Lifetime of the 0_2^+ State of ^{206}Pb and the State Dependence of the Monopole Effective Charge

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(Received 14 August 1972)

The mean lifetime of the 0_2^+ state of ^{206}Pb is found to be 0.97 ± 0.10 nsec. This corresponds to a monopole strength $\rho = (2.6 \pm 0.3) \times 10^{-2}$ and $B(E2{:}0_2^+ \rightarrow 2_1^+) < 2.0e^2\ \mathrm{F}^4$. The $E0$ strength can be accounted for with standard shell-model wave functions using a state-dependent monopole effective charge derived from isotope-shift data.

It is widely believed that the shell closures at ^{208}Pb are exceptionally effective. In a recent Letter, Griffin and Donne[1] reported an unusually strong $E0$ decay branch of the 1.165-MeV 0_2^+ state of ^{206}Pb. If the simple shell-model picture of the low-lying ^{206}Pb states as two neutron holes in a closed ^{208}Pb core is valid, the monopole matrix element, $\langle f|\sum_p r_p^2|i\rangle$, should vanish since it involves a sum over charged particles. The size of the $E0$ matrix element is then of considerable interest since it is sensitive to components of the ^{206}Pb wave functions which arise from polarization of the proton core. From the branching ratios of Ref. 1, one cannot distinguish an unusually strong $E0$ from an unusually weak competing $E2$ transition to the 2_1^+ state. We have measured the lifetime of the 0_2^+ state using a pulsed-beam delayed-coincidence technique and have extracted the $E0$ and $E2$ matrix elements. These will be discussed in terms of the usual shell-model description of the states involved.

A beam of 12.25-MeV protons inelastically scattered from a 1-mg/cm^2 self-supporting ^{206}Pb foil excited the state.[2] Internal conversion electrons emitted at 90° to the beam direction entered a simple low-dispersion magnet, were deflected 90° in the reaction plane, and were detected by a conventional, cooled Si(Li) detector with an active area of 200 mm^2. The electron energy analysis was done using the Si(Li) detector, the purpose of the magnet being only to remove unwanted low-energy electron and charged-particle background. Strong lines at 1078 ± 3 keV and 1155 ± 3 keV were observed in the electron spectrum corresponding to K and L internal-conversion transitions between levels separated by 1166 ± 3 keV, in agreement with the results of Ref. 1. The measured K/L ratio of 6.0 ± 0.2 agrees with the theoretical value of 5.85 for $E0$ transitions.[3]

A standard fast-slow coincidence system with a time-to-amplitude converter (TAC) was used to observe the time delay between the electron decay and the beam pulse. TAC spectra in slow coincidence with electrons in eight selected energy regions were stored on line in an SDS 930 computer. The system time resolution was measured by observing the internal-conversion decay of the prompt ($\tau = 13$ psec[4]) 2^+ state at 0.803 MeV in separate runs.

TAC spectra in coincidence with K conversion electrons from the prompt (2^+) and delayed (0^+) decays were analyzed by first subtracting random coincidences due to the background under the conversion lines. A smooth curve drawn through the prompt peak was used to obtain a resolution function $P(t'-t)$, which is related to a delayed function $D(t)$ by

$$D(t) = \tau^{-1}\int_0^\infty e^{-t'/\tau}P(t'-t)\,dt'.$$

Delayed spectra, calculated using the above equation for different values of the mean lifetime τ, were compared with the experimental delayed data to obtain a best value of τ. The resolution function, the delayed data, and the best-fit calculated delayed function for $\tau = 0.97$ nsec are shown in Fig. 1. An uncertainty of 0.10 nsec arises from assumed 5% errors in the time calibration and an estimate of the reliability of the fitting procedure.

We checked that the lifetime measured with our pulsed-beam technique is that of the 0_2^+ level and not of another state which feeds the 0_2^+ level in a subsidiary experiment. There we used detectors without magnets to show that the total (p,p') cross section feeding the 0_2^+ state was consistent with the number of internal-conversion electrons detected from its decay.

Combining the measured mean life, the branch-

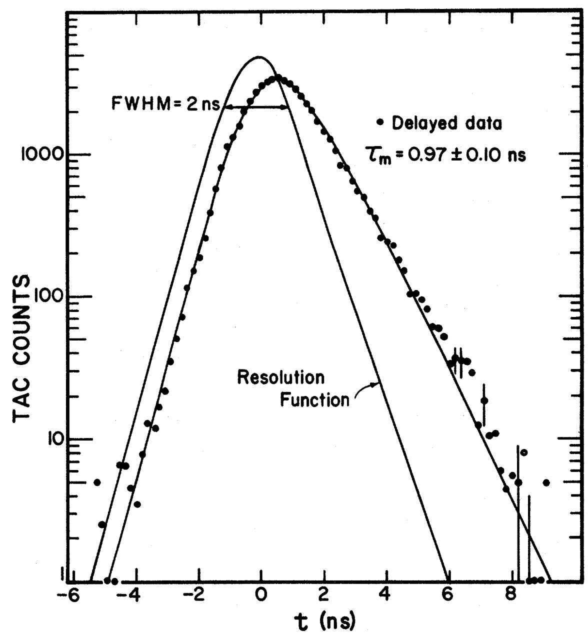

FIG. 1. TAC spectrum from the $0_2^+ \to 0_1^+$ decay in ^{206}Pb. The resolution function is derived from the $2_1^+ \to 0_1^+$ decay in the same target. The line through the delayed data points is calculated as described in the text for a mean lifetime $\tau_m = 0.97$ nsec.

