Precise α_K Internal Conversion Coefficients Measurements of 30.77-keV M4 Transition in ^{93m}Nb: Last Test of Internal Conversion Theory

TEXAS A&M PROGRAM TO MEASURE ICC

N. Nica[1], V. Horvat[1], J.C. Hardy[1], V.E. Iacob[1], E.E. Tereshatov[1], C.M. Folden III[1], M.B. Trzhaskovskaya[2]

[1] Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA

[2] Petersburg Nuclear Physics Institute, Gatchina 188300, Russia

Internal Conversion Coefficients (ICC):

- ***Big impact on quality of nuclear science***
- ***Central for the nuclear data evaluation programs***
- ***Intensely studied by theory and experiment***
- ***Important result: hole calculation now standard***

2002RA45 survey ICC's theories and measurements

- **Theory: RHFS and RDF comparison**

  Exchange interaction, Finite size of nucleus, ***Hole treatment***

- **Experiment:**

  100 *E2, M3, E3, M4, E5* ICC values, 0.5%-6% precision,

  very few <1% precision!

- **Conclusions, Δ(exp:theory)%:**

  No hole*: +0.19(26)% *BEST!

  (bound and continuum states - SCF of neutral atom)

  ***Hole-SCF*: -0.94(24)%**

  (continuum - SCF of ion + hole (full relaxation of ion orbitals))

  ***Hole-FO*: -1.18(24)%**

  (continuum - ion field from bound wave functions of neutral atom (no relaxation of ion orbitals))

  PHYSICAL ARGUMENT

  K-shell filling time vs. time to leave atom

  ~10^{-15} – 10^{-17} s » ~10^{-18} s

Overview of the scope and completeness of the method

- **Scope:** ***Minimize*** **ICC measurement unc (~1%) and** ***maximize***

  Δ_{theory}(FO,NH)% (>4%, *E3*, *M4*)

- **Completeness: There is no criterion to reach the scope of comparison between ICC theories "with hole" and "no hole" except for measuring precisely as many relevant cases as practically possible**

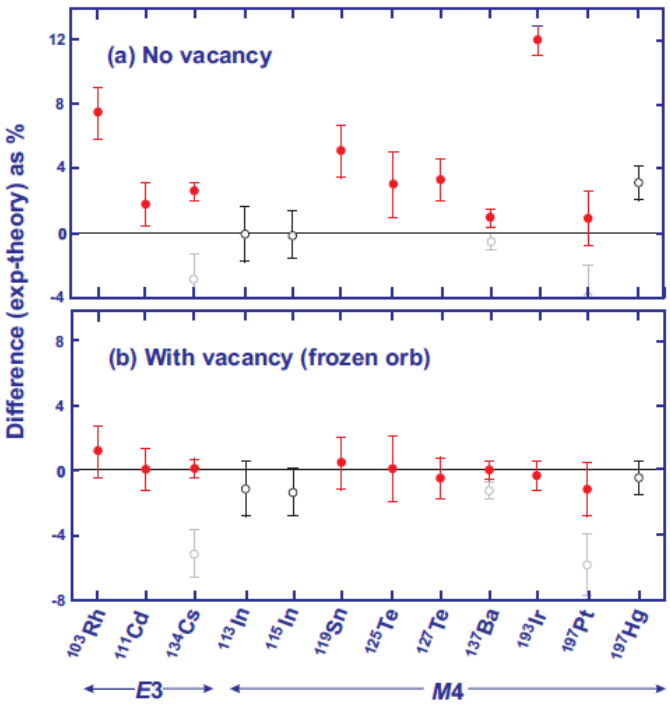
OUR RESULTS

Frozen orbital:
X ray emitted before atomic orbitals have time to rearrange after electron's removal.

Self-consistent field (SCF):
After electron emission, the Ion orbitals fully relax before the x ray is emitted.

