Neutron Deformation Parameter from Comparative Study of π^+ and π^- Inelastic Scattering

S. Iversen, A. Obst, and Kamal K. Seth
Northwestern University, Evanston, Illinois 60201

and

H. A. Thiessen, C. L. Morris, N. Tanaka, and E. Smith
Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545

and

J. F. Amann
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

and

R. Boudrie
University of Colorado, Boulder, Colorado 80302

and

G. Burleson and M. Devereux
New Mexico State University, Las Cruces, New Mexico 88001

and

L. W. Swenson and P. Varghese
Oregon State University, Corvallis, Oregon 97331

and

K. Boyer, W. J. Braithwaite, W. Cottingame, and C. Fred Moore
University of Texas, Austin, Texas 78712
(Received 30 August 1977)

Differential cross sections for the excitation of the 2^+ state in ^{18}O by 230-MeV pions are found to be about 70% larger for π^- than for π^+. Since the π-nucleon interaction at this energy is dominated by the (3,3) resonance, it is concluded that the results imply that $\langle\beta R\rangle_n \approx 1.3\langle\beta R\rangle_p$, or alternatively, that $(\beta R)_n$ (valence neutrons) $\approx 3(\beta R)_c$(core), where β is the deformation parameter and R the equilibrium radius of the deformed potential. We believe that these results constitute the first example of measurement of the neutron deformation parameter.

The Coulomb interaction and the presence of neutron excess imply that the density distributions of neutrons and protons in nuclei may be different in size and/or shape. This would give rise to an isovector potential with radius and/or deformation different from that of the isoscalar potential. For a long time attempts have been made to unravel these differences in nuclear ground states and excited states by comparing the interactions of projectiles which are expected to have different sensitivities to the different components of these distributions.[1,2] Several such detailed comparisons of deformation parameters have been made.[2,3] However, the differences observed have generally been quite small and it has not been possible to draw any convincing conclusions in view of the usual uncertainties associated with the analyses of the different kinds of data from different sources, and for different projectiles and energies. Pions are potentially an exceptional tool for such investigations because at low energies the elementary pion-nucleon interaction is dominated by the so-called (3, 3) or $J=\frac{3}{2}$, $T=\frac{3}{2}$ resonance, which makes the resonant π^-n (or π^+p) amplitude 3 times larger than the π^-p (or π^+n) amplitude. This should give rise to differential effects in π^+ and π^- interactions with nuclei with different numbers or different distributions of neutrons and protons.[4,5] In order best to study these effects it is necessary to measure transitions to discrete nuclear states in specific reaction channels. For example, as suggested by Bohr and Mottelson,[6] the deformations of the isovector field could be obtained by comparing the cross sections for excitation of the rotational states by inelastic scattering of π^+ and π^-. With the advent of meson "factories" and the construction of large magnetic spectrometers, such investigations have finally become possible. In this Letter we report on the first successful attempt to deduce separate neutron and proton deformation parameters by inelastic scattering of π^+ and π^-.

The most dramatic effects due to the ability of pions to differentiate between protons and neutrons in the nucleus may be expected for inelastic scattering in cases of "pure" valence neutron (or proton) transitions with a completely inert core, for which $\sigma(\pi^-)/\sigma(\pi^+) = 3^2$ (or 3^{-2}) is predicted. Hopefully, a good approximation to this hypothetical case is provided by the $0_1^+ \to 2_1^+$ transition in a nucleus with doubly magic core plus two valence neutrons, such as ^{18}O. The 0_1^+(g.s.) and 2_1^+(1.98 MeV) states of ^{18}O are rather well understood[7]; both consist primarily of two valence neutrons in $1d_{5/2}$ and $2s_{1/2}$ shells (85–90%) with rather small ($\leq 15\%$) deformed core components. With these wave functions, it is predicted that $Q_2(2_1^+) = (-4 \text{ to } -6)e \cdot \text{fm}^2$ and $B(E2)_\uparrow = (36-40)e^2 \cdot \text{fm}^4$. These compare well with the best experimental results,[8] which average to $Q_2(2_1^+) \approx (-7 \pm 3)e \cdot \text{fm}^2$ and $B(E2) = (45 \pm 5)e^2 \cdot \text{fm}^4$.