ing ratio limit,[1] the $K/(L+M+\cdots)$ ratio for the $E0$ decay,[3,5] and the $E2$ conversion coefficient[6] for the γ branch results in a monopole strength $\rho = \langle f|r^2|i\rangle/(1.2A^{1/3})^2 = (2.6\pm0.3)\times10^{-2}$ ($\Omega_K = 1.2\times10^{12}$ sec^{-1}, Ref. 5) and an $E2$ strength $|M|_{E2}^2 < 2.8 \times 10^{-2}$ Weisskopf units or $B(E2) < 2.0e^2$ F^4.

Evidently the $0_2^+ \to 2_1^+$ $E2$ transition is considerably hindered. Calculations of the $E2$ strength for the $2_1^+ \to 0_1^+$ and $0_2^+ \to 2_1^+$ transitions, using True's shell-model wave functions,[7] yield $B(E2;\, 2_1^+ \to 0_1^+) = 308.7e_n^2$ F^4 (in good agreement with experiment for an $E2$ effective charge $e_n \sim 0.9$) and $B(E2;\, 0_2^+ \to 2_1^+) = 24.89e_n^2$ F^4. The hindrance of the calculated $0_2^+ \to 2_1^+$ $E2$ strength is not as great as the experimental retardation; however, the calculation depends on the cancelation of terms, and a small change in the coefficients of the wave functions will have a large effect on the $B(E2)$ value.

The monopole strength is also weak, being large only with respect to the shell-model prediction of $\rho = 0$. Contributions to the monopole matrix element from the breakup of the ^{208}Pb proton core must arise from configurations in which the initial and final proton wave functions are different; otherwise the orthogonality of the neutron parts of the wave function will give zero. In addition the proton wave functions must involve configurations from different major shells. (For harmonic-oscillator wave functions, $\langle r^2\rangle$ is constant within a major shell, therefore, $\langle f|\sum r^2|i\rangle = \langle r_n^2\rangle\langle f|i\rangle = 0$ by orthogonality if $\langle f|$ and $|i\rangle$ are from the same major shell.) The most important admixture is probably the configuration in which a single proton has been excited from an orbit nlj to an orbit $(n+1)lj$; the particle-hole pair thus formed is coupled to $J=0$.

The shell-model description of ^{206}Pb as two neutron holes in ^{208}Pb has been reasonably successful in accounting for other properties of ^{206}Pb,[2] therefore, it is desirable to retain this simple picture if possible and account for the effects of the core polarization in some way which does not involve the closed proton shell directly. Similar situations involving $E2$ transitions have been handled by introducing an $E2$ effective charge[8] for the valence nucleons. Can a monopole effective charge account for the $E0$ strength in ^{206}Pb as well as changes in the mean square charge radius of nuclei near closed proton shells? It is known, for example, that the change in the charge radius between ^{208}Pb and ^{209}Bi cannot be described solely by the addition of an $h_{9/2}$ proton; the effect of core polarization must be included also.[9] Isotope shifts (the change in the mean square charge radius when neutrons are added) indicate that neutrons also affect the proton core and thus possess an effective charge. In particular, the isotope shift between ^{207}Pb and ^{208}Pb can be thought of as due to the contribution from the matrix element $z^{-1}\langle p_{1/2}|e_n r^2|p_{1/2}\rangle$ for the added neutron. (e_n is the neutron effective charge.)

In the simple shell model, the wave functions for the first two 0^+ states in ^{206}Pb can be written as follows:

$$0_1^+ = \sum_j X_j (j^{-2})^{J=0}, \quad 0_2^+ = \sum_j Y_j (j^{-2})^{J=0},$$

where j represents neutron single-particle states and $\sum X_j Y_j = 0$ by orthogonality. Then, if we utilize the effect-charge concept,

$$\langle 0_1^+|\sum e_n r^2|0_2^+\rangle = -2\sum_j X_j Y_j \langle j|e_n r^2|j\rangle.$$

However, if e_n is independent of j and all components are from the same major shell, $\langle r^2\rangle$ will be zero.[10]

