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Observation of Parametric X - Radiation from Moderate Relativistic Carbon Nuclei in W Crystal

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Abstract

Preliminary results of the first experiment on observation of parametric X- radiation (PXR) from 2 GeV/u carbon nuclei extracted from the NUCLOTRON (JINR, Dubna) in a tungsten crystals (the Laue geometry) are presented. A unique situation is realized when the parametric X- radiation from relativistic particle in a crystal is formed by a few families of crystallographic planes. The observed maxima in detected X-Ray spectrum correspond to calculated positions of PXR lines. It was the first observation of PXR from moderate relativistic nuclei in a tungsten crystal.

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1. Introduction

The parametric X-ray radiation (PXR) was observed for the first time during penetration of 800 MeV electrons through a diamond crystal [1]. To date, this type of radiation from the relativistic electrons is investigated in details both experimentally and theoretically. The first experimental observation of the PXR generated not by electrons but by the relativistic nuclei in silicon crystal was done using 70 GeV proton beam [2]. PXR was registered using low resolution spectrometer, which did not allow a separation of PXR line. Later, two experiments on observation of PXR from relativistic protons and carbon nuclei were carried out [3, 4] using the semiconductor detector with much better resolution. The positions of the peaks of monochromatic radiation observed during these experiments corresponded to that of the PXR lines

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predicted by PXR theory. Moreover, for the first time an increase of the PXR yield was observed with increase of the particle charge Z. The features of the PXR generated by the relativistic nuclei, in particular Z^2 dependence , were studied theoretically in the papers [5, 6].

The first experimental results of the PXR observation from the nuclei penetrating through a tungsten crystal are presented. The experiment was carried out using the beam of the carbon nuclei with the an energy equal to 2 GeV per nucleon, in the Laue geometry, when the carbon nuclei moved along the <111> and <110> axes in the tungsten crystal with a thickness equal to 200 μm.

The studies of PXR from relativistic nuclear beams are interesting from the point of view of possible applications to the control of structure and state of the crystal deflectors. The silicon deflectors are already used in high energy physics [7]. However, using of heavy metal crystals, e.g. tungsten can increase efficiency of deflection to large angles and also can be applied for a deflection of intensive proton beams.

2. Experiment

The experimental scheme is presented in Fig. 1.

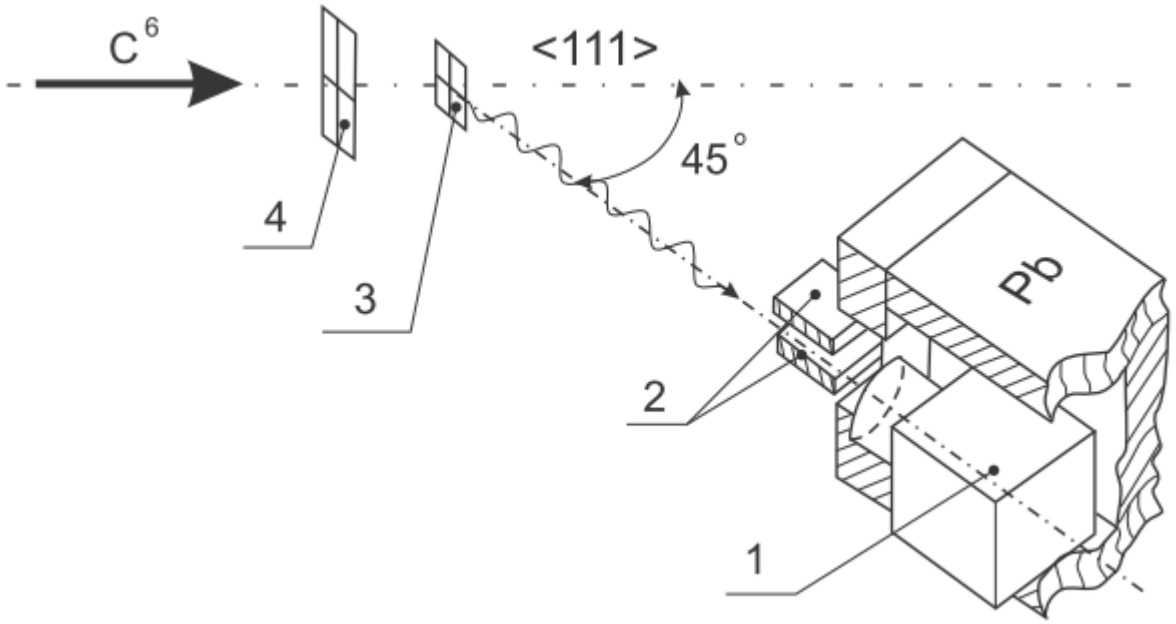

Fig. 1. Experimental layout : 1- detector; 2- magnets; 3- target; 4- ionization chamber

