Nuclear structure investigations in light nuclei

D. Tonev, G. de Angelis, A. Dewald, I. Deloncle, G. De Gregorio, P. Petkov, S. Iliev, P.G. Bizzeti, R. Menegazzo, N. Goutev, D. R. Napoli, A. Demerdjiev, I. Pantaleev, G. D. Dimitrova, N.N. Petrov, S.G. Genchev, E. Geleva

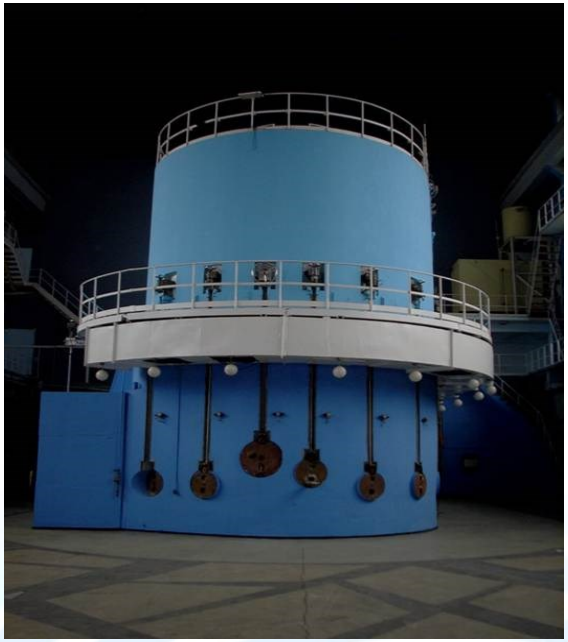
Institute for Nuclear Research and Nuclear Energy, BAS, Bulgaria
INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy
INFN and Dipartamento di Fisica, Universita di Padova, Italy
IKP, Cologne University, Germany
CSNSM, CNRS/Universite Paris Sud XI, Orsey Campus, France
INFN, Sezione di Napoli, Italy
INFN, Sezione di Firenze, Italy

ISINN-30, Sharm El-Sheikh, Egypt, April 14-18, 2024

fppt.com

Institute for Nuclear Research and Nuclear Energy – Bulgarian Academy of Sciences TODAY

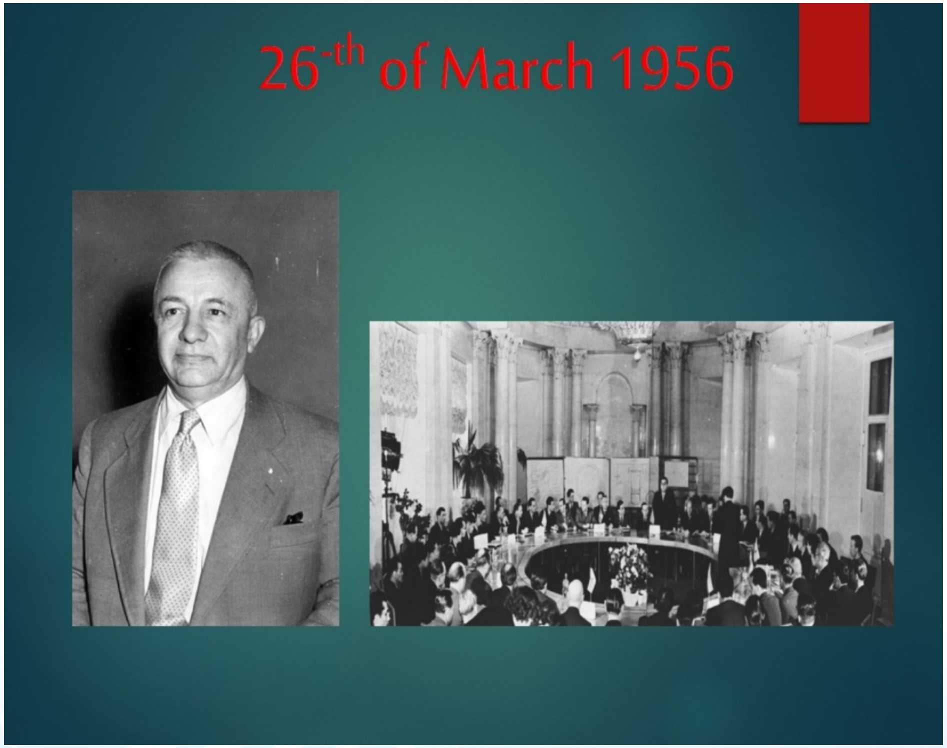
The biggest complex centre in Bulgaria for scientific and application investigations in the fields of:



- Nuclear physics
- Nuclear energy, nuclear methods and technologies
- High energy physics
- Radiation environment and ecology
- Theoretical and mathematical physics
- The research reactor of the INRNE-BAS
- Basic environmental observatory at peak Moussala
- Cyclotron laboratory
- World recognized results of the INRNE notified during the European Science Foundation evaluation of the BAS
- An important part of the Bulgarian Nuclear Society

fppt.com

Bulgaria is among the founders of JINR



Member States

- Armenia
- Azerbaijan
- Belarus
- Bulgaria
- Cuba
- Egypt
- Georgia
- Kazakhstan
- North Korea
- Moldova
- Mongolia
- Romania
- Russia
- Slovakia
- Uzbekistan
- Vietnam

The most significant milestone in the relations between Egypt and JINR was the improvement of the status of the country up to the full Member State of the Institute. This decision was unanimously taken by the CP members at the visiting session of the Committee of Plenipotentiaries in Bulgaria on 22-nd November 2021.

fppt.com

Motivation to study lifetimes in light nuclei along N=Z line

- A check for the charge symmetry of the nuclear forces.
- Role of the Coulomb effects on the nuclear structure.
- Isospin study.
- Comparison of the determined transition probabilities with model calculations. Applicability of the models.
- Analysis of data obtained in Doppler-shift attenuation experiment with an advanced method for lifetime determination.
- Lifetime measurements in two mirror couples will be presented, namely A=31 (^{31}P and ^{31}S) and A=47 (^{47}V and ^{47}Cr).

fppt.com

ELSEVIER

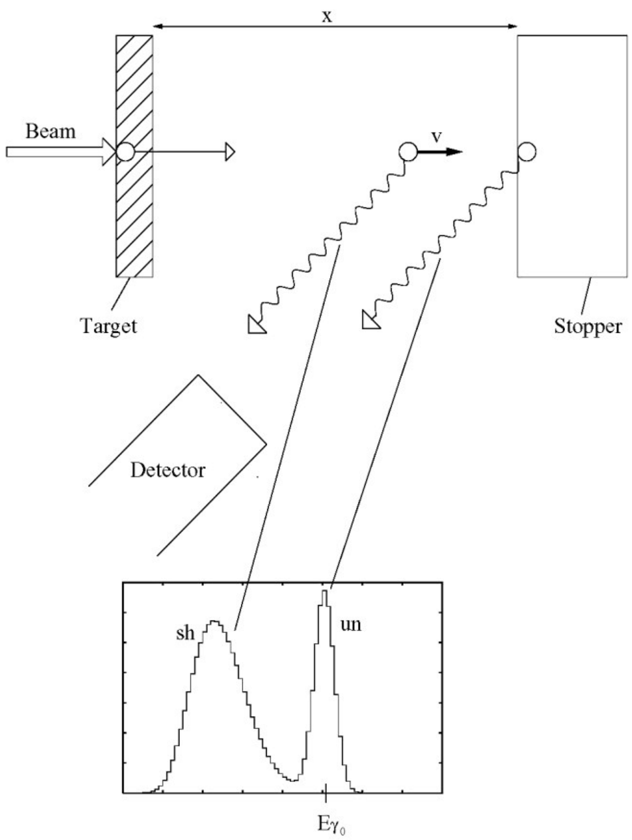
Nuclear Instruments and Methods in Physics Research A 431 (1999) 208–223

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.nl/locate/nima

On the line-shape and lifetime determination in recoil distance Doppler-shift measurements

P. Petkov[a,b,*], D. Tonev[a,c], J. Gableske[a], A. Dewald[a], T. Klemme[a], P. von Brentano[a]



Factors determining lineshape:

- Stopping powers of the target and stopper
- Reaction
- Beam Energy
- Detectors – position and resolution
- Time dependence of the population of the level of interest
- Relativistic effects
- Evaporation of light particles from the compound nucleus

