Proton excitation of 1^+ states in ^{208}Pb and a lower limit on the strength of the isoscalar spin-flip part of the effective nucleon-nucleon interaction

C. Djalali, N. Marty, M. Morlet, A. Willis, and J.-C. Jourdain
Institut de Physique Nucléaire, 91406 Orsay, France

N. Anantaraman, G. M. Crawley, and A. Galonsky
National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824

(Received 2 November 1984)

Excitation of 1^+ states in ^{208}Pb has been studied by 201 MeV proton inelastic scattering. Strength assigned to 1^+ isovector states is found between 6.0 and 8.2 MeV excitation energy and compared with theoretical predictions. From the cross section of the recently discovered 1^+ "isoscalar" state at 5.846 MeV, a lower limit is extracted for the volume integral of the total equivalent isoscalar spin-flip part of the nucleon-nucleon interaction.

In spite of more than ten years' work, the problem of 1^+ strength in ^{208}Pb still remains a puzzle.[1] The theoretical calculations of Vergados[2] predict two low energy states at 5.45 and 7.52 MeV with $B(M1)\uparrow$ equal to 1.20 μ_0^2 and 48.1 μ_0^2, respectively, but very little of this strength has been found. Calculations which include coupling to two-particle—two-hole states give a fragmentation of the higher energy component without much change in its total strength.[3,4]

Recently a state at 5.846 MeV was firmly established as 1^+ by resonance fluorescence measurements[5] with polarized photons. This state is generally called "isoscalar" due to its structure as the isoscalar combination of neutron and proton spin-flip configurations. In a two state model it is described as

$$|1^+\rangle = a_\pi |\pi h_{9/2} \pi h_{11/2}^{-1}\rangle + (1-a_\pi^2)^{1/2} |\nu i_{11/2} \nu i_{13/2}^{-1}\rangle , \quad (1)$$

with a_π positive. The "isoscalar" nature of this state was confirmed by (e,e′) (Ref. 6), (p,p′) (Ref. 7), and (d,d′) (Ref. 8) experiments. Since the isoscalar state at 5.846 MeV was also clearly observed in the present experiment, its strength can be used to set a lower limit on the isoscalar spin-flip interaction. At present the isoscalar part of the nucleon-nucleon potential is not well known, so that any definite limits which can be established are important.

At higher excitation energies many strong states originally claimed to be 1^+ states were shown to be 1^- excitations,[9] and only some concentrations of 1^+ states near 7.5 and perhaps 7.99 MeV seem not to be questioned.

Inelastic scattering of 200 MeV protons at very forward angles has been shown to be very selective for exciting 1^+ spin-flip isospin-flip transitions.[10,11] Therefore this reaction should be a useful tool for investigating the isovector 1^+ strength. Unfortunately, Coulomb excited 1^- transitions display a similar forward peaked angular distribution, and in heavy nuclei such excitations can have significant strength. These 1^- excitations must therefore be carefully considered before any conclusions are drawn about isovector 1^+ strength.

The inelastic proton scattering on ^{208}Pb was carried out at the Orsay synchrocyclotron. The angular range covered was from 2.5° to 7° and the energy resolution was between 50 and 60 keV. At very forward angles and low excitations energies, the background due to rescattering of the elastically scattered beam could be greatly reduced by setting windows on both the horizontal and vertical angles of the trajectories. The remaining background was then subtracted by assuming that its shape was the same inside and outside the windows. It was verified that the shape of the background was structureless and was almost the same for trajectories above and below the scattering plane. The average shape of these two backgrounds was fitted by a polynomial and then normalized in the low excitation energy region to the lower points of the experimental spectrum. A spectrum at 3° before and after the smoothed background subtraction is given in Fig. 1.