The nuclear beam hit a tungsten crystals which were placed perpendicular (normal) to it. The latter were cut out along the crystallographic planes (111) and (110) with thickness of each of 200 μm and mosaicism ~ 0.3 mrad . The targets were made of monocrystal ingots with the sizes 15×15×5 mm^3 received with a solid-phase recrystallization method under conditions of high vacuum. The orientation accuracy of entrance target surfaces was 1-2′, 20′ for a directions <110> and <111>,

respectively. The rocking curve width of the W(110) after mechanical and chemical processing was equal to 62″ (Fig. 2), and density of dislocations ≈ 10^4 cm^{-2}.

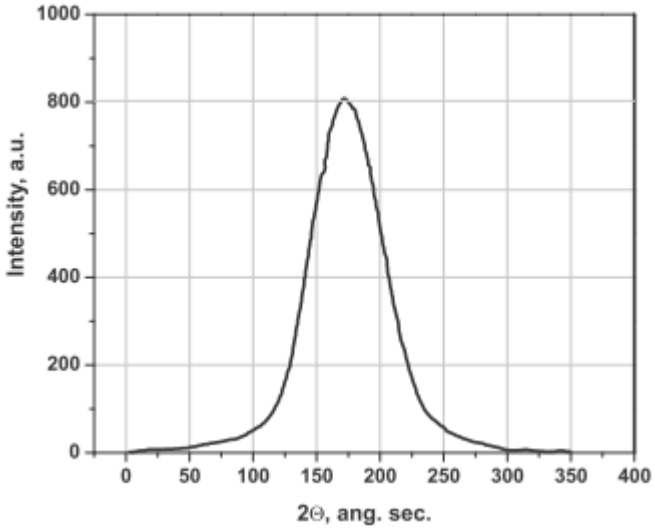

Fig. 2. Rocking curve of the samples W (110) after processing

The beam spot of completely ionized carbon ions on the target had the size 23×7 mm^2. The divergence of nuclear beam did not exceed 1 mrad in both directions. The average number of particles in an acceleration cycle was about $1.5 \cdot 10^8$. Duration of spill of a beam on a target was 3 s. The orientation accuracy of a beam with respect to the crystallographic direction did not exceed 8 mrad. The energy of the carbon nucleus was equal to 2 GeV per nucleon.

The radiation was registered using the semiconductor silicon detector with the sensitive surface area equal to 3.65×3.65 mm^2. The detector was placed under the angle 45° relative to a beam. The distance between the crystal and the detector was 502 mm. The number of particles falling to the target was controlled by ionization chamber.

The calibration of the detector was carried out using characteristic X- radiation (CXR), which was excited in the copper target by carbon nuclear beam (K_α = 8.046 keV, K_β = 8.904 keV). The FWHM of the K_α-line was equal to 330 eV [3].

The spectra obtained in the experiment are presented in Fig. 3. The PXR peaks, after background subtraction were fitted by Gaussians. The maxima positions, 13.06±0.08 and 16.1±0.2 keV, corresponded to calculated values of PXR lines from tungsten (111) and (110), respectively (see, Fig. 4).

Fig. 4 shows the simulated spectra of the PXR with taking into account of the radiation absorption inside the crystal. The PXR angular density obtained by simulations, in the case of (111)W (photon energy equal to 13 keV) was equal $n_{\gamma t}$ = $1.76 \cdot 10^{-4}$ photon/C^6/sr. In the case of W(110) $n_{\gamma t}$ = $9.12 \cdot 10^{-5}$ photon/C^6/sr (photon energy equal to 16.0 keV).

