PHYSICAL REVIEW C VOLUME 35, NUMBER 6 JUNE 1987

Energy dependence of inelastic proton scattering to the 3^-, 2.614 MeV state in ^{208}Pb

S. Kailas

Nuclear Physics Division, Bhabha Atomic Research Centre, Trombay, Bombay 400085, India

(Received 27 October 1986)

The recent work of McDaniels *et al.* regarding the inelastic excitation of the 3^- state at 2.614 MeV in ^{208}Pb by protons with energies between 100 and 800 MeV has been expanded with the inclusion of the data at other proton energies down to ~ 35 MeV. It is found that the deformation length, δ, for this state, extracted using the collective distorted-wave Born approximation formalism, remains nearly the same in the energy region between 35 and 800 MeV. Combining the δ values determined from the (p,p′) measurements with those obtained from the electromagnetic methods, the ratio of the neutron and proton transition matrix elements (M_n/M_p) has been determined for this state.

From an analysis of medium energy proton inelastic scattering data, with the collective distorted-wave Born approximation (DWBA) formalism, McDaniels *et al.*[1,2] have shown that the reduced transition probabilities, $B(E3)$ for the (3^-, 2.614 MeV) state in ^{208}Pb remain nearly a constant in the energy region between 100 and 800 MeV. This result, they conclude, can be taken as an evidence that supports the validity of the collective formalism for medium energy inelastic proton scattering. In their work they have included the data available at 98 (Ref. 3) (not 104 MeV as quoted in Refs. 1 and 2), 135,[4] 156,[5] 200,[2] 334,[6] and 800 MeV.[7,8] The purpose of the present work is to extend this investigation to proton energies down to ~ 35 MeV, with the inclusion of the data measured at 35,[9] 54,[10] 61,[11] 65,[12] 80,[13] and 120 MeV.[13]

McDaniels *et al.*[1,2] have also pointed out that the $B(E3)$ values determined with 98 (Ref. 3) and 201 MeV (Ref. 14) protons are rather low and differ from the adopted value[2,8] by about 40% and 90%, respectively. Earlier studies by Tinsley *et al.*[15] and Bertrand *et al.*[16] with 200 MeV protons also reported $B(E3)$ values which were too low by almost a factor of 2—3 when compared to the adopted value. However, in the recent publication[2] by the above group, it is reported that the $B(E3)$ value determined with 200 MeV protons is in good accord with the one obtained from the electromagnetic method[2,8] when proper optical model parameters are used in the analysis. McDaniels *et al.*[2] have also shown that since both the elastic and the inelastic scattering cross section data reported in Ref. 14 were low when compared to their measurements[2] the $B(E3)$ values determined in Ref. 14 also came out to be quite different from the adopted value.

When we rechecked the analysis of the data carried out at $E_p \sim 98$ MeV, it was realized that the result quoted in Ref. 3 was obtained by considering only a few data points lying between $\theta \sim 10°$ and 25°, even though the data were measured up to $\sim 75°$. This resulted in a value of deformation length $\delta = 0.67$ fm. In the present work we have removed this deficiency of the earlier work by reanalyzing the data between $\theta \sim 10°$ and 50° (the data points beyond this range had larger statistical errors and hence were not included in the analysis) and determined the new value of $\delta \simeq 0.75$ fm for $E_p \sim 98$ MeV (Table I). In Fig. 1 the experimental data along with the DWBA calculations are shown (solid line, $\delta = 0.75$; dashed line, $\delta = 0.67$).

It can be seen from the figure that although the calculations with $\delta = 0.67$ fm fit the data in the angular range between 10° and 25° very well, they do not fit the data in the θ range 25°—50°. However, the DWBA calculations with $\delta = 0.75$ fm give the best fit to the data in the whole angular range $\theta = 10°$—50°.

The inelastic scattering data available[13] at 80 and 120 MeV were also analyzed using the Indiana University Cyclotron Facility global parameters[17] and the collective DWUCK-4 (Ref. 18) was used for carrying out the analysis. The data measured at $E_p \sim 80$ and 120 MeV along with the DWBA calculations are also shown in Fig. 1. It can be seen from Fig. 1 that the data are explained satisfactorily by the macroscopic collective model. The δ values determined are listed in Table I.

