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PION-MASS MEASUREMENT BY CRYSTAL DIFFRACTION
OF MESIC X RAYS

Robert E. Shafer, Kenneth M. Crowe, and David A. Jenkins

April 26, 1965
We report here the recent measurement at the 184-inch cyclotron of the 4F-3D transitions in π-mesic calcium and titanium, using a 7.7-m bent-crystal spectrometer, and present the preliminary results of a new determination of the charged pion mass.

The experimental arrangement is shown in Figs. 1 and 2. The π- beam, produced on an internal target, was extracted at 185 MeV/c with a 60% macroscopic duty cycle, and transported to the bent-crystal target. Pions stopping in the target were identified by a six-counter telescope. Typical stopping rates were 800 pions/g/sec for the 4-g calcium and 6-g titanium targets. The bent-crystal spectrometer, built on the DuMond geometry (focus at a stationary target), has about a 1×10^-6 effective fractional solid angle for the mesic x rays emanating from the target. A fast coincidence between the pion telescope and a 7- by 7- by 1/4-in. NaI(Tl) crystal behind the spectrometer identified a "real" event, which gated a pulse-height analyzer storing the integrated NaI pulses. The spectrometer was rotated to scan alternately the right and left first-order diffraction peaks.

The data (Fig. 3) were analyzed by a least-squares minimization method, using a known calculated line shape of arbitrary height above an arbitrary flat background. Analysis indicated a counting rate of about two events per hour above a three-per-hour random background.
The spectrometer was calibrated by using the K_{a1} x-ray (52.389 ± 0.001 keV)\(^4\) and the nuclear γ ray (84.261 ± 0.003 keV)\(^5\) of Yb\(^{170}\), yielding a quartz (310) \(d_{18}\) spacing of 1177.54 ± 0.05 xu.

The measured transition energies and the results of calculations of these transitions are shown in Table I. As pions have no spin, the Klein-Gordon equation is used. The vacuum polarization\(^6,7\) has been checked to 1% in the hydrogen atom\(^8\) and 3% in μ-mesic phosphorus.\(^9\) The strong-interaction shift is calculated by scaling the measured shift in the 3D-2P μ-mesic aluminum transition\(^2\) to the present cases by first-order perturbation theory using an optical model to represent the interaction. Some studies have been made on the Z, \(T\), and effective-mass dependence in the nuclear interaction in \(\pi\)-mesic atoms,\(^10\) but as the interaction is not well understood and the experimental data is scarce, an error of ±100% is being assigned.

The quantum-electrodynamic corrections not included here can be estimated from the energy-level calculation for the 3D-2P μ-mesic phosphorus transition.\(^11\) The largest remaining correction is expected to be the fourth-order vacuum polarization (\(~+2\) eV). Wave-function corrections to the second order are about +1 eV.\(^12\) The finite-nuclear-size effect on the Coulomb potential is less than 0.1 eV. We use here an all-inclusive 3±3-eV correction to include these effects.

The weighted average of the two measurements in Table I is 139.580 ± 0.015 MeV,\(^13\) in agreement with the presently accepted value of 139.60 ± 0.05 MeV. The latter value was derived by combining the muon mass\(^9\) with the measured muon momentum from pion decay at rest,\(^14\) assuming that the muon neutrino has zero mass. By comparing these measurements, we find the most probable (real) value of the muon neutrino mass to be zero, with upper limits of 2.1 MeV (68% confidence level) and 2.8 MeV (90% confidence level).
The authors are indebted to Professors Robert Karplus and Emilio Segrè for their helpful discussions on the energy-level calculations, and to Professor Felix Boehm for his suggestions on the calibration of the spectrometer. The authors are also grateful to Drs. A. Astbury, J. P. Deutsch, and R. E. Taylor for their contributions to earlier phases of the mesic x-ray program.
FOOTNOTES AND REFERENCES

* Work performed under the auspices of the U. S. Atomic Energy Commission.

