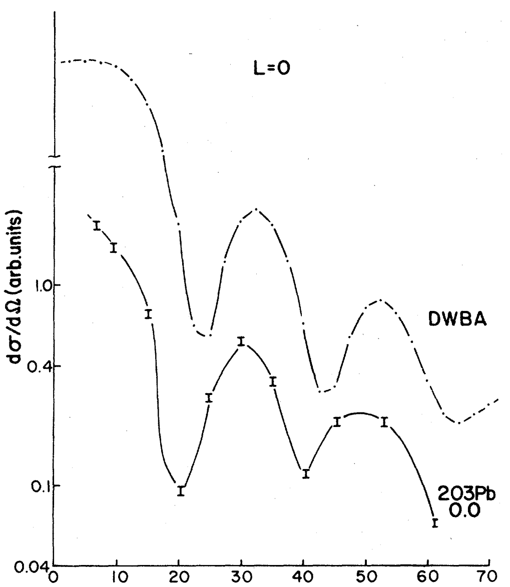


FIG. 2. Angular distribution of the ground state in the $^{205}Pb(p,t)^{203}Pb$ reaction. The unnormalized DWBA calculation shown above is discussed in the text. The curve through the data is shown to guide the eye.

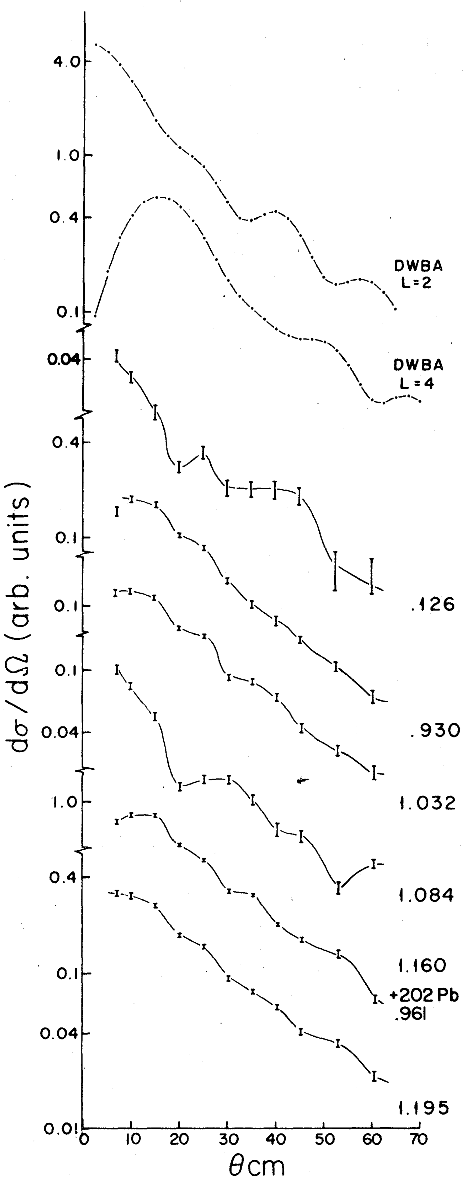


FIG. 3. Angular distribution obtained for the low-lying transitions that are populated in the $^{205}Pb(p,t)^{203}Pb$ reaction other than the proposed multiplet. The unnormalized $L=2$ and $L=4$ DWBA calculations are shown for comparison.

the angular distribution, shown in Fig. 4 for these levels are in good agreement with the $L=2$ DWBA predictions and with the shapes found by Lanford and McGrory[6] for the lowest $2^+$ levels populated in the $(p,t)$ spectroscopy of the even-mass lead isotopes. The level at 595 keV is not resolved from the $2^+$ level at 899 keV from the $^{206}$Pb$(p,t)^{204}$Pb reaction. However, comparison of the $^{205}$Pb$(p,t)$ and low enrichment $^{204}$Pb$(p,t)$ spectra indicate that the 595 keV level in $^{203}$Pb is responsible for $(65\pm5)\%$ of the strength in this peak at all angles. It is interesting to compare the strengths of these five levels with expectations based on a simple weak coupling model. The $^{203}$Pb spectrum is expected to exhibit a quintet of states due to the coupling of the odd-$f_{5/2}$ neutron to a $^{202}$Pb $2^+$ collective core. Figure 5 compares the level diagrams of $^{202}$Pb and $^{203}$Pb for the states of interest. Also indicated in the figure are the ratios of the