In the literature one finds that there are several ways in which the deformation length δ are defined[19] and used. The most commonly used procedure is to define the deformation β as

$$\beta^2 = \sigma_{\text{expt}}/\sigma_{\text{DWBA}} \quad \text{(procedure I)} ,$$

with the condition $\beta_R = \beta_I = \beta$. The δ value is then obtained starting with this β as follows:

(a) $\delta = \beta R_R$ (R_R = real potential radius) ,

(b) $\delta = \beta R_I$ (R_I = imaginary potential radius) ,

(c) $\delta = \beta (R_R + R_I)/2$.

The other procedure involves defining

$$\delta \text{ as } (\beta R)_R = (\beta R)_I \quad \text{(procedure II)} ,$$

where one matches the product of β and the radius parameter for the real and the imaginary parts. It is found that the δ value obtained by the latter procedure is in reasonable agreement with that extracted using procedure I(c) mentioned above. In the present work we have taken care to define δ either using procedure II or procedure I(c). In the case of protons one has the additional problem

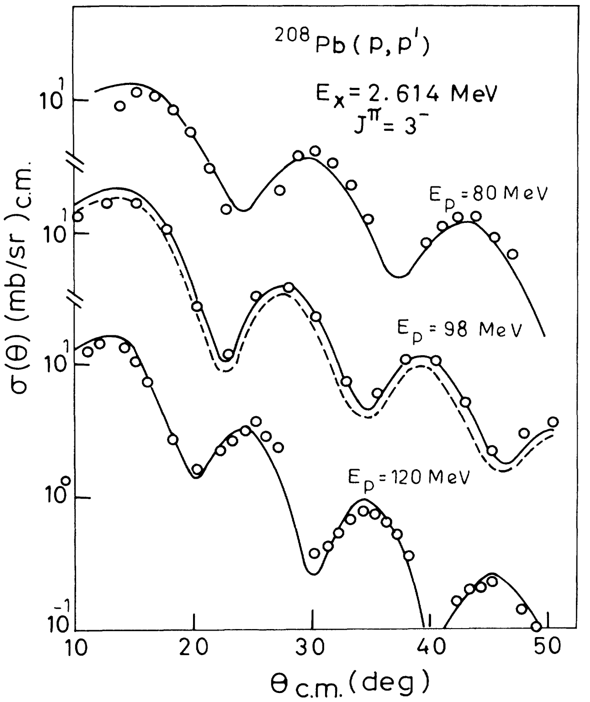

FIG. 1. Angular distribution for the 3^- state at $E_x \sim 2.614$ MeV measured with 80, 98, and 120 MeV protons. The solid curves are the predictions from the collective model. The δ values are listed in Table I. The dashed curve is a calculation with $\delta = 0.67$ fm.

of introducing the deformation β_{so} for the spin orbit coupling. The effect of this term is expected to be progressively important for higher proton energies[19] ($E_p \gtrsim 120$ MeV). Again, β_{so} is defined in several ways in relation to β_x ($x = R$ or I). This, in turn, will alter the δ value extracted. It has already been pointed out by McDaniels *et al.*[2] that the δ value extracted is sensitive to the optical model fits to the elastic scattering data and the resultant parameters. Further, the δ value will have an uncertainty arising mainly from the fitting of the experimental angular distribution data with the theoretical prediction made using the DWBA formalism. Considering this and the other problems discussed above, it is expected that the δ value can be, in general, determined with an uncertainty of 5–10 %.

TABLE I. Deformation lengths for the 2.614 MeV, 3^- state in ^{208}Pb.

Proton energy (MeV)	Deformation length δ (fm)	Ref.	K
35	0.89±0.08	9	2.93
54	0.83±0.08	10	2.87
61	0.78±0.08	11	2.85
65	0.83±0.08	12	2.84
80	0.70±0.07	This work	2.80
98	0.75±0.06	This work	2.75
120	0.65±0.08	This work	2.69
135	0.77±0.06	4	2.65
156	0.77±0.08	5	2.59
200	0.75±0.03	2	2.47
334	0.83±0.04	6	2.10
800	0.76±0.06	7	0.80
800	0.83±0.03	8	0.80

In Table I the δ values extracted for $E_p \sim 35$–800 MeV are listed. The uncertainty on the δ value is taken as ±10% for those cases where they are not explicitly stated. Within their respective errors, the δ values in this energy region are in good agreement with each other and an average value of $\delta = 0.79 \pm 0.01$ fm can be obtained. This value is in very good agreement with the value of $\simeq 0.79$ fm obtained from electromagnetic methods.[2,8] It may be remarked that Horen *et al.*[20] and Jones *et al.*[21] have also concluded that the δ values are energy independent and the macroscopic collective formalism works quite well for $E_p \sim 25$–800 MeV protons from their analyses of proton scattering data from ^{40}Ca and ^{12}C targets, respectively.