Comparison of all nine TAMU experimental α_K values with the three theories

Theory	χ^2
with hole (frozen orb.)	1.3
with hole (SCF)	21
no hole	241

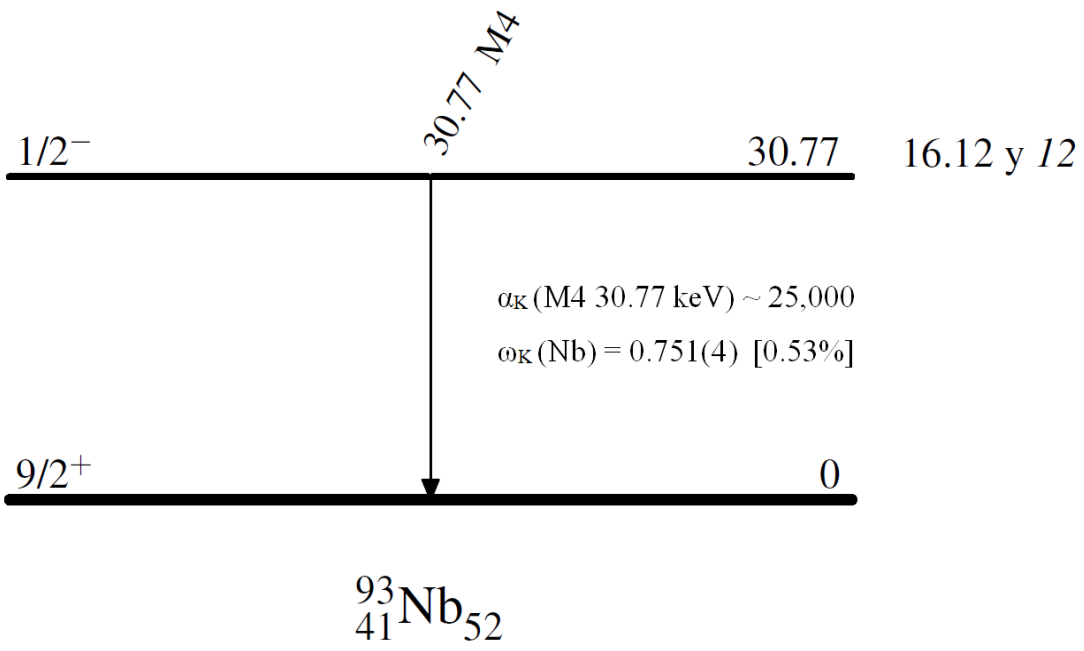


III. ^{93m}Nb 30.77(2) keV, M4 transition

- **α(K)exp: 25800 *1500* [1], 17000 *3000* [2]**
- **$\alpha(K)_{hole\_FO}$ = 26000 *400*, $\alpha(K)_{no\_hole}$ = 23900 *400*,**
  Δ_{Theory}(FO,NH) = 8.5% - *Second most favourable case after ^{193}Ir*

[1] M.Jurcevic, A.Ljubicic, D.Rendic, Fizika 8, 81 (1976)
[2] J.Morel, J.-P. Perolat, N.Coursol, C.R.Acad.Sci., Ser.B 284, 223 (1977)

Decay scheme of ^{93m}Nb (ENSDF)



Texas A&M precision ICC measurements:

- **KX to γ rays ratio method**

$$\beta^-: \alpha_K = \frac{N_K}{N_\gamma} \cdot \frac{\varepsilon_\gamma}{\varepsilon_K} \cdot \frac{1}{\omega_K}$$

  - N_K, N_γ **measured from *only one K-shell converted transition***
  - ω_K **from 1999SCZX (**compilation and fit**)**

- **Very precise detection efficiency for ORTEC γ-X 280-cm^3 coaxial HPGe at standard distance of 151 mm:**

  - **0.2% , 50-1400 keV**
  - **0.4% , 1.4-3.5 MeV**
  - **~1% , 10-50 keV (KX rays domain)**

Preparation and properties of the ^{93m}Nb source

- We purchased a solution of ^{93m}Nb in 1 M HNO_3 / 0.3 M HF.

- Dr. Tereshatov (from Dr. Folden's group) used *molecular electroplating technique*† to deposit Nb on (12 μm thick) aluminum backing in the form of Nb_2O_5.

- Chemical identity of the source was confirmed by means of Energy Dispersive Spectroscopy (EDS) and X-ray Photoelectron Spectroscopy (XPS), as well as by visual inspection.

- Five sources were prepared, but only the most active one was used in the measurements (~3.6 μCi of ^{93m}Nb).

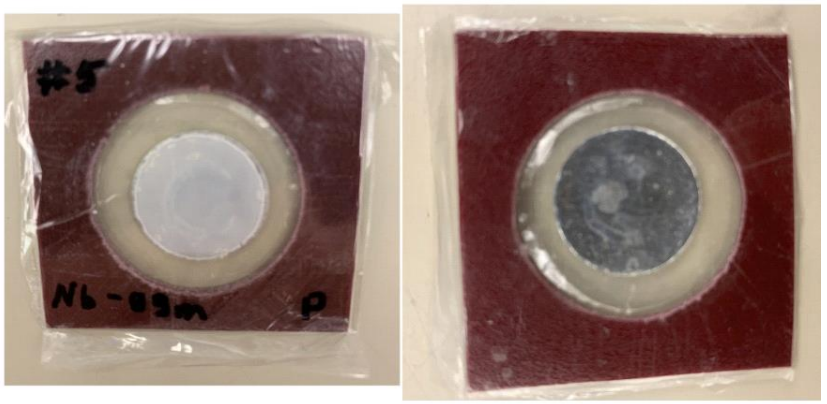
† D.A. Mayorov, E.E. Tereshatov, T.A. Werke, M.M. Frey, C.M. Folden III, NIMB **407**, 256 (2017).

Preparation and properties of the ^{93m}Nb source

- The mounting frame was placed on a big piece of Scotch tape and the backing side of the source was glued onto the exposed tape in the center of the frame.