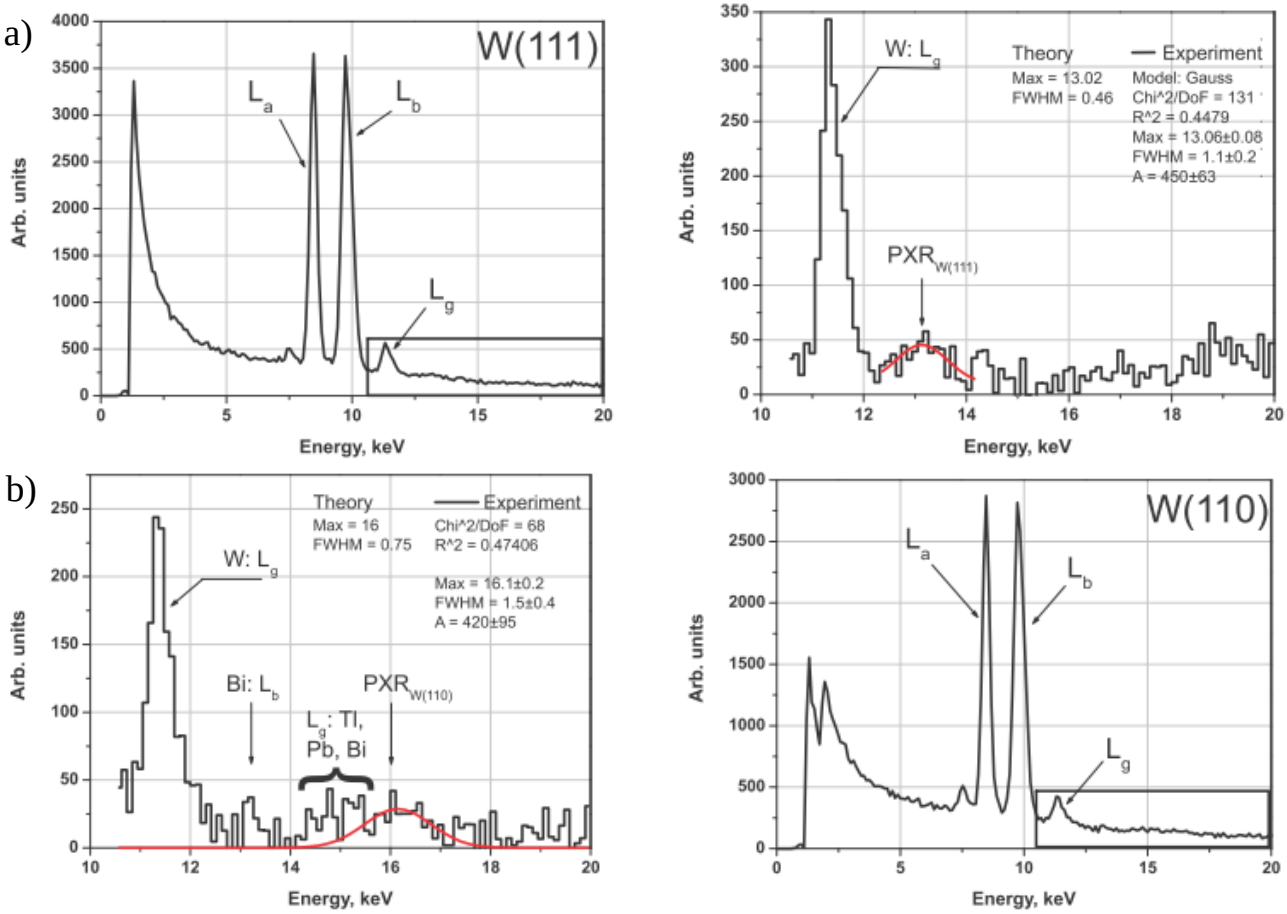

Fig. 3. The X-ray spectra detected in the experiment, for (111) (a) and (110) (b) alignments of W crystal