Except for the well-known 2^+ state at 4.086 MeV and states at 6.50 and 6.95 MeV, the prominent peaks all have a forward peaked angular distribution and they all correspond to states excited in the (γ,γ') experiment.[12,13] The isoscalar 1^+ state at 5.846 MeV is clearly seen. Its angular distribution is given in Fig. 2 and is compared with DWIA theoretical predictions obtained with the model of Vergados[2] and the nucleon-nucleon interaction of the Paris potential,[14] using the code RESEDA.[15] The agreement in shape is very good; absolute cross sections will be discussed later.

All the other peaks observed below 7.2 MeV correspond to 1^- states observed in the (γ,γ') experiment. We find that for most cases it is possible to predict the (p,p′) angular distributions, both in magnitude and shape, for these Coulomb excited 1^- states, using the code ECIS79 (Ref. 16) and taking the $B(E1)$ values deduced from the widths $\Gamma_{\gamma 0}$ obtained from electromagnetic measurements.[12,13,17] Above the neutron emission threshold, 7.38 MeV, and up to about 8.2 MeV excitation energy, the (p,p′) cross sections were deduced in a similar way using the widths $\Gamma_{\gamma 0}$

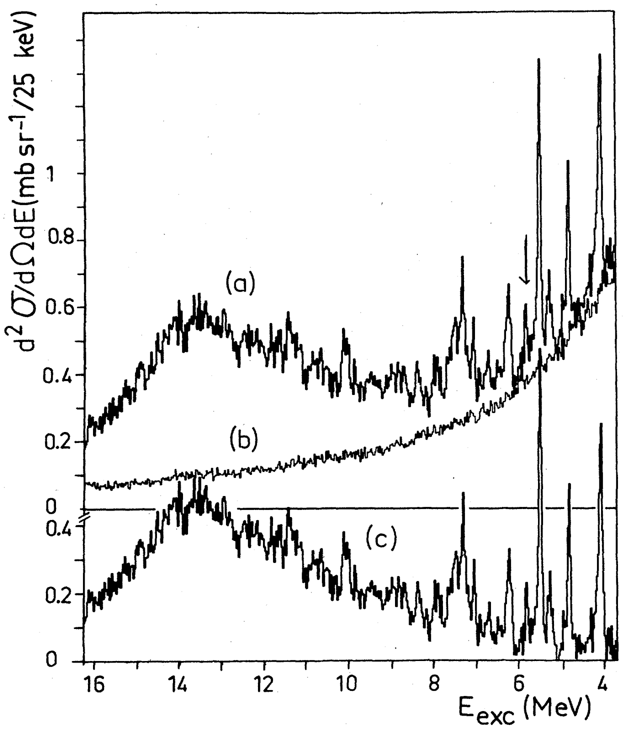

FIG. 1. Spectrum of protons inelastically scattered at 3° from ^{208}Pb: (a) taken within the vertical windows; (b) background taken outside the vertical windows; and (c) spectrum obtained after background subtraction.

