Shifts and Widths of $2p$ Levels in Pionic Atoms

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Strong-interaction shifts and widths for $2p$ levels in pionic atoms of Al, Si, S, Ca, Fe, Cu, and Zn have been measured with generally an order of magnitude better accuracy than before. Parameters of an effective pion-nucleus potential have been determined.

In the present Letter we report measurements of the shifts and widths of $2p$ pionic levels in natural targets of Al, Si, S, Ca, Fe, Cu, and Zn, where the experimental errors are typically an order of magnitude smaller than in previous measurements of the same quantities. We also report values of the parameters for the pion-nucleus effective potential which were adjusted to fit these results.

The experiments were performed using the stopped meson beam from the 7-GeV proton synchrotron NIMROD. An electrostatically separated beam of 200-MeV/c pions was used; stopping pions were detected with a counter telescope system as described earlier.[1] X rays were detected using a planar 5-cm^3 Ge(Li) detector and a coaxial 70-cm^3 Ge(Li) detector with 600-eV resolution at 122 keV and 1.68-keV resolution at 1.33 MeV, respectively. Data and calibration spectra were taken simultaneously and routed into different 8192-channel regions of an analog-to-digital-converter computer system.

The peaks in the calibration spectra were analyzed using a least-squares fitting procedure to obtain the energy calibration and detector response. This response function was then folded with a Lorentzian and fitted to the strong-interaction–broadened peaks to obtain the energies and natural widths of the relevant x-ray lines. The data on Al and Cu have been corrected for the quadrupole moment of the ground state of 0.15 and -0.21 b, respectively.

The calculated electromagnetic energies used 139.5688 MeV for the pion mass. The uncertainty due to the method of calculation is estimated to be less than 10 eV and has been included in the errors for the derived values for the shifts. There is an additional uncertainty arising from the values of the charge distribution parameters used to calculate the finite-size effect. This uncertainty is small except for Fe, Cu, and Zn where it is still less than the errors in the measured energies. Experimental results for the various transitions are summarized in Table I. Values of shifts and widths for the $2p$ level are compared with previous work in Table II. In obtaining the values in Table II a small correction has been made to the measured shift for the shift of the $3d$ level while the measured width has been corrected for the electromagnetic widths of the $3d$ and $2p$ levels.

The measured level shifts and widths have been compared with calculations using an effective nonlocal pion-nucleus potential which has previously[2] been shown to yield good average fits to experimental results. The effective potential V, to be inserted into the Klein-Gordon equation, is written as[2]

$$2\mu V(\vec{r}) = q(\vec{r}) - (\nabla \alpha(\vec{r}) \cdot \nabla), \tag{1}$$

where μ is the pion-nucleus reduced mass. The local part of the potential is given by

$$q(\vec{r}) = -4\pi(1+\mu/m)\{b_0[\rho_n(\vec{r})+\rho_p(\vec{r})]+b_1[\rho_n(\vec{r})-\rho_p(\vec{r})]\} - 4\pi(1+\mu/2m)[\mathrm{Re}B_0 + i\mathrm{Im}B_0]4\rho_p(\vec{r})\rho_n(\vec{r}), \tag{2}$$

where $\rho_p(\vec{r})$ and $\rho_n(\vec{r})$ are the density distributions of protons and neutrons, respectively, and m is the nucleon mass. b_0, b_1, and B_0 are parameters adjusted to fit experimental results. Note that we have written $4\rho_p\rho_n$ instead of the customary $(\rho_p+\rho_n)^2$ since the absorption of pions is known to occur preferentially on neutron-proton pairs[3] and the present form should be more suitable for nuclei with an ex-

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TABLE I. Experimental results for transitions to $2p$ levels.