- The source side was covered with 3.8 µm thick Mylar foil (540 µg/cm^2).

Source side



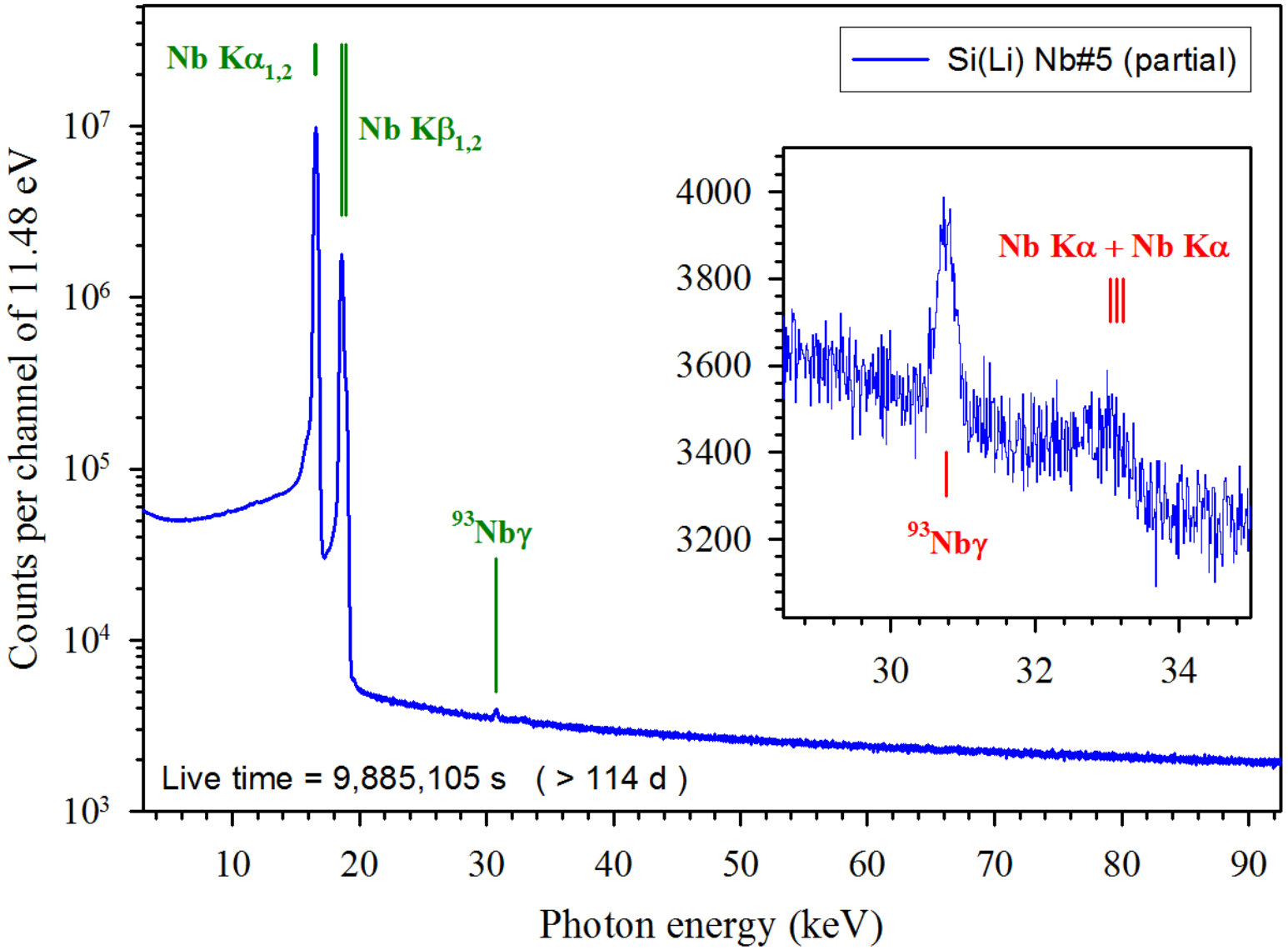
Backing side

Mass = 3.0 mg, Diameter = 17 mm ==> Mass thickness = 1.3 mg/cm^2