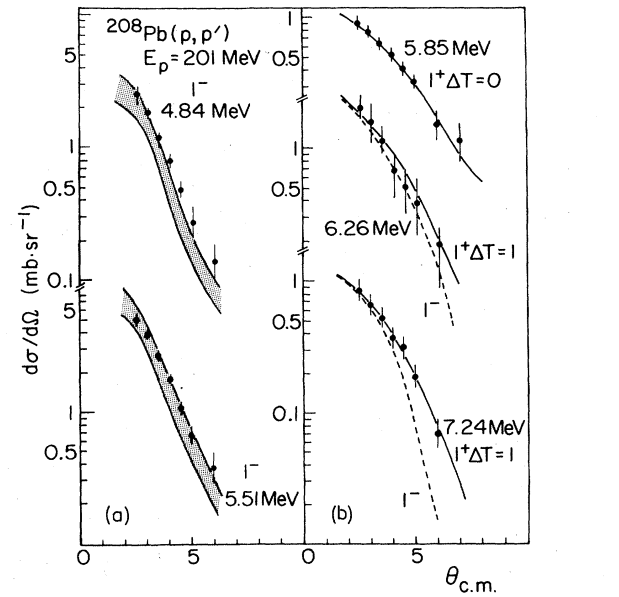

FIG. 2. Experimental and theoretical angular distributions (a) for two 1^- states at 4.84 and 5.51 MeV excitation energy (the shaded areas come from the uncertainty on the $\Gamma_{\gamma 0}$ width) and (b) for the 1^+ state at 5.846 MeV, the state at 6.26 MeV, and the region near 7.2 MeV (the remaining strength after the predicted cross section for the 1^- states has been subtracted) compared to isovector 1^- and 1^+ predictions. (The predicted angular distributions are given by the model of Ref. 2.)

from (n,γ) experiments.[9] [Above 8.2 MeV, the measurements of J^π and $B(E1)$ values are not sufficiently consistent and accurate for us to make reliable (p,p') predictions.] Our angular distributions for two 1^- states are compared with the ECIS predictions in Fig. 2. The agreement in shape and magnitude is quite good.

A comparison is made in Fig. 3 between part of the measured (p,p') spectrum at 3° and a spectrum predicted using the experimental (p,p') peak shape with the strengths determined from electromagnetic measurements for the 1^- states.

A few exceptions to the generally good agreement should be noted. Near 6.3 MeV, there are two 1^- states known from (γ,γ') experiments to be at 6.26 and 6.31 MeV. The predicted summed (p,p') cross section is less than 30% of the value observed. The angular distribution of the strength remaining after the predicted cross section for the 1^- states is subtracted is consistent with 1^+ (or 1^-) strength [see Fig. 2(a)]. Since there is good correspondence for most of the other states, this suggests that in this region there is possibly extra 1^+ strength which may not be observed in the electromagnetic measurements.

A similar situation exists in other excitation energy regions, in particular near 7.2, 7.5, and 7.8 MeV. In these regions the observed (p,p') cross section is greater than that predicted from the electromagnetic measurements. The angular distribution of the excess strength seen near 7.2 MeV is shown in Fig. 2(b).

If the net excess (p,p') cross section in the region between 6.0 and 8.2 MeV is assumed to be isovector 1^+ strength, then the total strength observed is about 30% of that expected using the Vergados wave function. This is almost certainly an upper limit on the isovector strength in this excitation energy region.

We next turn to the calculation of the "isoscalar" state. The DWIA calculations for this state were performed us-

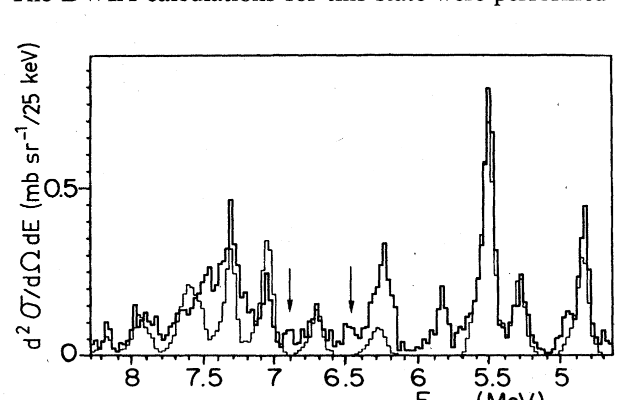

FIG. 3. A spectrum predicted using the experimental (p,p') peak shape, with the strengths determined from electromagnetic measurements of the 1^- states, is compared with the experimental spectrum at 3° after subtraction of the continuum. The peaks marked by an arrow correspond to states of spin higher than 1. The predicted spectrum is given by the lighter line.