ELSEVIER

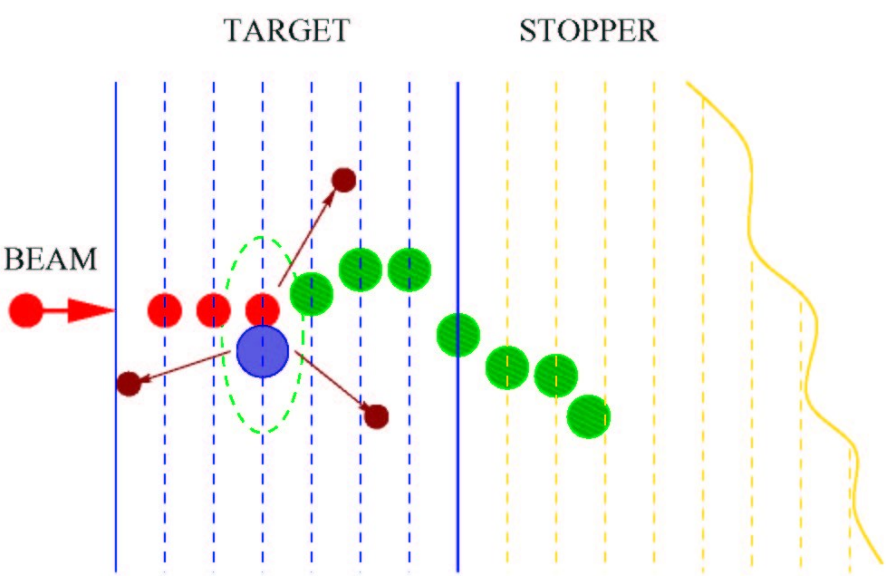
Nuclear Instruments and Methods in Physics Research A 437 (1999) 274–281

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

www.elsevier.nl/locate/nima

Lifetime analysis using the Doppler-shift attenuation method with a gate on feeding transition

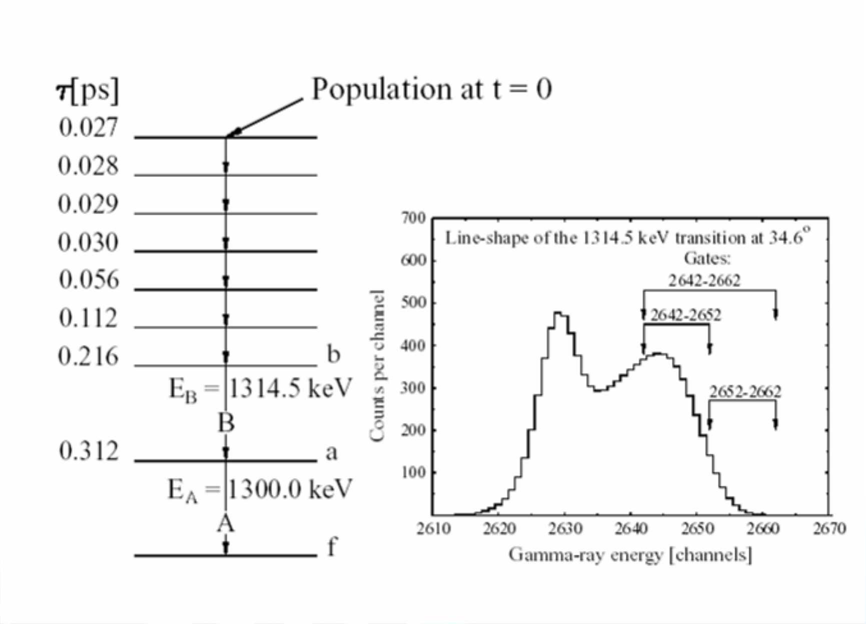
P. Petkov[a,b,*], D. Tonev[a,c], J. Gableske[a], A. Dewald[a], P. von Brentano[a]