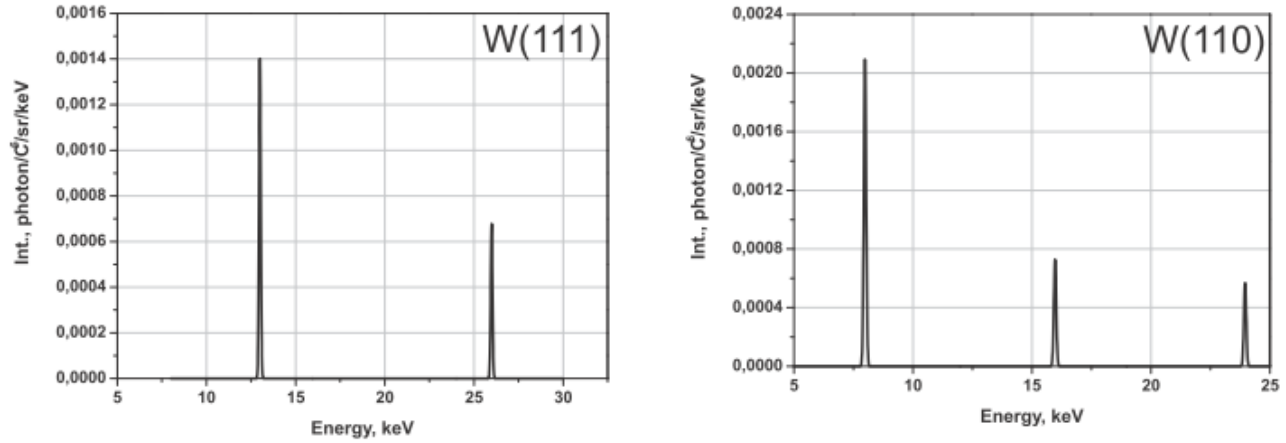

Fig. 4. Simulated spectra of PXR

The total intensity of an initial beam was equal to $N = 9 \cdot 10^{10}$ nuclei during measurements with W(111), and $8.3 \cdot 10^{10}$ nuclei in the case of W(110). The nuclear beam was not completely overlapped by a crystal in the horizontal direction. The overlapping factors of the beam by the target were determined by simulation of the

beam cross-section sizes with 2D-Gaussians function for W(111) K_b = 0.71, for W(110) K_b = 0.91. The number of the registered PXR photons during the measurement using (111)W was equal to N_γ = 450±63 photons. Thus, the PXR angular density, with taking into account of incomplete overlapping is:

$$n_\gamma = \frac{N_\gamma}{K_b K_r N \Delta\Omega} = (2.5 \pm 0.4) \cdot 10^{-4} \text{ [photon/C}^6\text{/sr]},$$

where $K_r = K_{abs} \cdot K_{ef}$ is coefficient which takes into account the radiation absorption onto its way to crystal-detector and the registration efficiency of the detector. The registration efficiency K_{ef} is equal to 0.5224 and 0.3497 for energy of photons 13.0 and 16.0 keV, respectively. $\Delta\Omega = 5.29 \cdot 10^{-5}$ sr – the solid angle.

In the measurement with (110)W, N_γ = 420±95 photons. Therefore,

$$n_\gamma = \frac{N_\gamma}{K_b K_r N \Delta\Omega} = (3 \pm 0.7) \cdot 10^{-4} \text{ [photon/C}^6\text{/sr]}.$$

Taking into account the possible contribution of CXR from Bi, Pb and Tl, the PXR angular density was about n_γ = (2.1±0.4) $\cdot 10^{-4}$ and n_γ = (2.5±0.7) $\cdot 10^{-4}$ [photon/C^6/sr] for W(111) and W(110), respectively.

3. Discussion of experimental results

In our experiment, the relativistic factor of carbon nuclei was γ = 3.13 and the PXR characteristic angle (the angle near the Bragg direction, at which the PXR distribution has a maximum) was γ^{-1} = 0.297 rad. In this case, the PXR reflection width was enough to lead to their superposition [8]. Moreover, if the condition is satisfied [9]:

$$(\boldsymbol{g}_i \cdot \boldsymbol{v}) \approx (\boldsymbol{g}_j \cdot \boldsymbol{v}), \qquad (1)$$

where $\boldsymbol{v}$ – the particle velocity vector, $\boldsymbol{g}$ – the reciprocal lattice vector, where indices *i*, *j* indicate the PXR reflex, the photon energies of different PXR reflections coincide, that leads to increase of the observable line intensity.

