New measurements of the mass of the K^- meson

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The energy of the $4f$-$3d$ transition in the K^-–^{12}C atom has been measured with the help of a Cauchois crystal diffraction spectrometer at the proton synchrotron of the Institute of High-Energy Physics. A new value has been found for the mass of K^- meson: 493.6960 ± 0.0059 MeV. This figure is significantly different from the previously accepted value.

An accurate value of the mass of the K^- meson is important for correctly determining the level shifts caused by the strong interaction in K^- atoms. The accepted value $M_{K^-} = 493.646 \pm 0.009$ MeV, given in the review in Ref. 1, is based on essentially a single experiment, which was a study of the x-ray emission from K^-–Pb and K^-–W atoms by means of a semiconductor spectrometer.[2] In the absence of independent experiments of comparable accuracy, it is difficult to check for systematic errors.

Such a check is important for the following reasons: First, calculating transition energies in heavy atoms is an extremely complicated task, since the higher-order quantum-electrodynamic corrections must be taken into account, and the relatively large correction for electron screening must be calculated correctly. Second, when a K^- meson is absorbed by a heavy nucleus, a rich spectrum of γ-ray lines is emitted. When a semiconductor spectrometer with a resolution of about 1 keV is used, there is accordingly a significant probability for a superposition of a γ-ray line on the mesic x-ray line under study. The latter circumstance is particularly important for the experiment mentioned above, since most of the statistical base came from essentially one mesic x-ray transition.

We have now carried out an experiment in which a crystal diffraction method has been used for the first time to study the x-ray emission of K^- atoms. This diffraction method substantially improves the metrological quality of the measurements. Because of the high resolution and the selection of a light nucleus for the measurements, the probability for a superposition of γ-ray lines is substantially reduced.

The study was carried out at the proton synchrotron of the Institute of High-Energy Physics, by the method proposed in Ref. 3. The key part of the apparatus is a Cauchois crystal diffraction spectrometer, similar to that described in Ref. 4. The source of the mesic x radiation is a target bombarded by the dumped proton beam (the proton energy was 70 GeV, the acceleration cycle was 9 s long, the beam intensity was 4×10^{12} protons/cycle; the lengthening was 0.8 s, and the transverse dimension was 3 mm).

For the measurements we selected the $4f$–$3d$ transition of the K^-–^{12}C atom, because of several advantages: The electron screening is negligible; the transition is perturbed only slightly by the strong interaction; and the transition energy (≈ 22.1 keV) lies in the part of the working range of the spectrometer which is the best part from the standpoint of the signal-to-background ratio.

A layered target of graphite, copper, and molybdenum was used in order to raise the intensity of the mesic x radiation and to weaken the electron bremsstrahlung (graphite with a density of 2.1 g/cm^3 is the basic material; copper and molybdenum are added to intensify the mesic x radiation and to weaken the bremsstrahlung, respectively). To verify that there was no superposition of a K^--atom line and prompt γ lines from radionuclides produced in the molybdenum, we used a control target of carbon. We verified that there was no superposition of γ-ray lines from long-lived radionuclides produced in the target by recording two spectra in each angular position: one during a beam dump and one between dumps. A piece of silver foil was attached to an auxiliary target. The characteristic radiation from silver was used in calibration measurements. For this purpose we used a ^{182}Ta γ source. The energies of the Kα_1 and Kα_2 lines of silver were recalculated, by the procedure described in Ref. 5, from earlier measurements[6,7] of the ratios $\lambda(\text{CuK}\alpha_1)/\lambda(\text{AgK}\alpha_1)$ and $\lambda(\text{AgK}\alpha_1)/\lambda(\text{AGK}\alpha_2)$ ratios, with the new physical constants from Ref. 8: $hc = 12.398\,424(4)\times 10^{-10}$ keV·m and $xu(\text{CuK}\alpha_1) = 1.002\,077\,89(70)\times 10^{-13}$ m. As a result, we found $E(\text{AgK}\alpha_1) = 22.163\,022(30)$ and $E(\text{AgK}\alpha_2) = 21.990\,43(16)$ keV.