Element	Transition	Measured energy (keV)	Electromagnetic energy (keV)	Shift (keV)	Measured Width (keV)
Aℓ	3 - 2	87.472 ± 0.007	87.273	0.199	0.124 ± 0.007
	4 - 2	117.912 ± 0.016	117.696	0.216	
	5 - 2	131.962 ± 0.024	131.768	0.194	
	6 - 2	139.634 ± 0.045	139.407	0.227	
Si	3 - 2	101.596 ± 0.007	101.288	0.308	0.198 ± 0.009
	4 - 2	136.895 ± 0.018	136.587	0.308	
	5 - 2	153.256 ± 0.033	152.914	0.342	
	6 - 2	162.040 ± 0.047	161.777	0.263	
S	3 - 2	133.154 ± 0.017	132.511	0.643	0.430 ± 0.021
	4 - 2	179.276 ± 0.032	178.668	0.608	0.438 ± 0.044
	5 - 2	200.655 ± 0.052	200.018	0.637	0.421 ± 0.072
Ca	3 - 2	209.608 ± 0.010	207.683	1.922	1.611 ± 0.023
	4 - 2	281.887 ± 0.052	279.933	1.954	1.681 ± 0.153
	5 - 2	315.269 ± 0.115	313.353	1.916	
Fe	3 - 2	356.758 ± 0.087	352.413	4.345	6.93 ± 0.21
Cu	3 - 2	445.63 ± 0.24	439.02	6.61	11.53 ± 0.82
Zn	3 - 2	476.37 ± 0.33	470.02	6.35	12.60 ± 1.40

TABLE II. Strong-interaction shifts and widths for $2p$ levels.

Element	present work shift (keV)	present work width (keV)	previous work shift (keV)	previous work width (keV)	reference
Aℓ	0.201 ± 0.009	0.120 ± 0.007	0.212 ± 0.023		7
			0.12 ± 0.10	0.36 ± 0.15	8
Si	0.308 ± 0.010	0.192 ± 0.009	0.29 ± 0.15		8
S	0.635 ± 0.016	0.422 ± 0.018	0.54 ± 0.10	0.79 ± 0.15	8
			0.7 ± 0.3	0.8 ± 0.4	9
Ca	1.929 ± 0.014	1.590 ± 0.023	1.97 ± 0.18	2.00 ± 0.25	8
			1.6 ± 0.3	2.1 ± 0.6	9
Fe	4.368 ± 0.088	6.87 ± 0.21	4.0 ± 0.3	8.7 ± 0.6	8
			4.4 ± 1.0	6.0 ± 2.5	9
Cu	6.67 ± 0.24	11.4 ± 0.8	7.0 ± 2	15.9 ± 4	8
Zn	6.44 ± 0.33	12.4 ± 1.4	8 ± 3	16.8 ± 6	8
			7.0 ± 1.4	15.6 ± 4	10

cess of neutrons. The nonlocal part is written as

$$\alpha(\vec{r}) = \alpha_0(\vec{r})/[1 - \tfrac{1}{3}\alpha_0(\vec{r})], \tag{3}$$

where the denominator results from the Lorentz-Lorenz effect with short-range anticorrelations. Spherical symmetry is assumed and then

$$\alpha_0(r) = -4\pi(1+\mu/m)^{-1}\{c_0[\rho_n(r)+\rho_p(r)]+c_1[\rho_n(r)-\rho_p(r)]\} - 4\pi(1+\mu/2m)^{-1}(\mathrm{Re}C_0 + i\,\mathrm{Im}C_0)4\rho_p(r)\rho_n(r). \tag{4}$$

The parameters of the nonlocal part (c_0, c_1, and C_0) may also be obtained from fits to experimental results.

Rather than carrying out a global χ^2 fit to all available data it was felt that at this stage a better feeling as to the physical aspects of the problem would be obtained by making detailed fits to a small number of precisely measured level shifts and widths, as measured in the present work, and then to compare the predictions with the full range of experimental data available. It was soon established that

whenever the Ca results were reproduced by a set of parameters, the results for the lighter nuclei Al, Si, and S were also very well reproduced. Therefore, the analysis was carried out in two stages. First a fit was made to the level shift and width for Ca and then a fit to data for Fe, Cu, and Zn (which have $N>Z$) was made by adjusting only the coefficients of $\rho_n-\rho_p$.