The condition (1) for all resolved PXR reflections is realized in the suggested geometry when the beam is directed along crystallographic axes, such as <111> or <110>. As the result, it was obtained the useful increase of the line intensity. According to calculation, the increase of the yield in the chosen direction (see, in Fig. 1) was about 800 % and 600 % with respect to the strongest reflex of $(11\bar{1})$ type for crystal W(111) and $(02\bar{2})$ in the case of W(110), accordingly.

To compare the theory and the experiment of observable positions of the CXR line it was taken out an agreement. On the other hand, positions of maxima for (111)W and (110) W are different and are not overlapped. The thicknesses of the crystals are approximately equal. That means, the maxima cannot be completely formed by imposing of the CXR lines from substance of an environment, that also confirms formation of observable peaks by the PXR mechanism.

The large width of the PXR peaks was determined by the large sizes of irradiated crystals area, and consequently, a large spread of of PXR registration angles. In the experiment, the beam was not completely overlapped by the crystals in the horizontal direction. The PXR line width considerably depends on the irradiation area (see, in Fig. 5). In the case of W(111) crystal, the FWHM = 460 eV if K_b = 0.71, and FWHM = 650 eV if K_b = 1. In calculations, the estimated FWHM = 645 eV for W(110) at K_b = 0.9, and FWHM = 740 eV for K_b = 1. The calculations were carried out using the Monte Carlo method (sample size is 10^3). In order to take into account the detector resolution, the PXR line was convoluted with the energy resolution of the detector.

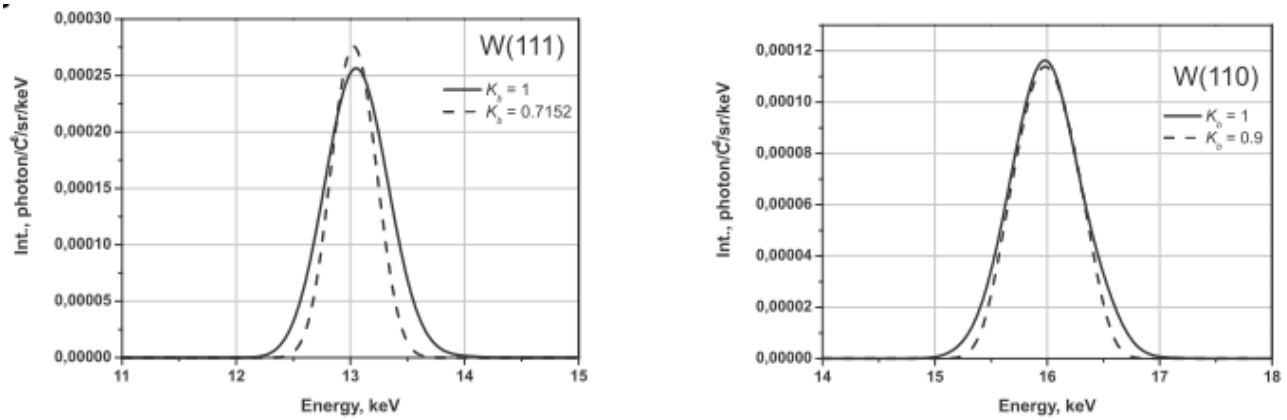

Fig. 5. Simulatied lines of PXR from W crystals with taking into account of size, beam divergence and detector resolution

It is necessary to note that this scheme is sensitive to off-orientation of the beam relative crystallographic axes. Fig. 5 shows simulated PXR lines from W(111) and W(110) for off-orientation angle equal to 0 degree. The off-orientation equal to 8 mrad results in lines broadening of order of 27%. Thus, the PXR line width can achieve a size about 1 keV at orientation accuracy ~ 10 mrad.

In the Bragg geometry, an increase of photon yield due to the contribution of lateral reflections during experiments with silicon [4], was ~ 150 %, thus except for the basic line arise satellites. In a case of tungsten crystal, calculations show an increase at the level of about 200 %.

In the future experiments it is propose to use the nickel filter and to reduce the beam size in the horizontal direction. The nickel K-edge corresponds to the photon energy 8.234 keV. Thus, using a nickel foil in measurements with tungsten (110), we hope to obtain more pronounced PXR maximum near photon energy 8 keV and to cut off parasitic peaks of tungsten CXR. In Fig. 6, the simulation spectra with the nickel filter of the thickness 30 μm and without it are presented.