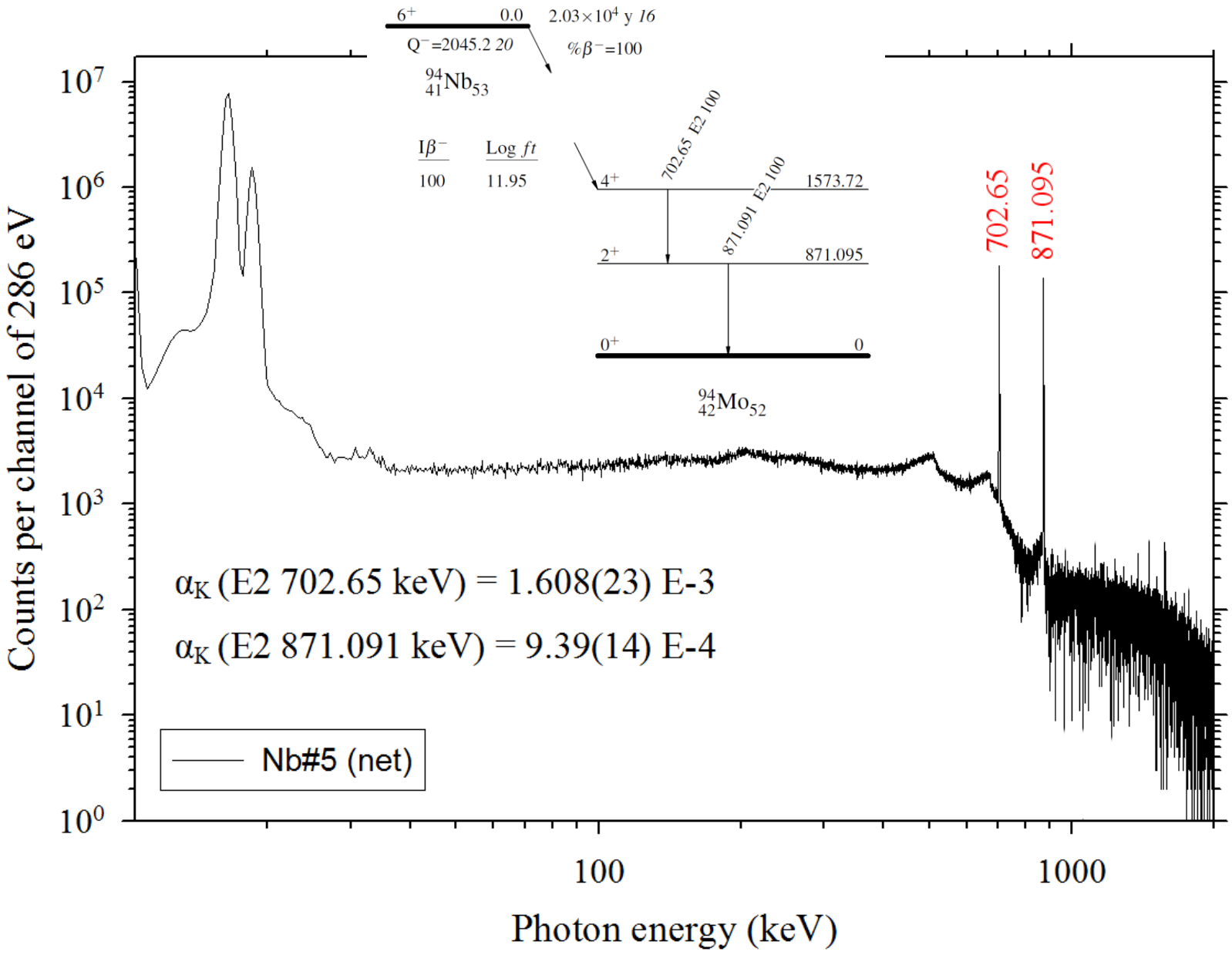
Density (Nb_2O_5) = 4.6 g/cm^3 ==> Thickness = 2.87 µm


29-Oct-19 15:39:30 Nb_TS5-b
3000
2200
60
80
100
120
140
160
180
29-Oct-19 15:39:34 Nb_TS5-b
1000000
100000
10000
60
80
100
120
140
160
180