The nucleon density distributions form an essential ingredient of the effective potential (1). For most calculations we have used the geometrical parameters of the charge distribution,[4] where the inclusion of the finite size of the proton takes into account, in a simple and convenient way, possible effects due to a "finite range" of the pion-nucleon interaction. However, repeating the calculations with density distributions obtained by unfolding the finite size of the proton made no difference to the conclusions of the present work and only slightly affected the values of the potential parameters. For Fe, Cu, and Zn we used a range of neutron distributions which had rms radii larger by 0.05 to 0.15 fm than those for the protons.

As Ca consists mainly of ^{40}Ca, only the parameters b_0, B_0, c_0, C_0 are relevant. The parameters of the local part of the potential (b_0 and B_0) were kept fixed at the values obtained[5] from analyses of 1s states and the Ca results were then used to determined the values of c_0 and C_0, since the 2p states are more sensitive than the 1s states to the parameters of the nonlocal part of the potential. Two procedures were used: (a) assuming $\mathrm{Re}C_0=0$ and then adjusting c_0 and $\mathrm{Im}C_0$ to fit the data; and (b) keeping c_0 fixed at its "theoretical" value[3] of $c_0=0.21m_\pi^{-3}$ (for free nucleons) and adjusting both $\mathrm{Re}C_0$ and $\mathrm{Im}C_0$. The second procedure is, perhaps, to be preferred because in previous work[2] and also in the first procedure used here the values of c_0 obtained were found to be close to this theoretical value. Also the nonlocal interaction is confined to the surface region of the nucleus where the free-pion–nucleon interaction could be appropriate. $\mathrm{Im}C_0$ is, in any case, an empirical parameter and it has been suggested[3] that dispersive effects will lead to a real part in the π-NN term thus making the introduction of a $\mathrm{Re}C_0$ term quite natural.

In Table III results for both procedures are given, where the parameters of the local potential (except b_1) are taken from Ref. 5. Figure 1 shows comparisons between calculation and experiment where the dashed curve was obtained with the value of $b_1=-0.087m_\pi^{-1}$ taken from Ref. 5 (before attempting to fit to the Fe, Cu, and Zn data). Both procedures (a) and (b) lead to almost identical curves. As can be seen from Fig. 1, the calculated values of the level shifts do not agree with experiment for nuclei with an excess of neutrons.

TABLE III. Parameters for effective pion-nucleus potential. The conventional units of $m_\pi^{-1}=1.4138$ fm are used.

	Procedure (a)	Procedure (b)
b_0 (m_π^{-1})	-0.017 [a]	-0.017 [a]
b_1 (m_π^{-1})	-0.13 ± 0.02	-0.13 ± 0.02
$\mathrm{Im}B_0$ (m_π^{-4})	0.0475 [a]	0.0475 [a]
$\mathrm{Re}B_0/\mathrm{Im}B_0$	-1 [a]	-1 [a]
c_0 (m_π^{-3})	0.255 ± 0.003	0.21
c_1 (m_π^{-3})	0.17 [a]	0.17 [a]
$\mathrm{Im}C_0$ (m_π^{-6})	0.090 ± 0.005	0.080 ± 0.005
$\mathrm{Re}C_0/\mathrm{Im}C_0$	0 [a]	1.9 ± 0.1

[a] Quantities kept fixed.