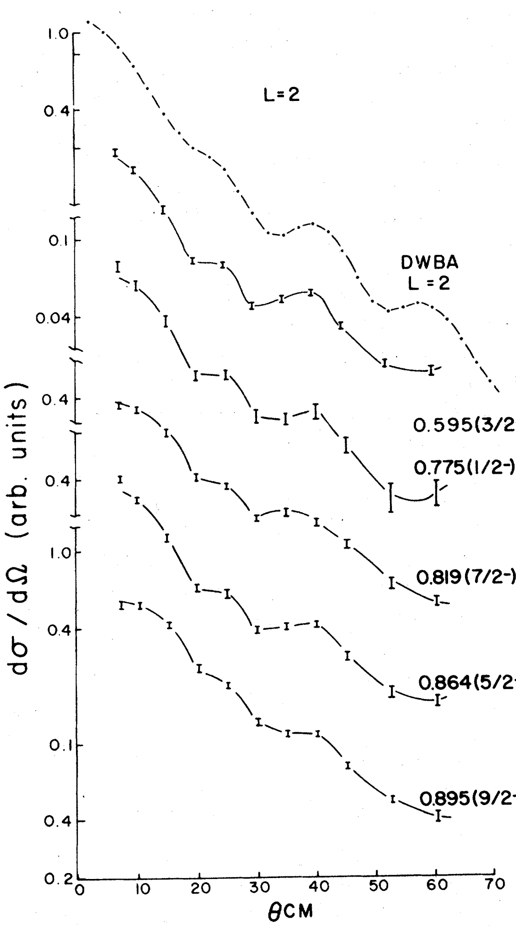


FIG. 4. Angular distribution for the transitions to the proposed multiplet in $^{203}$Pb populated in the $^{205}$Pb$(p,t)^{203}$Pb reaction. The unnormalized $L=2$ DWBA curve is shown to indicate the expected shape of the angular distributions. The curves through the data are shown to guide the eye.

cross section of the various levels to the $^{202}$Pb parent state, the ratios of the members of the quintet to the total cross section of the quintet and the ratios expected from a simple $2J+1$ statistical weighting. It is gratifying to note that the spin and parity assignments of Richel *et al.*[7] agree with ours which are based on these $2J+1$ cross-section ratios and the assumption that these five levels are the members of a multiplet. While Richel *et al.*[7] did not see a $\frac{1}{2}^-$ level in this region they speculated on its existence. Our $(p,t)$ reaction results are consistent with interpretation of the level at 775 keV as the expected $\frac{1}{2}^-$ member of the quintet. While the $\frac{3}{2}^-$ level is lower that the other members of the quintet, its strength is consistent with our assignment. The total strength of the quintet is in good agreement with the strength seen to the $^{202}$Pb $2^+$ level. This is in contrast to the $L=0$ ground state transitions where the cross section for the $^{205}$Pb$(p,t)$ reaction is only 60% of that for the $^{204}$Pb$(p,t)$ reaction. However, Lanford and McGrory[6] have previously noted the marked decrease in the ground state to ground state $(p,t)$ cross sections for the even lead isotopes with increasing neutron number. Finally we note that the centroid of these five levels is at 810 keV, this is 150 keV lower than the $2^+$ level in $^{202}$Pb. This may indicate that the effective phonon energy is lower in the odd nucleus perhaps due to a blocking effect. Similar behavior is observed for the $p,t$ spectroscopy of even palladium and silver isotopes studied in this laboratory.[8]

Upon examination of the spectra at higher excitation energies we fail to find any clear evidence for a multiplet of states based on the coupling of the $^{202}$Pb $4^+$ collective state to the $f_{7/2}$ neutron. This is at least partly due to the density of levels in the region near 1.3 MeV arising from both the $^{205}$Pb$(p,t)$ reaction and other lead isotopes present in the target. Also we have limited the range of the triton spectra recorded to correspond to the lower energy range of the $^{203}$Pb spectrum.