At the EPICS facility at Clinton P. Anderson Meson Physics Facility,[9] we have measured differential cross sections, $\sigma(\theta)$, for elastic and inelastic scattering of 230-MeV π^+ and π^- from ^{18}O. A ~0.25-gm/cm^2 water target enriched to 88% in ^{18}O was used. The scattered pions were analyzed in a magnetic spectrometer and the energy-loss spectrum was constructed by the on-line computer from the x, y, θ, and φ information provided by four multiwire, position-sensitive detectors[10] at the entry and four at the exit of the spectrometer. An overall energy resolution of FWHM (full width at half-maximum) ≈ 500 keV was realized. The absolute cross-section normalization was determined by measuring $\pi^\pm p$ scattering simultaneously from the hydrogen in the target. The resulting $\sigma_{\rm el}(\theta)$ and $\sigma_{\rm inel}(\theta)$ for both π^- and π^+ and the ratios between them are illustrated in Fig. 1. We note that $\sigma_{\rm el}(\theta)$ for π^+ and π^- show small phasing differences which arise mainly from Coulomb-nuclear interference, while the integrated cross sections, defined as $\sigma \equiv \sum \sigma(\theta) \sin\theta$, remain essentially constant $[\sigma_{\rm el}(\pi^-)/\sigma_{\rm el}(\pi^+) = 1.06 \pm 0.04]$.[11] Similar results have been reported[12] for elastic scattering from ^{12}C, ^{16}O, and ^{40}Ca. However, the π^+ and π^- inelastic cross sections for the 2_1^+ state show a clear and large quantitative difference, with $\sigma(\pi^-)/\sigma(\pi^+) = 1.66 \pm 0.13$. This is in sharp contrast to the reported absence[12] of any differences in the π^+, π^- inelastic scattering from the 2_1^+ state in the self-conjugate nucleus ^{12}C.

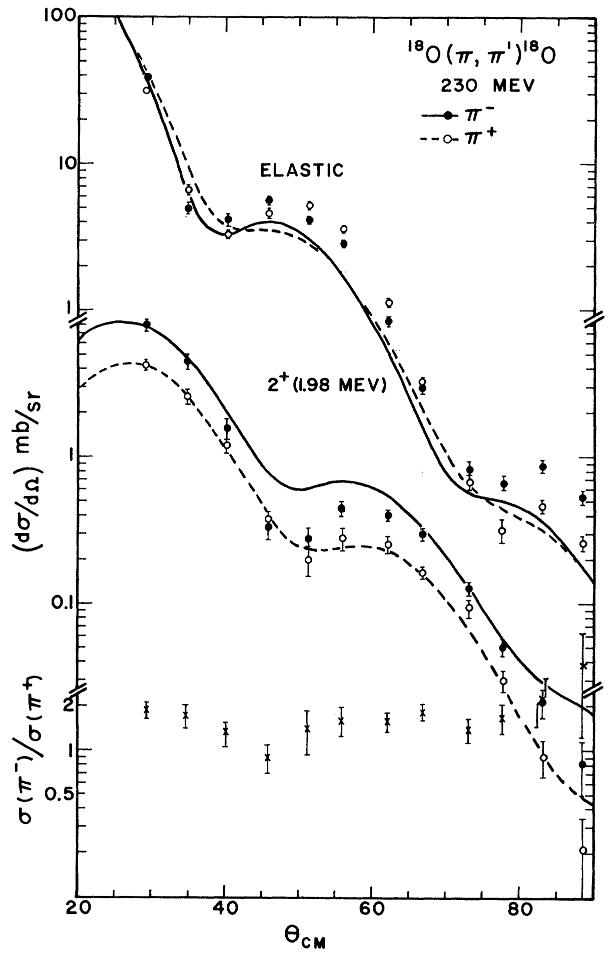

FIG. 1. Differential cross sections for π^+ and π^- elastic scattering and inelastic scattering to the 2_1^+ state in ^{18}O. Also shown is the ratio $\sigma(2^+)_{\pi^-}/\sigma(2^+)_{\pi^+}$. The curves are based on DWBA analysis.

