Title
PI-MESIC ATOMS

Authors
Jenkins, David A.
Crowe, Kenneth M.

Publication Date
1966-02-23

UCRL-16725

University of California

Ernest O. Lawrence Radiation Laboratory

PI-MESIC ATOMS

Berkeley, California

Submitted to Physical Review Letters

UCRL-16725

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

PI-MESIC ATOMS

David A. Jenkins and Kenneth M. Crowe

February 23, 1966

Pi-Mesic Atoms*

David A. Jenkins and Kenneth M. Crowe

Lawrence Radiation Laboratory
University of California
Berkeley, California

February 23, 1966

We have measured pi-mesic x-ray energies for 70 elements, by using a lithium-drifted germanium detector, and for aluminum by using a bent-crystal spectrometer. We observe differences between some x-ray energies and the energies predicted by the Klein-Gordon equation, and we interpret these differences as being due to vacuum polarization and the presence of the nucleus. The vacuum-polarization correction to the x-ray energies is well known, and we have used the work of Mickelwait and Corben to calculate this effect.[1] The presence of the nucleus induces both an energy shift and a broadening of the x-ray line because the pion interacts strongly with the nucleons in the nucleus. Furthermore, the nucleus has a finite size which produces a departure from the point approximation of the Coulomb interaction. These effects have not been precisely calculated, and in this paper we present our results for the nuclear energy-level shift.

The nuclear effect in pi-mesic x-ray energies has been discussed by Ericson,[2] who suggests that the level shift can be understood in terms of a Kisslinger potential[3] that contains a gradient operator. The gradient operator is introduced because of the strong p-wave force in the pion-nucleon interaction. Therefore, we have calculated the potential shift using perturbation theory and an optical-model potential of the form

$$V(r) = V_0\,\rho(r) + V_1\,\nabla \cdot \rho(r)\,\nabla, \tag{1}$$

where V_0 and V_1 are constants to be determined from experiment, ∇ is the gradient operator, and

$$\rho(r) = \{1 + \exp\,[(r - c)/z_1]\}^{-1} \tag{2}$$

is the Saxon-Woods potential function for the nucleus. We use $c = 1.08\,A^{1/3}$ Fermis and $z_1 = 0.545$ Fermi, as found by Anderson et al. from the mu-mesic x-ray data.[4] The mu-mesic x-ray parameters describe the Coulomb distribution of the nucleus, and this distribution is not expected to be the same as that seen by the pion because the pion interacts strongly with the nucleus. Lacking better information, we have used the mu-mesic x-ray parameters as a first approximation. Then the energy level shift for a level with principal quantum number n and orbital angular momentum ℓ is

$$\Delta E_{n\ell} = V_0 \int_0^\infty \rho(r)\,|\psi_{n\ell}|^2\,d\tau + V_1 \int_0^\infty \rho(r)\,|\nabla\psi_{n\ell}|^2\,d\tau, \tag{3}$$

where we have used nonrelativistic wave functions for $\psi_{n\ell}$.

Mesic x-ray energies for a series of elements were measured with a germanium detector. The accuracy of these measurements is limited by the electronics of the system used to measure pulse heights from the germanium. Gain shifts were minimized by using a digital gain stabilizer,[5] and the energy response was calibrated with radioactive sources at intervals of about 100 keV. The energy measurements were taken for periods of about 15 min, and the system's energy response was calibrated before and after each run. We therefore have confidence in our measurements to an accuracy of ± 1.0 keV. We are now making more measurements of these energies, after which a detailed description of the experiment will be presented. The aluminum measurement with a bent-crystal spectrometer has been reported earlier.[6]

The data are presented in Fig. 1, which shows the difference in energy between the measured x-ray energies and the value predicted by the Klein-Gordon equation, including reduced-mass and vacuum-polarization corrections. The data for the $2p \rightarrow 1s$ transition were taken from the work of West,[7] and the energies for this transition have been corrected for the Coulomb shift due to the finite size of the nucleus; this correction is negligible for the other transitions. A negative energy in Fig. 1 indicates that the measured energy level is higher than the calculated value, and therefore the x-ray energy is lower than predicted. The curves in Fig. 1 are computed from Eq. (3) after V_0 and V_1 have been varied to obtain a good fit to the data. Practically all of the shift in the x-ray energy is due to the 1s level for the $2p \rightarrow 1s$ lines, and similarly for higher transitions it is due to the level with smaller ℓ. This is theoretically very plausible and confirmed experimentally by the fact that the difference between the observed energy of the $3p \rightarrow 1s$ line and that predicted according to the Klein-Gordon equation is the same as for the $2p \rightarrow 1s$ line.

We assume that the energy difference plotted in the figure is due to the nuclear shift, and we observe that the sign of the 2p → 1s x-ray shift is different from that of other x-ray transitions. The gradient of the 1s wave function near the origin is small, therefore the 1s energy shift is dominated by the first term in Eq. (3) (the local potential). However, the gradients of the 2p, 3d, and 4f wave functions are large, and the energy shifts for these levels are dominated by the second term in Eq. (3) (the nonlocal potential). The negative shift for the 2p → 1s energy implies that the local potential is repulsive, while the positive shift for the 3d → 2p, 4f → 3d, and 5g → 4f energies implies that the nonlocal potential is attractive. Our best values for these potentials are $V_0 = -8.1$ MeV and $V_1 = 120$ MeV-fermi^2. The potentials do not give good agreement with the 5g → 4f uranium x-ray, but this could be a result of our using the wrong value for the nuclear radius.