Nevertheless, there are a few interesting features in this region. Figure 3 shows that the angular distributions of the levels at 930, 1032, and 1160 keV are quite similar and comparison with the DWBA curve for $L=4$ indicates that they may be $L=4$ transfers. The 1160 keV level is not resolved from the $^{202}$Pb $2^+$ level at 961 keV, however, the strength of this doublet exceeds that expected from the $^{202}$Pb $2^+$ level and at some larger angles is the strongest peak in the spectrum. The 930 and 1032 keV levels were assigned $J^\pi=\frac{5}{2}^-$ and $\frac{7}{2}^-$, respectively, by Richel *et al.*, while the level at 1160 keV was not seen by them. We also see a level at 1084 keV that was not seen by Richel *et al.* This level appears to

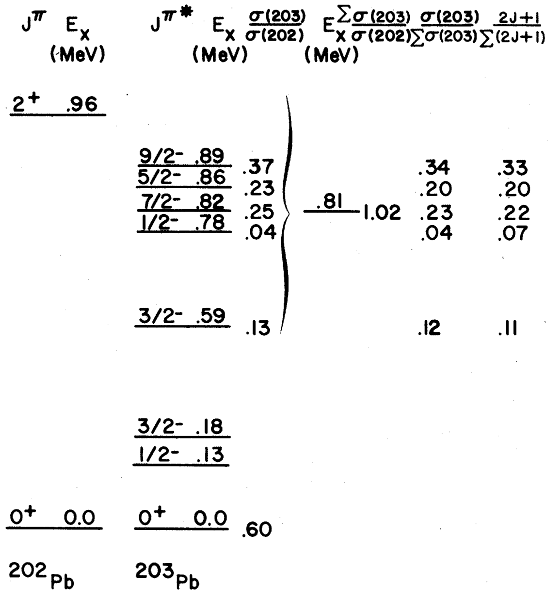


FIG. 5. Comparison of the excitation energies and cross sections of the multiplet members to the parent state in $^{202}$Pb. $\sigma$ (202) and $\sigma$ (203) refer to the cross section to the level indicated for the $^{204}$Pb$(p,t)^{202}$Pb and $^{205}$Pb$(p,t)^{203}$Pb reactions, respectively. $\Sigma\sigma$ (203) refers to the total cross section for the multiplet. * indicates that the spin and parities are those discussed in the text.

have a $L = 2$ angular distribution as seen in Fig. 3. Finally the level at 1195 keV not reported by Richel *et al.* has an angular distribution that is probably $L = 4$.

## CONCLUSION

We have presented evidence for the multiplet of levels in $^{203}$Pb that arises from the coupling of an odd-$f_{5/2}$ neutron to an excited $2^+$ core state. The proposed members of the multiplet all have $L = 2$ angular distributions and the relative cross sections for the indiviual members are closely proportional to the expected $2J+1$ ratio.

The previously identified quasiparticle states in $^{203}$Pb at 126 and 184 keV as well as a level at 1084 keV proceed by $L = 2$ transfers. We must point out the possibility that the 1084 level is the $J^\pi = \frac{1}{2}^-$ member of the multiplet. The relative $(p,t)$ cross section is in agreement with this possibility $[\sigma(1.084)/\sigma(202) = 0.05]$. Also, from our data alone, we could not rule out the possibility that the level at 930 keV is the $\frac{5}{2}^-$ level of the multiplet since its angular distribution is ambiguous and the strength is similar to that of the 864 level. However, we note that the particle structure of $^{203}$Bi is predominantly $\frac{9}{2}^-$ and that of $^{203}$Pb is predominantly $\frac{5}{2}^-$. All decays to members of the multiplet are second forbidden in particle coordinates and should have the same log$ft$ Richel *et al.* find for the $\frac{5}{2}^-$ 933.39 keV level a log$ft$ of 10.5 while for the $\frac{5}{2}^-$ 866.47 keV level they find log$ft$ = 8.9 which is more in accord with the other members of the multiplet. The log$ft$ values of the $\frac{9}{2}^-$ 896.85 keV and $\frac{7}{2}^-$ 820.23 keV in the $^{203}$Bi decay are 8.3 and 8.5, respectively.[7]

The problem of identifying the multiplet arising from the coupling of the $f_{5/2}$ neutron to the $4^+$ core excited state remains. However, the large number of contaminant levels in the expected excitation region and the low cross sections expected for these levels would require a $^{205}$Pb target of higher isotopic enrichment.


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