First measurement of the x-ray emission of Σ^- atoms by means of a crystal-diffraction spectrometer

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The intensity and energy of the $5g$–$4f$ transition of the Σ^-–^{12}C atom have been measured by a crystal-diffraction spectrometer with a Cauchois layout at the proton synchrotron of the Institute of High-Energy Physics. The mass of the Σ^- hyperon was found to be 1197.417 ± 0.040 MeV/c^2. This figure is in excellent agreement with the value found from studies of hyperon decays, while it is slightly at odds with a BNL experiment on heavy Σ^- atoms. There is a promising outlook for studying Σ^- atoms by the crystal-diffraction method, in which a target is bombarded by a beam of high-energy protons.

All known experiments on Σ^- atoms have been carried out in secondary K^--meson beams with semiconductor spectrometers. The experimental method is based on the fact that in the course of nuclear absorption of a K^- meson stopped in matter there is a significant probability (≈ 0.08) for the formation of a Σ^- hyperon. After the latter is slowed, it is captured in an atomic orbital.[1] Although extremely crude, this method has been used to determine the shifts and widths of several transitions for several nuclei.[2] There has been no further research on the strong hyperon–nucleus interaction in Σ^- atoms because of the low radiation intensity and the complex background conditions.

One possibility for avoiding this difficulty is to use the crystal-diffraction method, in which the radiation source is a target bombarded by a primary beam of high-energy protons.[3] In the absence of data on the production of slow hyperons, it is very difficult to derive a theoretical radiation intensity. However, our measurements have shown that this is a real possibility. For these measurements we selected the $5g$–$4f$ transition of the Σ^-–^{12}C atom, which has an energy ≈ 23.4 keV. As references we used the silver $K\alpha_1$ line, with an energy ≈ 22.1 keV, and the tin $K\alpha_2$ line, with ≈ 25.0 keV. As a control we measured the $4d$–$2p$ transition of the π^-–^{12}C atom, with an energy ≈ 24.8 keV.

The experiment was carried out at the Institute of High-Energy Physics. The apparatus was a focusing crystal-diffraction spectrometer with a Cauchois layout.[3] The sources of the radiation under investigation and the reference radiation were targets bombarded by a slowly dumped 70-GeV proton beam. The average beam intensity was about 4 × 10^{12} protons over the working cycle of the accelerator (≈ 9 s). The targets had a length ≈ 17 cm (along the beam direction), a height ≈ 10, and a width $\approx$ 3 cm. The length and height corresponded to the dimensions of the field of view of a multislit collimator which lay between the target and a curved crystal and which was oriented perpendicular to the axis of the proton beam. The width was determined by the absorption length for x radiation in the region of interest. To generate radiation from the Σ^-–^{12}C and π^-–^{12}C atoms, we used a layered target of graphite with a density of 2.1 g/cm^3, copper, and molybdenum. The copper and molybdenum auxiliary layers increased the target efficiency (molybdenum attenuated soft bremsstrahlung, which was the primary component of the background, while copper increased the yield of hyperons). Reference x radiation was generated by means of targets containing tin and silver.

The x radiation excited in the target passed through the collimator, was diffracted by a quartz plate 1.1 mm thick with a cylindrical curvature with a radius of curvature of 5 m. This plate had a working area of 80×80 mm^2 and (130) reflecting planes oriented normal to the large faces. The radiation was detected by a Ge(Li) detector. The instrumental linewidth was 14″ (the elastic quasimosaic angle was 12″, and the width of the detector slit was 0.35 mm). This configuration corresponded to an energy resolution of 7.1 eV at a radiation energy of 23.4 keV. The luminosity of the apparatus at this energy was $\approx 2 \times 10^{-9}$. The angular position of the crystal was determined with an optical interferometer with a scale division $\approx 0.04''$.

For all the lines having two reflections (right and left), corresponding to a reflection symmetric with respect to the quartz planes, we used the more intense left reflection for the measurements (the intensity difference of about 10% was caused by dynamic diffraction effects). In accumulating data we alternated measurements of the references lines and the line under study. Figure 1 shows the accumulated data for the left reflection of the $5g$–$4f$ line of the Σ^-–^{12}C atom. Also shown here is a curve drawn to fit the experimental data. The intrinsic linewidths were taken into account in the fitting procedure. For the hyperonic atom we also took account of the fine structure (not resolved by the spectrometer) due to the magnetic moment of the Σ^- hyperon. (However, calculations showed that the broadening of a reflection because of the fine structure was statistically insignificant.) The background was assumed flat in the fitting procedure.