The authors wish to thank Mr. F. Cooley, Mr. D. Girvin, Mr. P. Lindstrom, and Dr. R. Shafer for calculations and assistance in the measurements, Prof. H. Anderson for the loan of target materials, Prof. E. Segrè for helpful discussions, and Mr. J. T. Vale and the 184-In. -Cyclotron staff for their help. We also thank Mr. Guy Armentraut for furnishing the Ge detector.

FOOTNOTES AND REFERENCES

[*] Work sponsored by the U. S. Atomic Energy Commission.

1. A. B. Mickelwait, Ph. D. thesis, Carnegie Institute of Technology, 1954 (unpublished); A. B. Mickelwait and H. C. Corben, Phys. Rev. 96, 1145 (1954).
2. M. Ericson, Compt. Rend. 257, 3831 (1963).
3. L. S. Kisslinger, Phys. Rev. 98, 761 (1955).
4. H. L. Anderson, C. S. Johnson, and E. P. Hincks, Phys. Rev. 130, 2468 (1963).
5. M. Nakamura and R. L. LaPierre, Nucl. Instr. Methods 32, 277 (1965).
6. A. Astbury, J. P. Deutsch, K. M. Crowe, R. E. Shafer, and R. E. Taylor, Compt. Rend. Congr. Intern. Phys. Nucl. Paris 2, 225 (1964).
7. D. West, Rept. Progr. Phys. 21, 271 (1958).

FIGURE LEGENDS

Fig. 1. Mesic x-ray level shifts as a function of Z_1 (atomic number) for the (a) 2p → 1s, (b) 3d → 2p, (c) 4f → 3d, and (d) 5g → 4f x-rays.

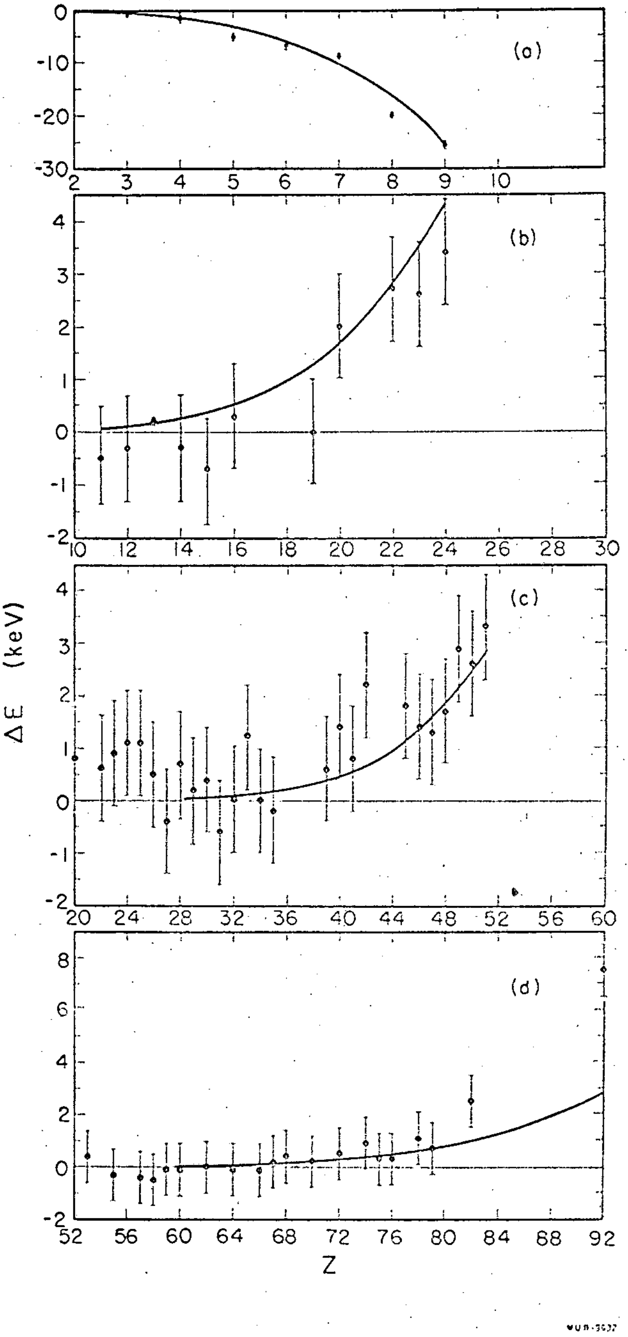
(a)
0
-10
-20
-30
2
3
4
5
6
7
8
9
10
(b)
4
3
2
1
0
-1
-2
10
12
14
16
18
20
22
24
26
28
30
(c)
ΔE (keV)
4
3
2
1
0
-1
-2
20
24
28
32
36
40
44
48
52
56
60
(d)
8
6
4
2
0
-2
52
56
60
64
68
72
76
80
84
88
92
Z
MUB-9637

Fig. 1