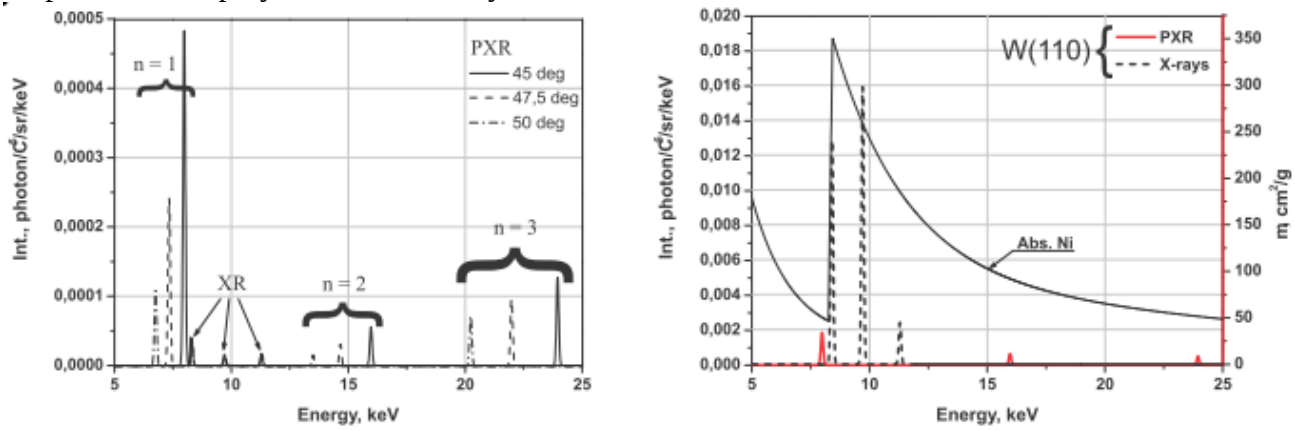

Fig. 6. Calculated spectra of PXR and X-rays from tungsten (110) with use of the nickel filter (on the right) and without it (at the left)

4. Summary

Using geometry suggested, which allows increasing the yield of the PXR line up to 800% due to energy coincidence of lateral reflections, it was possible to observe for the first time the PXR from relativistic nuclei in the tungsten crystals. The spectra of monochromatic X-radiation corresponded to calculated PXR lines positions were observed using the carbon nuclear beam extracted from NUCLOTRON (JINR, Dubna). The measurements with (111)W agree with theoretical calculations of the radiation yield. In the case of (110W the intensity of PXR exceeded the theoretical calculation 2.7 times.

The PXR yield per carbon nucleus observed experimentally is considerably higher than that from protons. This agrees with the theory statement about the Z^2-dependence of the PXR yield [5-6].

For the Bragg geometry, the calculations show an increase of the line intensity due to contribution of lateral reflections, at a level of about 200%.

In the future experiments it is suggested to make a narrow beam in the horizontal direction that allows to receive narrower PXR lines. In the measurements with tungsten (110) it is suggested to use the nickel filter for separation of the PXR maximum near the energy of 8 keV.

There is the problem of increase of extraction efficiency of high energy protons and nuclei beams, which can be solved using crystal deflectors made of heavy metals. The parameters of modern proton beams with intensity up to 10^{14} p/s are those that ionization losses can lead to local heating of a crystal up to temperatures higher than Debye temperature. Hence, it is necessary to monitor a state of crystal deflector structure directly during the beam extraction. The PXR in this case can be represented itself as the tool for monitoring of the deflector state. That was confirmed by experiments carried out at the JINR. Estimations had shown an opportunity of deflector monitoring at “on-line” regime.

Also it is necessary to note, that the carried out calculations of the characteristic X-ray radiation yield for the tungsten L-lines using a model [10] showed a difference with experiment up to 50 % in the smaller side. The calculations and experimental results for amorphous copper agreed with error of about 15 %. Thus, it is possible to assume that in the crystal target the excitation of atoms occurs also due to the mechanism of parametric radiation which does not take into account model [10].

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