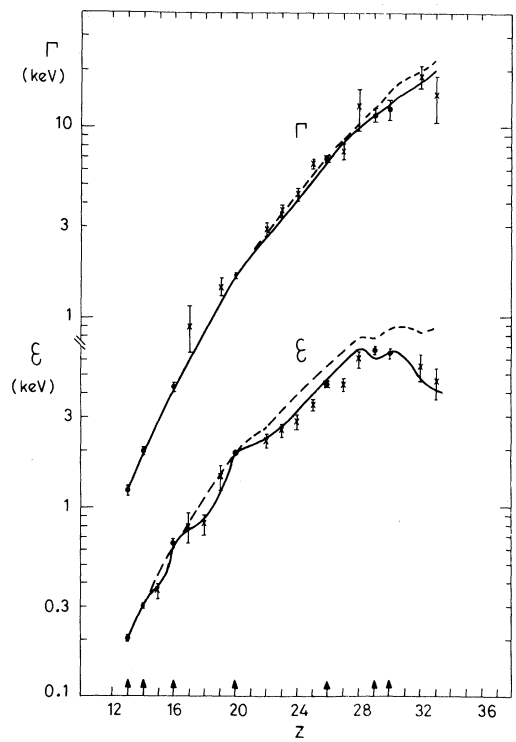

FIG. 1. Experimental and calculated strong-interaction level shifts (ϵ) and widths (Γ) for 2p states. Present experimental results are indicated by arrows. Previous results are from Refs. 6–9. Continuous curves are for $b_1=-0.13m_\pi^{-1}$; dashed curves are for $b_1=-0.087m_\pi^{-1}$.

In order to fit the shifts for $N>Z$ nuclei without adjusting the parameters of the potential it was necessary to increase the rms radii of the neutron distributions beyond those for the protons by unreasonably large amounts, e.g., 0.3 fm for P and Ar. It was therefore decided to adjust the coefficients of $\rho_n-\rho_p$ in the potential, and this was done in the second stage of the fit. The parameter c_1 was kept at its theoretical value and only b_1 was adjusted, since c_0 and c_1 represent interactions near the nuclear surface and since $c_1\approx c_0$ because the π^--N interaction is predominantly with neutrons. On the other hand, the local part of the potential represents interactions which take place throughout the nuclear volume and the parameter b_0 has already been adjusted[2] to include effects due to the Fermi motion. Analysis of the data for Fe, Cu, and Zn showed that the value obtained for b_1 is strongly dependent on the value chosen for r_n-r_p. However, if the values for r_n-r_p are constrained to be in the range 0.05 to 0.15 fm, a value of $(-0.13\pm0.02)m_\pi^{-1}$ is obtained for b_1. If the parameter c_1 is adjusted to fit the data then it differs by -200% from the theoretical value. The continuous curve in Fig. 1 shows the calculated values obtained for procedure (b) with $b_1=-0.13m_\pi^{-1}$ and $r_n-r_p=0.1$ fm where the fit to the data for $N>Z$ nuclei is greatly improved. The structure displayed by this curve results from the variations of $(N-Z)/A$. The value of $b_1=(0.13\pm0.02)m_\pi^{-1}$ is in good agreement with that obtained previously[10] from fits over the whole of the periodic table. The sign of $\mathrm{Re}C_0$ appears to disagree with theoretical predictions[3] but we emphasize that there is no significant difference between the fits with $\mathrm{Re}C_0=0$ and $\mathrm{Re}C_0>0$. However, $\mathrm{Re}C_0<0$ will require larger adjustments in the value of c_0.

In conclusion, we have made precision measurements of shifts and widths of $2p$ levels in pionic atoms of Al, Si, S, Ca, Fe, Cu, and Zn. Parameters have been determined for an effective pion-nucleus potential which lead to good agreement with all available experimental results.

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Enhanced Stimulated Raman Scattering Does Not Exist

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A recent Letter by Sparks and Sen challenges the viability of a recently proposed design for a commercial laser-fusion power plant. The basis for this challenge is the controversial theory of enhanced stimulated Raman scattering put forward by Sparks. This theory has been examined carefully. It is found to be in direct contradiction to both the classical and quantum theories of stimulated Raman scattering, and it is also in serious conflict with many experimental results.

The recent Letter by Sparks and Sen[1] is the latest in a series of papers[2] dealing with a highly controversial proposal. The essential feature of this proposal is that the gain experienced by the Stokes wave in stimulated Raman scattering (SRS) is larger than the steady-state gain and that the gain exponent in the steady state depends nonlinearly on the pump intensity. Although the proposal was made originally for SRS in gases it is apparently intended to apply to any process

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