Bernstein *et al.*[22] have shown that the δ values are, in general, related both to the probe used for exciting the level in the target and to the nuclear structure matrix elements of the target nucleus. They represent

$$\delta = \frac{Z\delta_p + N\delta_n K}{Z + NK} , \qquad (1)$$

where Z and N are, respectively, the proton and the neutron numbers of the target; $\delta_{p\,(n)}$ is the proton (neutron) deformation length. K is a measure of the interaction strength of the external field (probe) with the target proton and neutron, and is related to the isoscalar and the isovector parts of the probe nucleus interaction. Typical K values for the various probes are listed in Ref. 22. The authors of this reference have shown that the K value will change depending on the proton energy as both the isoscalar and the isovector parts of the interaction are energy dependent. It is found[22] that the K value decreases from ~ 3 at low E_p values to ~ 1 at high E_p values. Bernstein *et al.*[22] have established the probe dependence from a systematic analysis of the low-lying 2^+ states in a large number of nuclei excited through a variety of probes.

In view of the scatter observed in the δ values obtained in the present case, we have tried to analyze the present data using the above mentioned idea of "probe dependence" for the excitation of this state and to see whether the present data are consistent with this picture.

Combining the δ values determined at the various proton energies (Table I) with the average value of 0.79 fm obtained from electromagnetic methods and using Eq. (1), we have determined the δ_p and δ_n values for the 3^-, 2.614 MeV state in ^{208}Pb. In carrying out the analysis we assumed the K values to be ~ 3 at $E_p \sim 10$ MeV and ~ 0.8 at $E_p \sim 800$ MeV. The K values for the various proton energies lying between 10 and 800 MeV have been obtained by a smooth linear interpolation of the K values assumed at the two extreme energies. The K values for the various proton energies used in the present work are listed in Table I. From the analysis it is found $\delta_p \simeq 0.79$ fm and $\delta_n = 0.77$ fm. It may be pointed out that the result $\delta_p \simeq \delta_n$ obtained here is consistent with our earlier finding that δ is energy independent. [It can be easily shown that if δ is energy independent, then use of Eq. (1) will lead to the result $\delta=\delta_p=\delta_n$.] Starting from the values of δ_p and δ_n determined above, we have obtained the ratio of the neutron and proton transition matrix elements defined as

$$\frac{M_n}{M_p}=\frac{N\delta_n}{Z\delta_p} \tag{2}$$

for the 3^-, 2.614 MeV state in ^{208}Pb; we determine a value of 1.49 ± 0.04 for the above mentioned ratio. This value is in good agreement with the value of 1.27 ± 0.18 obtained[23] from an analysis of ^{3}He (270 MeV) and electron scattering data and the value obtained by Gazzaly *et al.*, 1.63 ± 0.08,[8] by combining the (800 MeV) proton and electron scattering data.

It is interesting to find that the M_n/M_p value determined for the 3^- state is very similar to the value of 1.5 obtained[24] for the low lying 2^+ state in ^{208}Pb. This value is also close to the homogeneous model value $[M_n/M_p=N/Z\ (\delta_n=\delta_p)]$, 1.54. It will be interesting to make a theoretical calculation of the random phase approximation type for the 3^- state, as is done for the 2^+ state.[24]

To conclude, we have extended the work of McDaniels *et al.*[1,2] down to $E_p\sim35$ MeV. In the energy region between 35 and 800 MeV, the δ values remain nearly the same. This is an observation and it needs an explanation from microscopic theories. Even though it has been shown that the collective DWBA formalism works in this large energy region, it is still to be proven as to why this formalism works so well. Combining this with the electron scattering data, we have also determined the ratio of the neutron and proton transition matrix elements for this state.

The author thanks Prof. P. Schwandt for kindly providing the data measured at 80 and 120 MeV and Dr. S. K. Gupta for useful comments.

---

[1] D. K. McDaniels, J. Lisantti, J. Tinsley, I. Bergqvist, L. W. Swenson, F. E. Bertrand, E. E. Gross, and D. J. Horen, Phys. Lett. **162B**, 277 (1985).

[2] D. K. McDaniels, J. R. Tinsley, J. Lisantti, D. M. Drake, I. Bergqvist, L. W. Swenson, F. E. Bertrand, E. E. Gross, D. J. Horen, T. P. Sjoreen, R. Liljestrand, and H. Wilson, Phys. Rev. C **33**, 1943 (1986).