The radiation to be measured passed through a converging multislit collimator, was diffracted by a curved quartz plate, was focused on a line slit, and was detected by

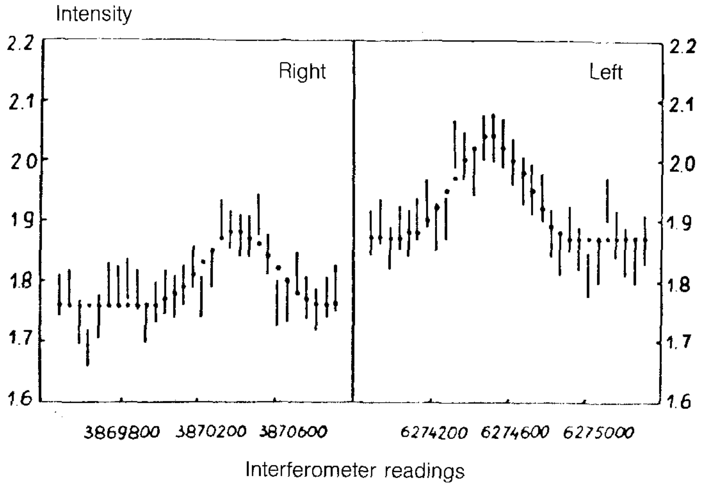

FIG. 1. Right and left reflections of the 4*f*–3*d* transition of the K^-–^{12}C atom. The interferometer readings are plotted along the abscissa; the detector count rate per 10^{12} protons is plotted along the ordinate. The vertical lines are the experimental values with the corresponding error; the heavy points are the results of a fit.

a detector behind this slit. This detector was a Ge(Li) spectrometer with a working volume of $4\times5\times160$ mm and a resolution of 1.8 keV. The collimator slits and the gap between the crystal and the detector were filled with helium. The quartz plate was cut in such a way that the (130) reflecting planes and the optical axis were perpendicular to the lateral faces. At a plate thickness of 1.1 mm and a radius of curvature of 5 m, this cut corresponds to an elastic quasimosaic of 12″. The working surface of the curved crystal had a area of 80×80 mm. The crystal was curved by squeezing the plate between two cylindrical steel mirrors. At a detection-slit width of 0.35 mm and a height of 160 mm, the angular resolution of the spectrometer was 14″. This figure corresponds to an energy resolution of 6.3 eV for radiation with an energy of 22.1 keV. The luminosity of the apparatus at this energy was about 2×10^{-9}. The angular position of the crystal was determined with the help of an optical interferometer with scale divisions of about 0.04″.

For each line, we measured two reflections (right and left), corresponding to symmetry with respect to the quartz planes. The instrumental lineshape was determined by measuring the shape of the reflection of the 67.75-keV line from ^{182}Ta. As a reference for the fit, we convolved the instrumental line with a Lorentzian distribution, with the tabulated width in the case of the x-ray lines, and with a calculated width in the case of the mesic x-ray line. The constant of the instrument, which is the product of the energy of the line and the distance between the right and left reflections, expressed in scale divisions of the interferometer ["optical units" (OU)], was determined by weighing the values found for the $K\alpha_1$ and $K\alpha_2$ lines of silver. It turned out to be 53 143 857 ± 133 keV·OU. Control measurements of silver lines excited by the ^{182}Ta γ source yielded a value for the constant of the instrument which agreed with the

TABLE I. Calculated energies of the transitions with $M_K = 493.6960$ and $M_\pi = 139.5688$ MeV.

Component of transition energy	Value of component, Ev $4f$–$3d$ K^-–^{12}C	 $4d$–$2p$ π^-–^{12}C
Coulomb interaction	22033.941	24782.721
Vacuum polarization, $\alpha(Z\alpha)$	71.110	42.790
$\alpha^2(Z\alpha)$	0.496	0.314
$\alpha(Z\alpha)^3$	− 0.012	− 0.009
Strong interaction	0.009	2.850
Relativistic correction	0.085	0.047
Electron screening*	− 0.016	− 0.373
Polarization of nucleus	0.018	0.009
Finite dimensions of meson	− 0.004	− 0.002
Lamb shift	0.000	− 0.001
Nuclear recoil	− 0.022	− 0.028
Sum	22105.605	24828.318

*The correction was calculated for one 1*s* electron.

value found during excitation by the proton beam. The distance between the right and left reflections of the K^--atom line (Fig. 1) is 2 404 089 ± 27 OU. The corresponding energy is 22 105.61 ± 0.26 eV. The fit of the line was carried out on the basis of an isolated peak, since the instrumental resolution was lower by at least an order of magnitude than the fine splitting and isotopic splitting, and no superposition of γ-ray lines was observed.