The qualitative aspects of our inelastic-scattering results are easiest to understand within the framework of the collective model. In the commonly used distorted-wave Born-approximation (DWBA) calculations with collective form factors, $\sigma_{\rm inel}$ is proportional to $(\beta R V)^2$ where β is the deformation parameter, R is the equilibrium radius of the deformed potential, and V is its depth.[13] For pions, for a typical interaction potential, say of the Kisslinger form, V is proportional to the sum of elementary π-nucleon amplitudes over the N neutrons and Z protons in the nucleus. In the (3, 3) resonance region, we may neglect other amplitudes. It then follows that $\sigma(\pi^-) \propto [(Z+3N)(\beta R)_{\pi^-}]^2 \equiv [Z(\beta R)_p + 3N(\beta R)_n]^2$, if we differentiate between neutron and proton deformation lengths $(\beta R)_n$ and $(\beta R)_p$. Similarly $\sigma(\pi^+) \propto [(3Z+N)(\beta R)_{\pi^+}]^2 \equiv [3Z(\beta R)_p + N(\beta R)_n]^2$, or

$$\frac{\sigma(\pi^-)}{\sigma(\pi^+)} = \left[\frac{(Z+3N)(\beta R)_{\pi^-}}{(3Z+N)(\beta R)_{\pi^+}}\right]^2 = \left[\frac{Z(\beta R)_p + 3N(\beta R)_n}{3Z(\beta R)_p + N(\beta R)_n}\right]^2. \quad (1)$$

While $\sigma(\pi^-)$ and $\sigma(\pi^+)$ individually depend on details of the potentials and the π-nucleon amplitudes, it has been shown[14] that their ratio in actual DWBA calculations remains remarkably close to the value given by Eq. (1).

According to Eq. (1), if $(\beta R)_p = (\beta R)_n$ or equivalently $(\beta R)_{\pi^-} = (\beta R)_{\pi^+}$, then $\sigma(\pi^-)/\sigma(\pi^+) = [(Z+3N)/(3Z+N)]^2 = 1.25$ for ^{18}O. This effect of different numbers of neutrons and protons is similar to the effect of the Lane term in a comparison of neutron and proton inelastic scattering. Our experimental ratio $\sigma(\pi^-)/\sigma(\pi^+) = 1.66 \pm 0.13$ is much larger than this. In terms of Eq. (1), it can only be explained by $(\beta R)_n/(\beta R)_p = 1.34 \pm 0.11$. This schematic calculation can be tested by actual DWBA calculation with a collective form factor. We have done so with the computer code DWPI,[15] using a Kisslinger-type potential with a density distribution given by a model-independent analysis of the new, but still preliminary, data[16] on elastic scattering of electrons from ^{18}O, and the scattering amplitudes obtained by summing the free-π-nucleon amplitudes over the eight protons and ten neutrons in ^{18}O. The results of this calculation, without any free parameters, were normalized to the data according to integrated cross sections, and are shown in Fig. 1. The fit to the π^+ inelastic data is quite good and gives $(\beta R)_{\pi^+} = (0.335 \pm 0.010)R = 1.05 \pm 0.03$ fm, if we use $R = 1.2A^{1/3} = 3.145$ fm. The fit to the π^- inelastic data is poorer and gives $(\beta R)_{\pi^-} = (0.385 \pm 0.011)R = 1.21 \pm 0.03$ fm. For $R = 1.2A^{1/3}$, these results are equivalent to $B(E2)_{\pi^+} = (40 \pm 2)e^2 \cdot \mathrm{fm}^4$ and $B(E2)_{\pi^-} = (53 \pm 3)e^2 \cdot \mathrm{fm}^4$. From Eq. (1) we obtain equivalently that $(\beta R)_n = 1.28 \pm 0.10$ fm, $(\beta R)_p = 0.96 \pm 0.10$ fm, and $(\beta R)_n/(\beta R)_p = 1.33 \pm 0.17$ fm. We may interpret these results as indicating larger β_n and/or larger R_n.