1. The spectrometer and experiment will be described in detail by R. E. Shafer (Thesis) (to be published).


5. E. N. Hatch and F. Boehm, Zeit. Physik 155, 609 (1959) quote 84.26 ± 0.01 keV; I. Marklund and B. Lindstrom, Nucl. Phys. 40, 329 (1963) quote 84.260 ± 0.004 keV. The calibration line of the latter has been adjusted to Bearden's value (Ref. 4). F. Boehm, California Institute of Technology, Pasadena, private communication (1965) has obtained 84.261 ± 0.003 keV.


13. All errors are quoted here in standard deviations. When a reference has used another deviation, it has been changed assuming a normal error curve.

Table I: Calculations of the 4F-3D transition energies using $M_\pi c^2 = 139.580$ MeV.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Calcium</th>
<th>Titanium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klein-Gordon equation(^a)</td>
<td>$72.388 \pm 0.001$ (\text{keV})</td>
<td>$87.622 \pm 0.001$ (\text{keV})</td>
</tr>
<tr>
<td>Reduced mass</td>
<td>$-0.270$ (\text{keV})</td>
<td>$-0.273$ (\text{keV})</td>
</tr>
<tr>
<td>Vacuum polarization (second order)</td>
<td>$+0.228$ (\text{keV})</td>
<td>$+0.298$ (\text{keV})</td>
</tr>
<tr>
<td>Orbital-electron screening</td>
<td>$-0.001 \pm 0.001$ (\text{keV})</td>
<td>$-0.001 \pm 0.001$ (\text{keV})</td>
</tr>
<tr>
<td>Strong-interaction shift</td>
<td>$+0.002 \pm 0.002$ (\text{keV})</td>
<td>$+0.004 \pm 0.004$ (\text{keV})</td>
</tr>
<tr>
<td>Other quantum electrodynamics</td>
<td>$+0.003 \pm 0.003$ (\text{keV})</td>
<td>$+0.003 \pm 0.003$ (\text{keV})</td>
</tr>
<tr>
<td>Transition energy (calc.)</td>
<td>$72.350 \pm 0.004$ (\text{keV})</td>
<td>$87.653 \pm 0.005$ (\text{keV})</td>
</tr>
<tr>
<td>Transition energy (meas.)</td>
<td>$72.352 \pm 0.009$ (\text{keV})</td>
<td>$87.652 \pm 0.009$ (\text{keV})</td>
</tr>
<tr>
<td>Natural line width</td>
<td>($\sim 6$ (\text{eV}))</td>
<td>($\sim 10$ (\text{eV}))</td>
</tr>
<tr>
<td>Calculated $\pi^-$ mass</td>
<td>$139.584 \pm 0.020$ (\text{MeV})</td>
<td>$139.578 \pm 0.017$ (\text{MeV})</td>
</tr>
</tbody>
</table>

\(^a\) $\alpha^2 = 5.32492 \times 10^{-5} \pm 9$ \(\text{ppm}\) [Phys. Today 17, No. 2, 49 (1964)].
FIGURE LEGENDS

Fig. 1. Experimental arrangement. The autocollimator line of sight was held to ±0.002 in. throughout the experiment. Considerable shielding was required around the NaI detector because of cyclotron-generated neutrons.

Fig. 2. Counter telescope. Logic 1 2 3 4 5 identified a stopping pion.

Fig. 3. The right and left first-order diffraction peaks for Ca and Ti, plotted as events per $10^7$ stopped pions vs sine-screw turns. The smooth curve represents the best fit as described in the text, yielding (for all curves combined) $\chi^2/N - 1 = 31/41$. Horizontal flags represent the calculated means and their standard deviations. The two midpoints differ by 0.009 ± 0.007 turns (20% probability). The standard deviation of the spectrometer resolution is 60 eV for Ca and 90 eV for Ti.
Fig. 2.
Fig. 3.
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