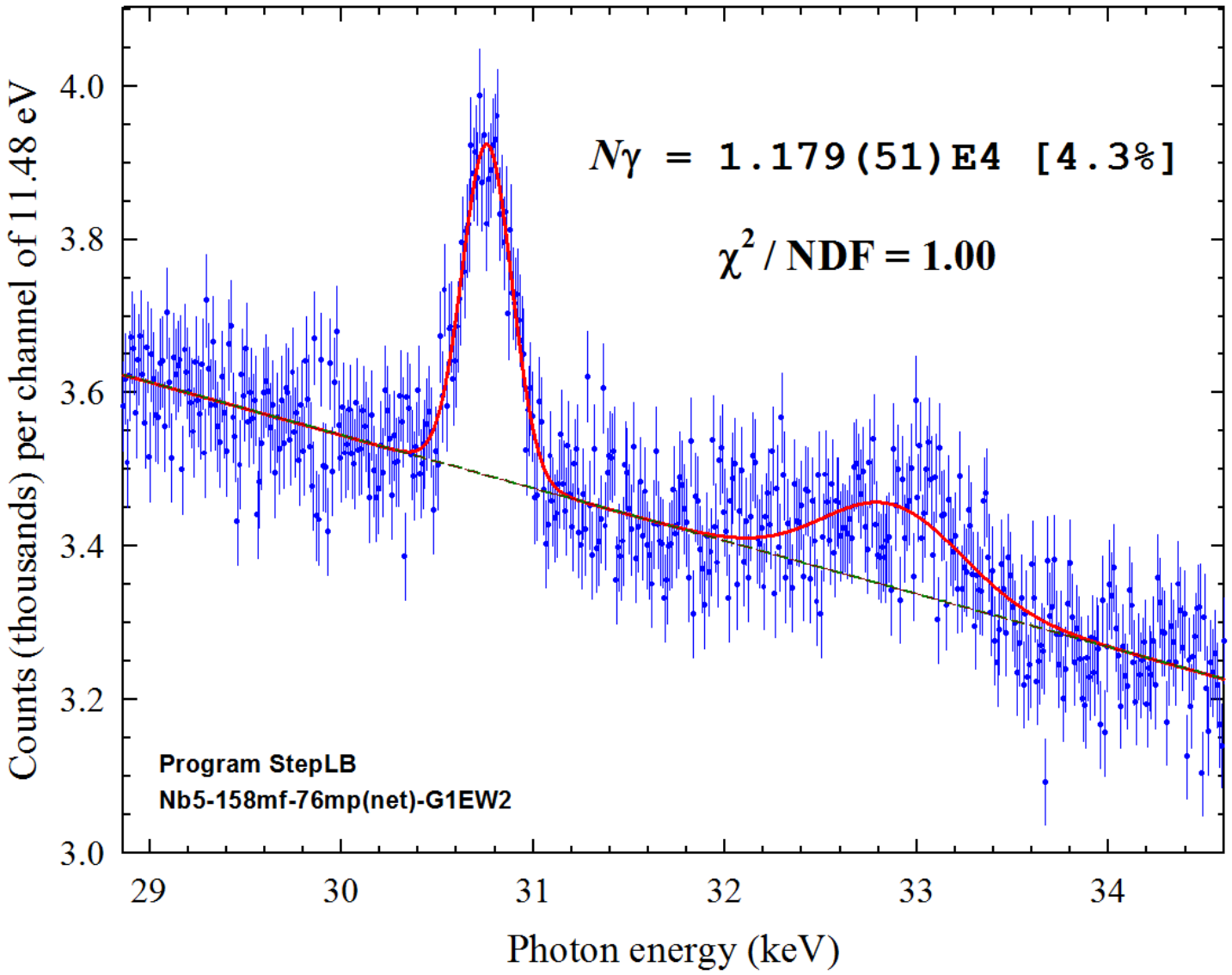
Spectrum measured with the Si(Li) detector