It might be argued that use of a collective form factor for a transition in which two valence particles play a most important part is questionable. A microscopic form factor based on realistic wave functions[7] should be used for the valence particles. Since the observed ratio of π^- and π^+ cross sections is 1.66 while scattering from valence neutrons alone would predict ~9, we must conclude that the ^{16}O core plays an important part. This may be included by using a collective form factor for it. Since the means for doing such a detailed core + particle DWBA calculation are not available, we present below a schematic calculation done in the same general spirit.

Consider Z neutrons (out of N) as forming a closed core with deformation $(\beta R)_c$, and $N-Z$ valence neutrons outside with average deformation $(\beta R)_n$. In this case, in analogy with Eq. (1) we may write

$$\frac{\sigma(\pi^-)}{\sigma(\pi^+)} = \left[\frac{(Z+3Z)(\beta R)_c + 3(N-Z)(\beta R)_n}{(3Z+Z)(\beta R)_c + (N-Z)(\beta R)_n}\right]^2. \quad (2)$$

Solving for the measured value of the ratio $= 1.66 \pm 0.13$, we get $(\beta R)_n/(\beta R)_c = 2.7 \pm 0.6$. This result, though new, is quite reasonable. According to Bohr and Mottelson,[6] if the deformation of the ^{16}O core were entirely due to the polarizing effect of the two valence neutrons, it would be of the *order* of $\frac{2}{16}$ of $(\beta R)_n$, i.e., $(\beta R)_n/(\beta R)_c = 8$. Any additional intrinsic deformation of ^{16}O would bring the ratio closer to our value.

In this Letter we have addressed ourselves only to the excitation of the 2_1^+ state. We note, however, that for the excitation of the 3_1^- state at 5.09 MeV we find $\sigma(\pi^-)/\sigma(\pi^+) = 0.92 \pm 0.08$. This is understandable in the microscopic model. The 3_1^- state can be excited by the promotion of either a proton or a neutron from the $1p$ core orbit to the $1d$ valence orbit which is partially blocked for neutrons. This should give $\sigma(\pi^-)/\sigma(\pi^+) < 1$.

In summary, we conclude that the observed large enhancement of π^- inelastic scattering over π^+ scattering necessarily implies differences in neutron and proton distributions in $^{18}O(2_1^+)$. While the individual values of $(\beta R)_{z,n}$ may change with more refined analysis, we believe that our conclusions about the ratios, namely that $(\beta R)_n \approx 1.3(\beta R)_p$ or that $(\beta R)_{\mathrm{valence}} \approx 3(\beta R)_{\mathrm{core}}$ will remain essentially unchanged.

Claims about differences between neutron and proton distributions are, of course, not new.[2] However, all prior claims were based on comparisons of results of very dissimilar experiments, such as (e, e') and (α, α'), or (p, p') and (n, n') whose techniques of measurement and methods of analysis are difficult to compare. The inherent symmetry of our measurements and methods of analysis with respect to π^+ and π^- makes our results much more reliable. We believe that we have convincingly demonstrated the ability of differential studies of π^+ and π^- inelastic scattering to provide an insight into the neutron/proton or core/valence structures of excited nuclear states which has hitherto before not been possible. The pions may now be considered as beginning to deliver on their promise as a new and powerful tool in the study of nuclear structure!

The authors wish to acknowledge the valuable contribution of Professor D. Denhard in the conception of this experiment, the advice and critique of Professor E. Lomon and Professor A. Bernstein, and the help of Dr. B. Zeidman, Dr. S. Verbeck, S. Greene, and L. E. Smith during the measurements. This work was supported in part by the U. S. Energy Research and Development Administration, by the National Science Foundation, and by the Robert A. Welch Foundation.