[3] S. Kailas, P. P. Singh, D. L. Friesel, C. C. Foster, P. Schwandt, and J. Wiggins, Phys. Rev. C **29**, 2075 (1984).

[4] G. S. Adams, A. D. Bacher, G. T. Emery, W. P. Jones, D. W. Miller, W. G. Love, and F. Petrovich, Phys. Lett. **91B**, 3 (1980).

[5] V. Comparat, R. Frascaria, N. Marty, M. Morlet, and A. Willis, Nucl. Phys. **A221**, 403 (1974).

[6] F. E. Bertrand, E. E. Gross, D. J. Horen, R. O. Sayer, T. P. Sjoreen, D. K. McDaniels, J. Lisantti, J. R. Tinsley, L. W. Swenson, J. B. McClelland, T. A. Carey, K. Jones, and S. J. Seestrom-Morris, Phys. Rev. C **34**, 45 (1986).

[7] T. A. Carey, W. D. Cornelius, N. J. Di Giacomo, J. M. Moss, G. S. Adams, J. B. McClelland, G. Pauletta, C. Whitten, M. Gazzaly, N. Hintz, and C. Glashausser, Phys. Rev. Lett. **45**, 239 (1980).

[8] M. Gazzaly, N. M. Hintz, G. S. Kyle, R. K. Owen, G. W. Hoffman, M. Barlett, and G. Blanpied, Phys. Rev. C **25**, 408 (1982).

[9] W. J. Wagner, G. M. Crawley, G. R. Hammerstein, and H. McManus, Phys. Rev. C **12**, 757 (1975).

[10] M. Lewis, F. Bertrand, and C. B. Fulmer, Phys. Rev. C **7**, 1966 (1973).

[11] A. Scott, N. P. Mathur, and F. Petrovich, Nucl. Phys. **A285**, 222 (1977).

[12] Y. Fujita, M. Fujiwara, S. Morinobu, I. Katayama, T. Yamazaki, T. Itahashi, H. Ikegami, and S. I. Hayakawa, Phys. Rev. C **32**, 425 (1985).

[13] P. Schwandt, private communication.

[14] C. Djalali, N. Marty, M. Morlet, and A. Willis, Nucl. Phys. **A380**, 42 (1982).

[15] J. R. Tinsley, D. K. McDaniels, J. Lisantti, L. W. Swenson, R. Liljestrand, D. M. Drake, F. E. Bertrand, E. E. Gross, D. J. Horen, and T. P. Sjoreen, Phys. Rev. C **28**, 1417 (1983).

[16] F. E. Bertrand, E. E. Gross, D. J. Horen, J. R. Wu, J. Tinsley, D. K. McDaniels, L. W. Swenson, and R. Liljestrand, Phys. Lett. **103B**, 326 (1981).

[17] P. Schwandt, H. O. Meyer, W. W. Jacobs, A. D. Bacher, S. E. Vigdor, M. D. Kaitchuck, and T. R. Donoghue, Phys. Rev. C **26**, 55 (1982).

[18] P. D. Kunz, DWUCK-4 code, University of Colorado, 1982 (unpublished).

[19] G. R. Satchler, *Direct Nuclear Reactions* (Clarendon, Oxford, 1983), Chap. 14.

[20] D. J. Horen, F. E. Bertrand, E. E. Gross, T. P. Sjoreen, D. K. McDaniels, J. R. Tinsley, J. Lisantti, L. W. Swenson, J. B. McClelland, T. A. Carey, S. J. Seestrom-Morris, and K. Jones, Phys. Rev. C **30**, 709 (1984).

[21] K. W. Jones, C. Glashausser, R. de Swiniarski, S. Nanda, T. A. Carey, W. Cornelius, J. M. Moss, J. B. McClelland, J. R. Comfort, J. L. Escudie, M. Gazzaly, N. Hintz, G. Igo, M. Haji-Saeid, and C. A. Whitten, Jr., Phys. Rev. C **33**, 17 (1986).

[22] A. M. Bernstein, V. R. Brown, and V. A. Madsen, Comments Nucl. Part. Phys. **11**, 203 (1983).

[23] P. P. Singh, Q. Li, P. Schwandt, W. W. Jacobs, M. Saber, E. J. Stephenson, A. Saxena, and S. Kailas, Prāmana **27**, 747 (1986).

[24] V. A. Madsen, T. Suzuki, A. M. Bernstein, and V. R. Brown, Phys. Lett. **123B**, 13 (1983).