Table I shows the results of the analysis: the value of χ^2 per degree of freedom for each line, the position of the line on the interferometer scale ("optical units," OU), the peak height, and the background level in the detector counts per 10^{12} protons incident on the target (the detector count was determined in a height interval corresponding to the photopeak of the diffracted radiation). The intensity of the radiation of the Σ^- atoms turned out to be about the same as that of K^- atoms.[3] The difference between the intensities of the tin and silver lines stemmed from a difference in target assembly.

It can be shown that the distance between reflections is very accurately proportional to the difference in wavelength. A possible deviation from this relationship (in the absence of aberrations) would stem from a deviation of the spectrometer "zero" position, which corresponds to a zero diffraction angle, from the "zero" position of the angle-measuring interferometer, which corresponds to the minimum difference in the

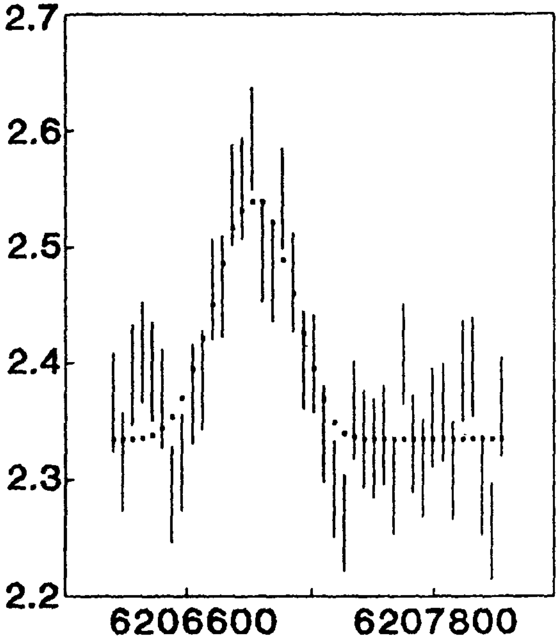

FIG. 1. Left reflection of the $5g$–$4f$ line of the Σ^-–^{12}C atom. The interferometer reading is plotted along the abscissa, and the detector count per 10^{12} protons along the ordinate. The vertical line segments show the experimental values along with the errors; the dots are the results of a fit.

path lengths of the interfering beams. In our case this discrepancy, an angle α, was $(0.69\pm0.02)^\circ$. Since α is small, and the diffraction angles for the lines under study are approximately equal, the wavelength of a line under study, λ_x, can be expressed within a relative error less than 10^{-6} in terms of the wavelengths of the reference lines, λ_1 and λ_2; the positions of the reflections, l_x, l_1, and l_2 (line 1 is Ag $K\alpha_1$, and line 2 is Sn $K\alpha_2$); the instrument constant C; and the interplanar distance of the working crystal, d:

$$\lambda_x=\lambda_1+(\lambda_2-\lambda_1)\,\frac{(l_x-l_1)}{(l_2-l_1)}\left[1+\tan\alpha\,\frac{(l_2-l_x)}{2dC}\right].$$

The value $d=1.1801$ Å was found by calculation, and the value $C\equiv\langle(l-r)/\lambda\rangle = 4\,286\,339.7 \pm 10.7$ OU/Å , was found by measuring the left (l) and right (r) reflections of x-ray lines of silver. The wavelengths of the reference lines were cor-

TABLE I. Experimental results.

Line	χ^2/ν	Position, OU	Amplitude/ $10^{12}p$	Background/ $10^{12}p$
Ag $K\alpha_1$	0.90	6 271 487±6	14.0±0.3	1.71±0.05
Σ^-–C	1.05	6 206 918±22	0.20±0.02	2.33±0.01
π^-–C	0.71	6 142 425±5	6.1±0.2	2.6±0.1
Sn $K\alpha_2$	1.16	6 133 146±4	178±3	6.5±0.5

rected to reflect changes in values of the physical constants.[4] The wavelength of the Ag $K\alpha_1$ line was recalculated with the help of the ratio $\lambda(\text{Cu } K\alpha_1)/\lambda(\text{Ag } K\alpha_1)$ from Ref. 5 and the new value of the X unit,[4] based on the wavelength of the Cu $K\alpha_1$ line. As a result, we found a value $\lambda(\text{Ag } K\alpha_1)=0.559\,419\,3(7)$ Å. The wavelength of the Sn $K\alpha_2$ line was then calculated from the ratio $\lambda(\text{Ag } K\alpha_1)/\lambda(\text{Sn } K\alpha_2)$, taken from Ref. 6: $\lambda(\text{Sn } K\alpha_1)=0.495\,062(3)$ Å.