The mass of the K^- meson was determined by fitting the calculated transition energy to the experimental value. The calculated energy was found through a numerical integration of the Klein-Gordon equation, with the potential for a nucleus of finite dimensions. The potential included the Coulomb interaction, the vacuum polarization potential of up to third order, and the optical potential for the strong meson-nucleus interaction, with the parameter values from Ref. 9. A two-parameter Fermi distribution was used to describe the nuclear density. We also incorporated a relativistic correction for the reduced mass and corrections for the nuclear polarization, the electron screening, the nuclear recoil, and the Lamb shift. The results of these calculations are shown in Table I. The error of these calculations is about 0.02 eV, or well below the experimental error. The calculation error is determined primarily by the uncertainty in the number of 1*s* electrons (± 1 electron) and the errors in the parameters of the nuclear charge distribution and the strong-interaction potential. As a result, we found the mass of the K^- meson to be $m_{K^-} = 493.6960 \pm 0.0059$ MeV. This result is quite different from the worldwide average value in Ref. 1.

As a control, we carried out measurements on the $4d$–$2p$ transition of a π^-–^{12}C atom in parallel with the K^--atom measurements (Fig. 2.). The measured energy turned out to be 24 828.36 ± 0.15 eV. The calculation was carried out for the mass of the π^- meson from Ref. 10; the result is shown in Table I. The error of the calculated value is no greater than 0.4 eV and is due primarily to the uncertainty in the number of 1*s* electrons. The good agreement between the measured and calculated values confirms the validity of this procedure.

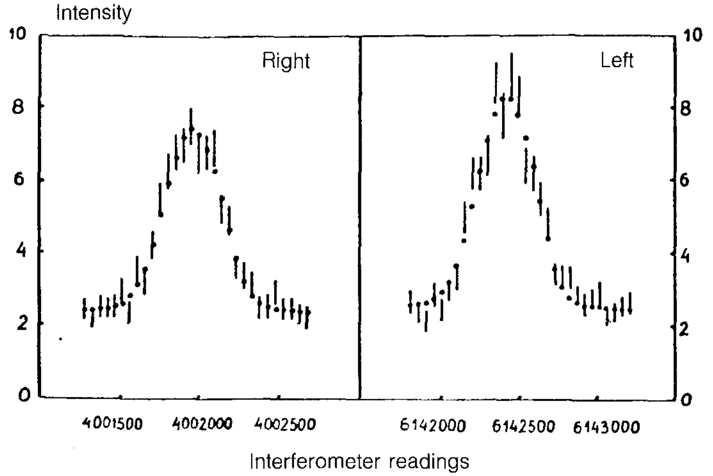

FIG. 2. Right and left reflections of the $4d$–$2p$ transition of the π^-–^{12}C atom. The notation is the same as in Fig. 1.

When we use the value which we found for the mass of the K^- meson to analyze the K^--atom data, we find an increase in the calculated electromagnetic energy of the transitions and a decrease in the magnitude of the shifts, found as the differences between the measured and electromagnetic energies. Since for most of the shifts, the effect due to the change in mass is small in comparison with the corresponding experimenal errors, there are no substantial changes from the parameters of the optical potential found in Ref. 9. In the case of heavy K^- atoms, however, this new determination of the mass makes it possible to resolve the problem which arose in Ref. 11, where positive shifts were found for 8–7 transitions in K^-–W and K^-–Ob atoms. Batty *et al.*[11] stated that these shifts were in contradiction of the results calculated from the optical model with the standard parameters. As a result of this new determination of the mass, the positive shifts for these transitions are reduced to the level of the error in the experimental energies.

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