FIRST MEASUREMENT OF THE X-RAY EMISSION OF $\sum^-$ ATOMS BY MEANS OF A CRYSTAL-DIFFRACTION SPECTROMETER

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The experiment was carried out at the Institute of High-Energy Physics [1]. The apparatus was a focusing crystal-diffraction spectrometer with a Cauchois layout [2]. The sources of the radiation under investigation and the reference radiation were targets bombarded by a slowly extracted 70-GeV proton beam. The average beam intensity was about 4×10^{12} protons over the working cycle of the accelerator ($\approx$9 s). The targets had a length $\approx$17 cm (along the beam direction), a height $\approx$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 was placed between the target and a curved crystal and was oriented perpendicular to the axis of the proton beam. The width of targets was determined by the absorption length for x-radiation in the region of interest. To generate radiation from the $\sum^- - {}^{12}C$ and $\pi^- - {}^{12}C$ 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 bent quartz plate of the 1.1 mm thick and 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), what 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 ≈0.04".

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

Table 1 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 an amplitude interval corresponding to the photopeak of the diffracted radiation). The intensity of the radiation of the $\sum^-$ atoms turned out to be about the same as that of K^- atoms [2]. The difference between the intensities of the tin and silver lines stemmed from a difference in target assembly.

Table 1

Experimental results

Line	χ^2/ν	Position, OU	Peak height/ 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
$\sum^- -C$	1.05	6 206 918±22	0.20±0.02	2.33±0.01
$\pi^- - C$	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

It can be shown that the distance between reflexes 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 path lengths of the interfering light beams. In our case this discrepancy, an angle α, was $(0.69 \pm 0.02)°$. 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 reflexes 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) reflexes of x-ray lines of silver. The wavelengths of the reference lines were corrected to reflect changes in values of the physical constants [3]. The wavelength of the $Ag\,K\alpha_1$ line was recalculated with the help of the ratio $\lambda(Cu\,K\alpha_1)/\lambda(Ag\,K\alpha_1)$ from Ref. [4] and the new value of the X-unit [3], based on the wavelength of the $Cu\,K\alpha_1$ line. As a result, we found a value $\lambda(Ag\,K\alpha_1) = 0.559\,419\,3(7)$ Å. The wavelength of the $Sn\,K\alpha_2$ line was then calculated from the ratio $\lambda(Ag\,K\alpha_1)/\lambda(Sn\,K\alpha_2)$, taken from Ref. [5]: $\lambda(Sn\,K\alpha_1) = 0.495\,062(3)$ 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 $\sum^- - {}^{12}C$ atom to be

$$E = 23\,420.47 \pm 0.49 \pm 0.62\,\text{eV}$$

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. [6], where it was shown that reflexes from targets with nonuniform brightness, are shifted because of aperture aberration of the crystal. The aberrational shifts of the right and left reflexes of a line are identical, so these shifts cancel out in a determination of the distance between these reflexes (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, ≈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 $\pi^- - {}^{12}C$ atom in symmetric and asymmetric measurements. The result in the former case was published in Ref. [2]: 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 $\sum^- - {}^{12}C$ atom was found through a numerical integration of the Dirac equation with the potential for a finitesize 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. [7] (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 2. The error of the calculations is negligible in comparison with the experimental error.

Table 2

Calculation of the energy of the $5g-4f$ transition of the $\sum^- - {}^{12}C$ atom with $M_{\sum^-} = 1197.43\ MeV/c^2$ and $\mu_{\sum^2} = -1.157$ nucl.magnetons from Ref. [10] (the values of the cotributions 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	23328.275	23325.686	23326.483
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	23422.669	23417.810	23419.301
Weighted energy with stat.wts. (27:1:35)		23420.720	

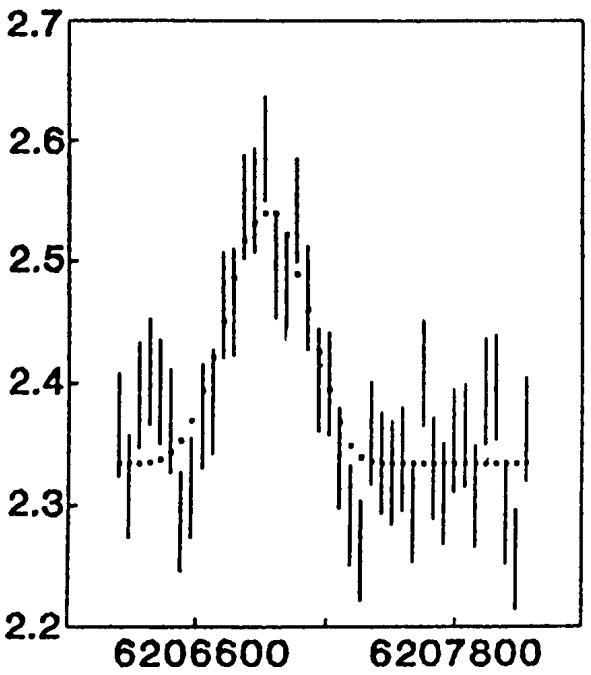

Fig. Left reflex of the $5g-4f$ line of the $\sum^- - {}^{12}C$ atom. The interferometer readings is plotted along the abscissa, and the detector counts per 10^{12} protons along the ordinate. The vertical line segments show the experimental values with the errors; the dots are the results of a fit

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 $\sum^- - {}^{12}C$ atom.

In addition, this result can be utilized for a new determination of the mass of the $\sum^-$ hyperon. The new value is found by equating the measured and theoretical energies of the $5g - 4f$ line. The result is

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

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 $\sum^-$ atoms at BNL [12].

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