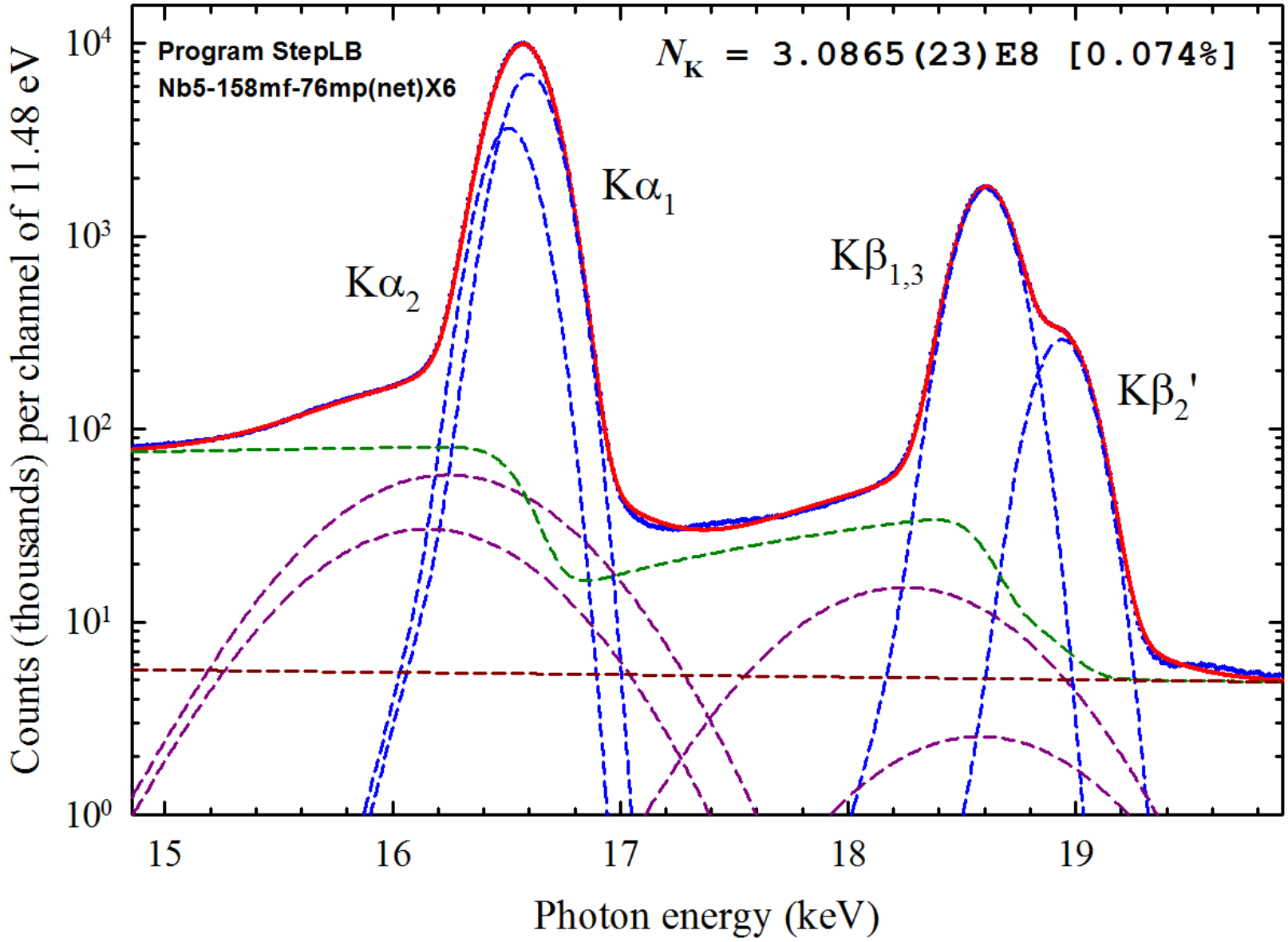
Contaminants in the source



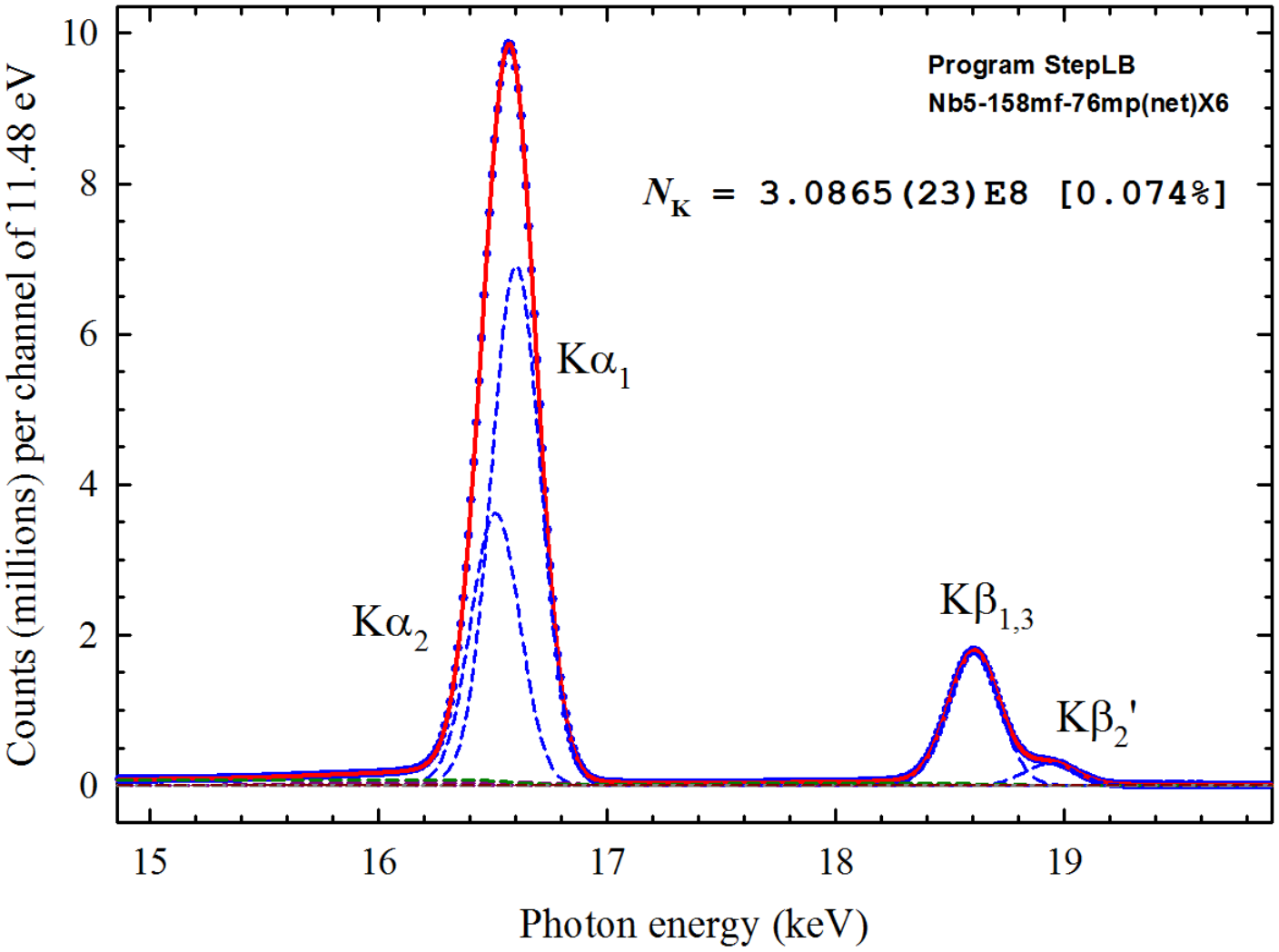
Determination of $N\gamma$



Determination of N_K