ing the Paris nucleon-nucleon interaction, the 200 MeV p + Pb optical potential measured at Orsay,[18] and the two-state model wave function given in Eq. (1). Two different values for a_π were used: $a_\pi=0.79$, which gives a $B(M1)$ value of 1.6 μ_0^2, in agreement with the experimental results of Ref. 6, and $a_\pi=0.83$, compatible with the spectroscopic factor extracted from the (d,^{3}He) measurement[7] which gives a $B(M1)=2.86\ \mu_0^2$. A third calculation was performed with the four state wave function of Vergados which gives $B(M1)=1.20\ \mu_0^2$. The quenching factors

$$Q=(d\sigma/d\Omega)_{\rm exp}/(d\sigma/d\Omega)_{\rm cal}$$

are, respectively, 0.64, 0.63, and 0.64. Unlike the $B(M1)$ value which changes by more than a factor of 2, the (p,p′) cross section is not very sensitive to the proton amplitude in the wave function. The reason is that at 200 MeV the proton-proton and proton-neutron interactions are nearly the same.

For a heavy nucleus such as ^{208}Pb the distortion effects are very important and reduce the cross section from plane wave calculations by a factor of 10. The cross sections calculated are then very sensitive to the optical potential. If instead of the Orsay optical potential, other optical potentials are used,[19,20] predicted cross sections can differ significantly. For example, if the potential of Ref. 21 extrapolated to 200 MeV is used, predicted cross sections are increased by about 30%. However, these optical potentials fail to reproduce the elastic scattering data of Ref. 18 at large angles.

For isoscalar $M1$ transitions, excited by (p,p′) at small momentum transfer, both the central spin and the tensor spin parts of the interaction contribute. A total equivalent spin-flip interaction is obtained in the following manner. The isoscalar nucleon-nucleon scattering amplitude can be expressed as follows:[21]

$$M=A+B\sigma_{1n}\sigma_{2n}+C(\sigma_{1n}+\sigma_{2n})$$
$$+E\sigma_{1q}\sigma_{2q}+F\sigma_{1p}\sigma_{2p}\ .$$

In this equation, 1 and 2 refer to the two nucleons, and n, p, and q are coordinate axes defined in Ref. 21.

It can be shown[22] that the spin-flip transitions are induced through the term T:

$$T=[\,|B|^2+|E|^2+|F|^2+|C|^2]^{1/2}/3\ .$$

The volume integral of the equivalent spin-flip interaction is defined as $J_\sigma^{\rm eq}=4\pi\hbar^2c^2T/E_{\rm c.m.}$, T being taken at a momentum transfer $q=0$.

For the Paris nucleon-nucleon potential which is used in the present calculations, the volume integral of the central spin part is $|J_\sigma^c|=30$ MeV fm^3, and the volume integral of the total equivalent spin-flip interaction is $|J_\sigma^{\rm eq}|=61$ MeV fm^3. We have checked that for the different models of the 5.846 MeV state, the isovector contribution to the calculated cross sections is less than 10%. Therefore, the strength of this state can be used to set a lower limit on the isoscalar spin-flip part of the interaction.

If we assume that the nuclear wave function is correct, then any disagreement between the experimental cross section and theoretical predictions can be attributed to the strength of the total equivalent spin part of the interaction. If the Orsay optical potential measured at 201 MeV is used,[18] the value of $|J_\sigma^{\rm eq}|$ that gives no quenching is 49 MeV fm^3. Since using a more complete wave function reduces the predicted cross section and increases $|J_\sigma^{\rm eq}|$, this value of 49 MeV fm^3 is the lower limit for the volume integral which is compatible with our data.

In conclusion, we see that from 201 MeV proton scattering of ^{208}Pb, isovector 1^+ strength can be deduced between 6.0 and 8.2 MeV. This newly revealed strength is at most 30% of the strength given by the model of Vergados. The 5.846 MeV "isoscalar" state is clearly seen in this experiment and the calculations performed with the Paris nucleon-nucleon potential, the Orsay optical potential, and either a two state model wave function or the Vergados model give a quenching factor of about 0.64. This value sets a lower limit of 49 MeV fm^3 for the volume integral of the total equivalent isoscalar spin-flip interaction.