[1]G. R. Satchler and W. G. Love, Nucl. Phys. A172, 449 (1971).

[2]V. A. Madsen, V. R. Brown, and J. D. Anderson, Phys. Rev. Lett. 34, 1388 (1975); A. M. Bernstein, V. R. Brown, and V. A. Madsen, to be published.

[3]O. Beer, A. El Behay, P. Lopato, Y. Terrien, G. Vallois, and Kamal K. Seth, Nucl. Phys. A147, 326 (1970).

[4]A. Abashian, R. Cool, and J. W. Cronin, Phys. Rev. 104, 855 (1956).

[5]B. W. Allardyce *et al.*, Nucl. Phys. A209, 1 (1973).

[6]A. Bohr and B. Mottelson, *Nuclear Structure* (Benjamin, New York, 1975), Vol. II, p. 137, also Vol. I, p. 334.

[7]T. K. Engeland and P. J. Ellis, Phys. Rev. Lett. 36, 996 (1976); T. Erikson and G. E. Brown, Nucl. Phys. A277, 1 (1977); R. D. Lawson, F. J. D. Serduke, and H. T. Fortune, Phys. Rev. C 14, 1245 (1976).

[8]B. G. Harvey *et al.*, Phys. Rev. 146, 712 (1966); J. L. Groh, A. P. Singhal, H. S. Caplan, and B. S. Dolbilkin, Can. J. Phys. 49, 2743 (1971); J. L. Escudie *et al.*, Phys. Rev. C 10, 1645 (1974); D. Denhard *et al.*, in Proceedings of a Conference on the Physics of Medium Light Nuclei, Florence, 1977 (unpublished); P. M. Vold *et al.*, Phys. Rev. Lett. 39, 325 (1977); C. Flaum, J. Barrette, M. J. Levine, and C. E. Thorn, Phys. Rev. Lett. 39, 446 (1977).

[9]H. A. Thiessen *et al.*, to be published.

[10]C. L. Morris, H. A. Thiessen, and G. W. Hoffman, in Proceedings of the IEEE Nuclear Science Symposium, San Francisco, California, October 1977 (to be published).

[11]The errors quoted in this Letter are due to statistical uncertainties in cross-section measurements, normalization, and peak shape fitting.

[12]J. Piffaretti *et al.*, Phys. Lett. 67B, 289 (1977); J.-P. Egger and E. Boschitz, private communication.

[13]R. H. Bassel, G. R. Satchler, and R. M. Drisko, Phys. Rev. 128, 2693 (1962).

[14]C. L. Morris, Phys. Rev. C 13, 1755 (1976).

[15]R. A. Eisenstein and G. A. Miller, Comput. Phys. Comm. 11, 95 (1976).

[16]W. Bertozzi *et al.*, private communication.

Long-Range Absorption in the Heavy-Ion Optical Potential

A. J. Baltz,[a] S. K. Kauffmann, N. K. Glendenning, and K. Pruess
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 7 September 1977)

A long-range imaginary optical potential approximating the effects of quadrupole Coulomb excitation is derived in closed form. An analytical closed form for sub-Coulomb elastic scattering is obtained by inserting this potential into a weak-absorption model.

A long-range absorption in the heavy-ion optical potential due to Coulomb excitation of a low-lying collective quadrupole state has been the subject of some interest recently. An experimental specimen is the elastic scattering data of 90-MeV ^{18}O on ^{184}W.[1] These data show a Fresnel pattern damped below the Rutherford cross section that is well reproduced by a coupled-channels calculation which includes Coulomb excitation of the 111-keV 2^+ rotational state in ^{184}W.

An alternative theoretical description is the construction of an optical-model component arising from two-step contributions to elastic scattering. This can be done using the Feshbach projection-operator formalism.[2] In this framework, Love, Terasawa, and Satchler have recently obtained a formula for a long-range imaginary potential (which we will refer to as the LTS potential) by making the approximation of using plane-wave intermediate states along with a classical correction for the Coulomb braking.[3] The potential obtained is dominantly negative imaginary,