Determination of N_K



^{109}Cd Efficiency Calibration

22.6-keV AgKx & 88.0-keV E3 γ regions

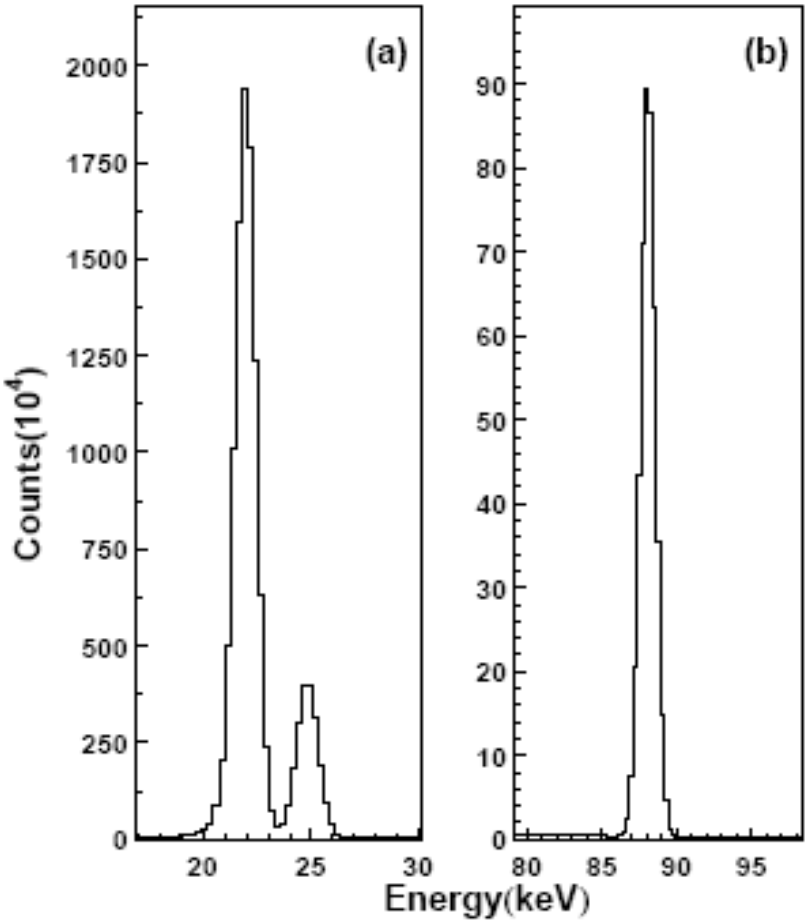
Photopeak efficiency:

^{109}Cd ε Decay: ***single 88γ***

-22.6-keV AgKx

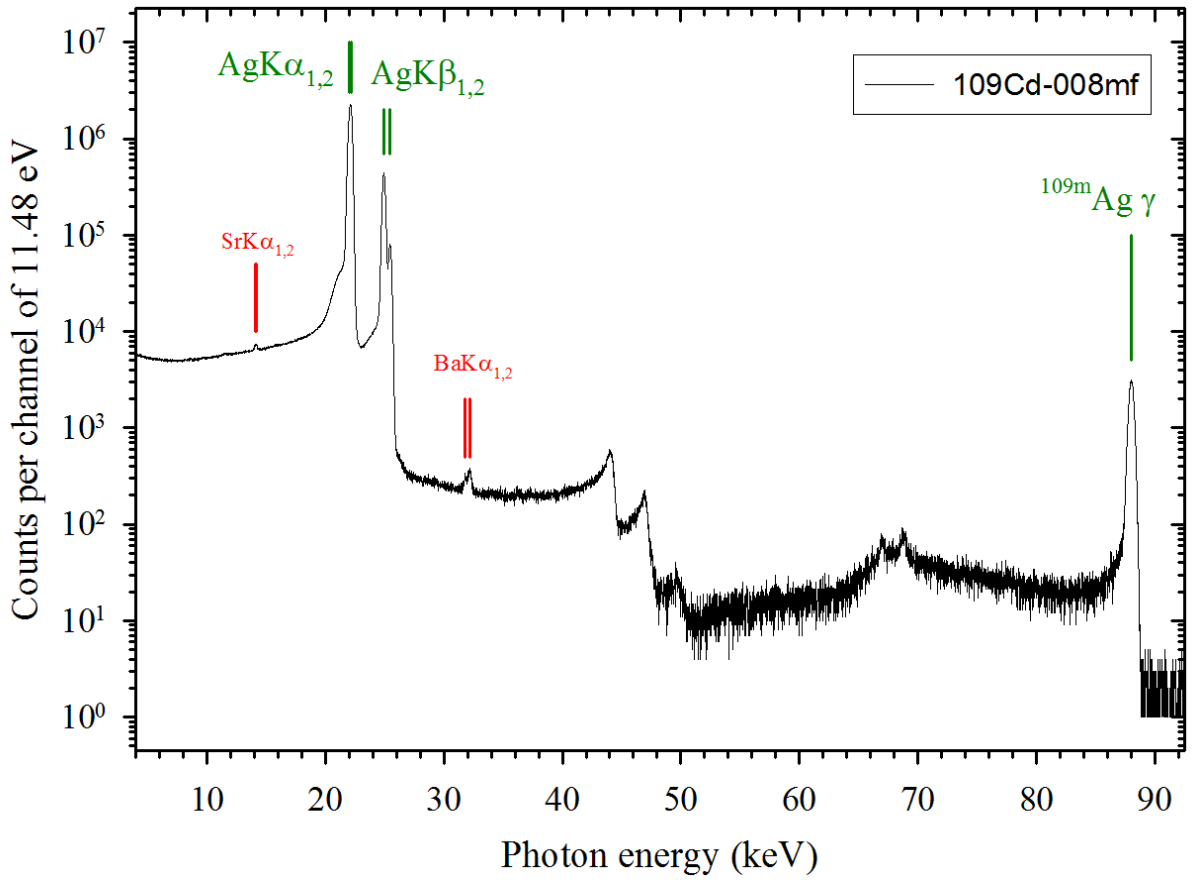
-88.0-keV E3 γ ray

$$\frac{\varepsilon_\gamma}{\varepsilon_K} = \frac{\omega_K(\alpha_K P_\gamma + P_{ec,K})}{P_\gamma} \cdot \frac{N_\gamma}{N_K}$$



Absolute efficiency calibration of the Si(Li) detector

Step 1: A ^{109}Cd source of known activity was put in front of the Si(Li) detector. This source emits K x rays of silver as well as 88.0336(10) keV gammas.



Absolute efficiency calibration of the Si(Li) detector

Step 2: For the K x rays of silver and for the 88.0336(10) keV gammas the *absolute efficiency* of the detector was found based on the *measured numbers of counts* in the corresponding peaks and the *known activity* of the source.

Step 3: The obtained results were compared to those *calculated* using CYLTRAN† Monte Carlo electron and photon transport code, taking into account the positions, shapes, sizes and materials of the detector and source components.

† J. A. Halbleib et al., Report SAND91-16734 (SNL, Albuquerque, 1992).

Absolute efficiency calibration of the Si(Li) detector

Step 4: We *modified* the values in the CYLTRAN *input* file for the position and effective thickness of the silicon crystal inside the detector so that the calculated efficiencies *match* the measured ones almost exactly (well within the statistical uncertainties).

thickness:	5.5 mm --> 5.08 mm	(-0.42mm)
position:	7 mm --> 10.4 mm	(+3.4mm)

Step 5: CYLTRAN was used to *calculate* absolute efficiencies for *niobium* K x rays and the 30.77 keV gammas, after making small adjustments in the input file for the position and size of the source.

Determination of relative efficiency

- Although absolute efficiencies calculated by CYLTRAN are sensitive to the variations of the input parameters, the relative efficiencies are sensitive much less.

- By considering reasonable variations of the input parameters, we concluded that *the relative efficiency that we need in this work is accurate within 0.5 %*.

Determination of α_K

$$\alpha_K = \frac{N_K}{N_\gamma} \cdot \frac{\epsilon_\gamma}{\epsilon_K} \cdot \frac{1}{\omega_K}$$

N_K = 3.0865(23) E8 [0.074%]

N_γ = 1.179(51) E4 [4.3%]

ω_K = 0.751(4) [0.53%]

$\varepsilon_\gamma / \varepsilon_K$ = 0.7200(36) [0.50%]

α_K = 2.51(11) E4 [4.4 %] (from the data above)

α_K = 2.62(15) E4 [5.7%] (from the remaining data)

α_K = 2.55(9) E4 [3.5%] (combined result)

Comparison with calculations

With correction for self-absorption [x 0.9974(13) (-0.26%)]:

α_K = 2.54(9)E4 [3.5%] (our preliminary final result)

The calculations predict

α_K = 2.39(4) E4 (ignoring K vacancy in the final state)

α_K = 2.60(4) E4 (including K vacancy in the final state)

==> Our results agrees with the calculations in which effects of the K vacancy in the final state are taken into account.