Electron scattering data on the Ni and Sn isotopes (closed proton shell plus valence neutrons) indicate that the isotope shift (and hence the monopole effective charge) depends on the angular momentum of the added neutrons.[11] If e_n is state dependent, $\langle r^2\rangle$ will be nonzero in general. The matrix elements $\langle j|e_n r^2|j\rangle$ can be obtained from isotope-shift data between nuclei which have valence neutrons in the state j. If the ^{206}Pb wave functions are written as

$$0_1{}^+ = a[p_{1/2}{}^{-2}]^{J=0} + b[f_{5/2}{}^{-2}]^{J=0},$$

$$0_2{}^+ = -b[p_{1/2}{}^{-2}]^{J=0} + a[f_{5/2}{}^{-2}]^{J=0},$$

then

$$\langle 0_1{}^+|\sum e_n r^2|0_2{}^+\rangle = 2ab[\langle p_{1/2}|e_n r^2|p_{1/2}\rangle - \langle f_{5/2}|e_n r^2|f_{5/2}\rangle].$$

The matrix element for the $p_{1/2}$ neutrons can be obtained from the ^{207}Pb-^{208}Pb isotope shift while, in a simple model, $\frac{1}{2}$ of that for ^{204}Pb-^{206}Pb yields the value of $z^{-1}\langle f_{5/2}|e_n r^2|f_{5/2}\rangle$. Using values quoted by Krainov and Mikulinskii[12] for the isotope-shift data and $a = 0.87$, $b = 0.25$ (obtained by truncating the wave functions of Ref. 7), one finds $\rho = \langle f|\sum e_n r^2|i\rangle/(1.2A^{1/3})^2 = (1.64 \pm 1.01)\times 10^{-2}$. This result is consistent with the experimental value $\rho = (2.6 \pm 0.3)\times 10^{-2}$. It would be most interesting to reduce the large uncertainty in the isotope-shift data so as to test more crisply the ideas presented here. Hopefully, this can be done with the intense muon beams available at the new meson physics facilities.

*Work supported in part by the U. S. Atomic Energy Commission.

†Work supported in part by the National Science Foundation.

[1]H. C. Griffin and A. M. Donne, Phys. Rev. Lett. 38, 107 (1972).

[2]P. Richard, N. Stein, C. D. Kavaloski, and J. S. Lilley, Phys. Rev. 171, 1308 (1968).

[3]R. S. Hager and E. C. Seltzer, Nucl. Data, Sect. A 6, 1 (1969).

[4]J. L. Quebert, K. Nakai, R. M. Diamond, and F. S. Stephens, Nucl. Phys. A150, 68 (1970).

[5]E. L. Church and J. Weneser, Phys. Rev. 100, 943 (1955), and 103, 1035 (1956).

[6]M. E. Rose, *Internal Conversion Coefficients* (North-Holland, Amsterdam, 1958).

[7]W. W. True, Phys. Rev. 168, 1388 (1968).

[8]S. Siegal and L. Zamick, Nucl. Phys. A145, 89 (1970).

[9]I. Sick, H. Flocard, and M. Veneroni, Phys. Lett. 39B, 443 (1972).

[10]In the calculations of True, Ref. 7, components outside the f-p-h shell ($i_{13/2}$) are too small to account for the experimental strength.

[11]A. S. Litvinenko, N. G. Shevchenko, A. Yu. Buki, G. A. Savitskii, V. M. Khvastunov, A. A. Khomich, V. N. Polishcuk, and I. I. Chkalov, Yad. Fiz. 14, 479 (1971) [Sov. J. Nucl. Phys. 14, 269 (1972)]; V. M. Khvastunov, N. G. Afanasyev, V. D. Afanasyev, I. S. Gulkarov, A. S. Omelaenko, G. A. Savitsky, A. A. Khomich, N. G. Shevchenko, V. S. Romanov, and N. V. Rusanova, Nucl. Phys. A146, 15 (1970).

[12]V. P. Krainov and M. A. Mikulinskii, Yad. Fiz. 4, 928 (1966) [Sov. J. Nucl. Phys. 4, 665 (1967)].

New Method for Determining Polarization Standards in Nuclear Reactions

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(Received 7 July 1972)

We discuss and apply a general method for measuring the difference of polarization observables from their maximum allowed value. Relatively crude double-scattering experiments determine the proton polarization for 12-MeV p-^{4}He scattering with an absolute uncertainty of 1 part in 1000. It is anticipated that these concepts can be applied to higher-energy reactions where experiments do not lend themselves easily to precision measurements and where basic symmetries appear more likely to break down.

A null technique is suggested that may be used to determine spin-polarization values very precisely. The technique is applied to determine a proton polarization standard 4 times more accurately than previously obtained. The goal is to eventually establish standards precise enough to test fundamental symmetries.

Linear and quadratic relations that are model independent exist between the polarization observables of two interacting particles.[1] When one of the observables is found to approach very nearly its maximum allowable value, the others in a quadratic relation must be close to zero. For example, in the reaction ^{4}He$(p,p)^4$He the Wolfenstein polarization observables P, R, and A obey the well-known relation $P^2+R^2+A^2=1$. [As the relation $P^2+R^2+A^2=1$ actually holds for any combination of particles which have the spin configuration $0+\frac{1}{2}\to 0+\frac{1}{2}$, the concept also applies to ^{12}C$(t,p)^{14}$C, $\pi+p\to\pi+p$, etc.] At appropriate energies and angles where it is known that the proton polarization P approaches its maximum value