Using the formula above, along with the relation between the energy and wavelength of the radiation, we found the energy of the $5g$–$4f$ transition of the Σ^-–^{12}C atom to be

$$E=23\,420.47\pm0.49\pm0.62 \text{ eV}.$$

The first error here is the statistical error, and the second is a systematic error. The rms value of these two errors, 0.79 eV, serves as a measure of the accuracy within which the energy was determined. The corresponding relative error is 34×10^{-6}.

The systematic error was estimated on the basis of the analysis of Ref. 7, where it was shown that reflections from targets, which are nonuniform in terms of surface brightness, are shifted because of aperture aberration of the crystal. The aberrational shifts of the right and left reflections of a line are identical, so these shifts cancel out in a determination of the distance between these reflections (in the case of a symmetric measurement), and the systematic error is small. In our case (of an asymmetric measurement) we should use the maximum shift, $\approx$ 60 OU, to estimate the systematic error. This approach leads to an error of ± 30 OU, which corresponds to ±0.62 eV. The validity of our estimate of the systematic error is checked by comparing the measured energies of the $4d$–$2p$ transition of the π^-–^{12}C atom in symmetric and asymmetric measurements. The result in the former case was published in Ref. 3: 24 828.36±0.15 eV. The result for the latter case was found by the method outlined above in the present study; it is 24 827.67±0.29 eV. The difference between the two energies is 0.69±0.33 eV and agrees with the systematic error given above.

A theoretical energy of the $5g$–$4f$ transition of the Σ^-–^{12}C atom was found through a numerical integration of the Dirac equation with the potential for a finite-size nucleus, including the Coulomb interaction, the vacuum polarization potential up to third order, and the optical potential of the strong hyperon–nucleus interaction from Ref. 2 (the calculation method is described in detail in Ref. 8). To describe the nuclear density, we used a two-parameter Fermi distribution, taking the parameter values from Ref. 9. We also incorporated a relativistic correction for the reduced mass and corrections for electron screening and atomic recoil. The results of these calculations are shown in Table II. The error of the calculations is negligible in comparison with the experimental error.

Comparison of the experimental and theoretical energies reveals that they agree within the error (the difference is -0.25 ± 0.79 eV). This good agreement confirms the validity of interpreting the measured line as radiation of the $5g$–$4f$ transition of the Σ^-–^{12} C atom.

In addition, this result can be utilized for a new determination of the mass of the

TABLE II. Calculated radiation energies of the 5*g*–4*f* transition of the $\Sigma^- {-} {}^{12}C$ atom with $M_{\Sigma^-} = 1197.43$ MeV/c^2 and $\mu_{\Sigma^2} = -1.157$ nucl. magnetons from Ref. 10 (the values of the contributions for the components of the transition are given in eV.

Contribution	$5g_{7/2}$–$4f_{5/2}$	$5g_{7/2}$–$4f_{7/2}$	$5g_{9/2}$–$4f_{7/2}$
Coulomb interaction	23 328.275	23 325.686	23 326.483
Anomalous magnetic moment	0.894	−1.334	−0.650
Vacuum polarization			
$\alpha(Z\alpha)$	92.772	92.731	92.741
$\alpha^2(Z\alpha)$	0.644	0.644	0.643
$\alpha(Z\alpha)^3$	−0.013	−0.013	−0.012
Strong interaction	0.015	0.014	0.014
Relativistic correction	0.111	0.111	0.111
Electron screening	−0.006	−0.006	−0.006
Atomic recoil	−0.023	−0.023	−0.023
Sum	23 422.669	23 417.810	23 419.301
Weighted energy with stat. wts. (27:1:35)			23 420.720

Σ^- hyperon. The new value is found by equating the measured and theoretical energies of the 5*g*–4*f* line. The result is

$$M_{\Sigma^-} = 1197.417 \pm 0.040M \text{ MeV}/c^2.$$

The relative error is 34×10^{-6}, which is smaller by a factor of 1.5 than the error in the mass found by fitting all other experiments.[10] This new mass value agrees with the value found from a study of the decays of hyperons by means of a bubble chamber,[11] while it is smaller by 0.115 ± 0.070 MeV/c^2 than the value found in an experiment with heavy Σ^- atoms at BNL.[12]

In summary, this study has proved that it is possible to use crystal-diffraction spectrometers to study the radiation of Σ^- atoms. The error in the determination of energies of lines could evidently be improved substantially by using a symmetrical measurement scheme and by accumulating data for a longer time. The fine structure of a line might be resolved by using working crystals with a smaller quasimosaic angle, to achieve a higher resolution.

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