This work was partly supported by the U.S. National Science Foundation under Grants No. PHY-80-17605 and INT-82-63242. One of the authors (G.M.C.) thanks the University of Paris XI for financial support.

[1]G. E. Brown and S. Raman, Comments Nucl. Part. Phys. **9**, 79 (1980).

[2]J. D. Vergados, Phys. Lett. **36B**, 12 (1971).

[3]T. S. H. Lee and S. Pittel, Phys. Rev. C **11**, 607 (1975).

[4]J. S. Dehesa, J. Speth, and A. Faessler, Phys. Rev. Lett. **38**, 208 (1977).

[5]K. Wienhard, K. Ackermann, K. Bangert, U. E. P. Berg, C. Blasing, W. Naatz, A. Ruckelshausen, D. Ruck, R. K. Schneider, and R. Stock, Phys. Rev. Lett. **49**, 18 (1982).

[6]S. Muller, A. Richter, E. Spamer, W. Knüpfer, and B. C. Metsch, Phys. Lett. **20**, 305 (1983); A. Richter, in *International Conference on Nuclear Physics, Florence, 1983,* edited by P. Blasi and R. A. Ricci (Tipografia Compositori, Bologna, 1983), p. 189.

[7]S. I. Hayakawa, M. Fujiwara, S. Imanishi, Y. Fujita, I. Katayama, S. Morinobu, T. Yamasaki, T. Itahashi, and H. Ikegami, Phys. Rev. Lett. **49**, 1624 (1982).

[8]G. P. A. Berg *et al., in Proceedings of the 1983 RCNP International Symposium on Light Ion Reaction Mechanisms,* edited by H. Ogata, T. Kammuri, and I. Katayma (RCNP, Osaka,

1983), p. 214.
[9]R. J. Holt and H. E. Jackson, Phys. Rev. Lett. **36**, 244 (1976); S. Raman, M. Mizumoto, and R. L. Macklin, *ibid.* **39**, 598 (1977); D. J. Horen, G. F. Auchampaugh, and J. A. Harvey, Phys. Lett. **79**, 39 (1978).
[10]C. Djalali, N. Marty, M. Morlet, A. Willis, J.-C. Jourdain, N. Anantaraman, G. M. Crawley, A. Galonsky, and J. Duffy, Nucl. Phys. **A410**, 399 (1983).
[11]C. Djalali, J. Phys. (Paris) **45**, 375 (1984).
[12]K. Ackermann, K. Bangert, U. E. P. Berg, G. Junghans, R. K. M. Schneider, R. Stock, and K. Wienhard, Nucl. Phys. **A372**, 1 (1981).
[13]U. E. P. Berg, J. Phys. (Paris) **45**, 359 (1984); private communication.
[14]M. Lacombe, B. Loiseau, J. M. Richard, R. Vinh Mau, J. Coté, P. Pires, and R. de Toureil, Phys. Rev. C **21**, 861 (1980).
[15]A. Willis, thesis, University of Paris, 1968 (unpublished).
[16]J. Raynal, Phys. Rev. C **23**, 2571 (1981); private communication.
[17]T. Chapurian, R. Vodhanel, and M. K. Brussel, Phys. Rev. C **22**, 1420 (1980).
[18]C. Djalali, N. Marty, M. Morlet, and A. Willis, Nucl. Phys. **A380**, 42 (1980).
[19]W. T. H. van Oers, Huang Haw, N. E. Davison, A. Ingemarsson, B. Fagerström, and G. Tibell, Phys. Rev. C **10**, 307 (1974).
[20]P. Schwandt, H. O. Meyer, W. W. Jacobs, A. D. Bacher, S. E. Vigdor, and M. D. Kaitchuck, Phys. Rev. C **26**, 55 (1982).
[21]W. G. Love and M. A. Franey, Phys. Rev. C **24**, 1073 (1981).
[22]C. Djalali, thèse d'Etat Orsay, 1984.