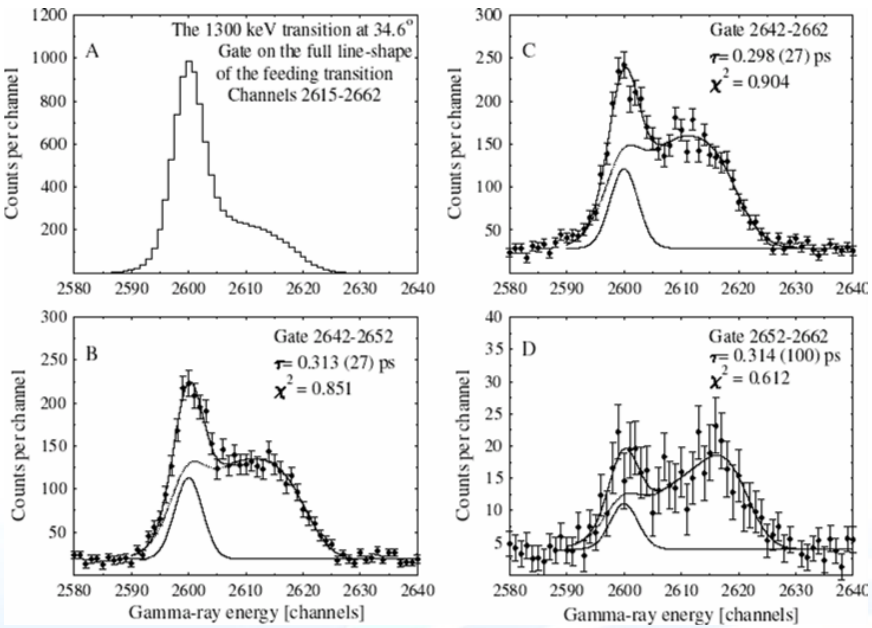
A Monte Carlo simulation of the velocity histories:

- The reaction happens in the randomly chosen place in the target.
- Evaporation of particles, slowing down in the target and stopper up to the moment when the recoil stops.

Lifetime analysis using the DSAM with a gate on feeding transition



Level-scheme used for the simulation of DSA line-shapes. Three different gates are shown in the insert.

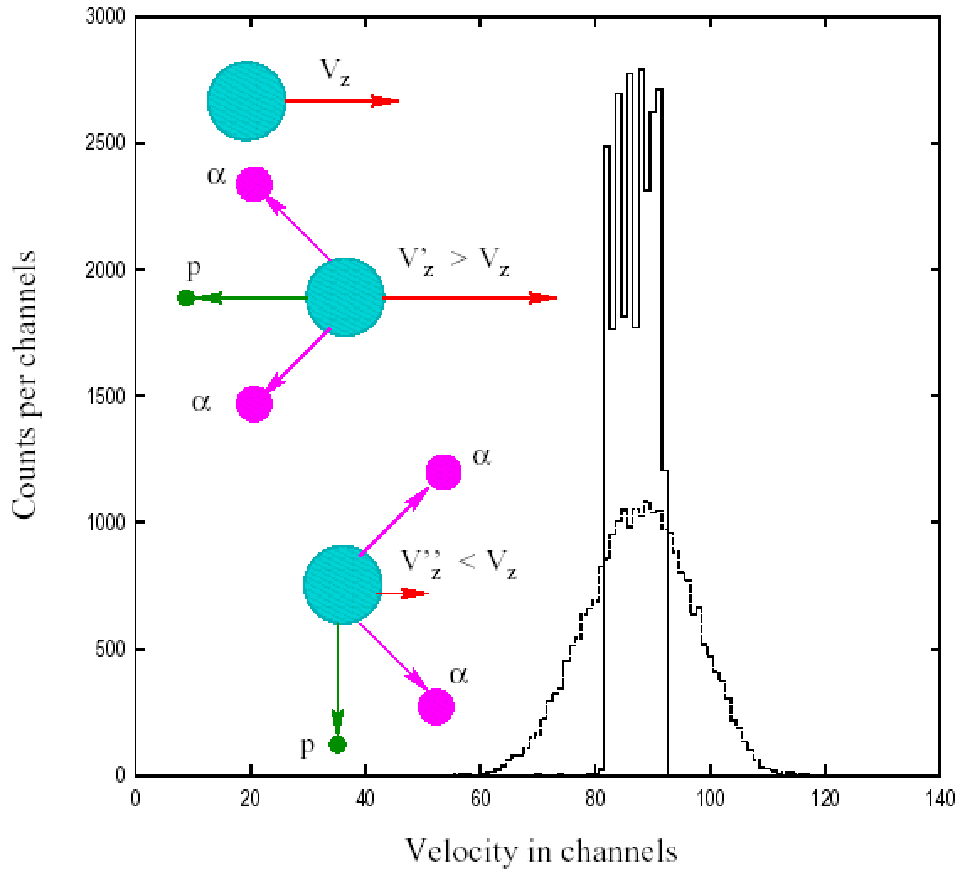


Fits of the line-shapes of the investigated transition, corresponding to different gates.

P. Petkov et. al., Nucl. Instrum. Meth. A 437 (1999) 274.

fppt.com

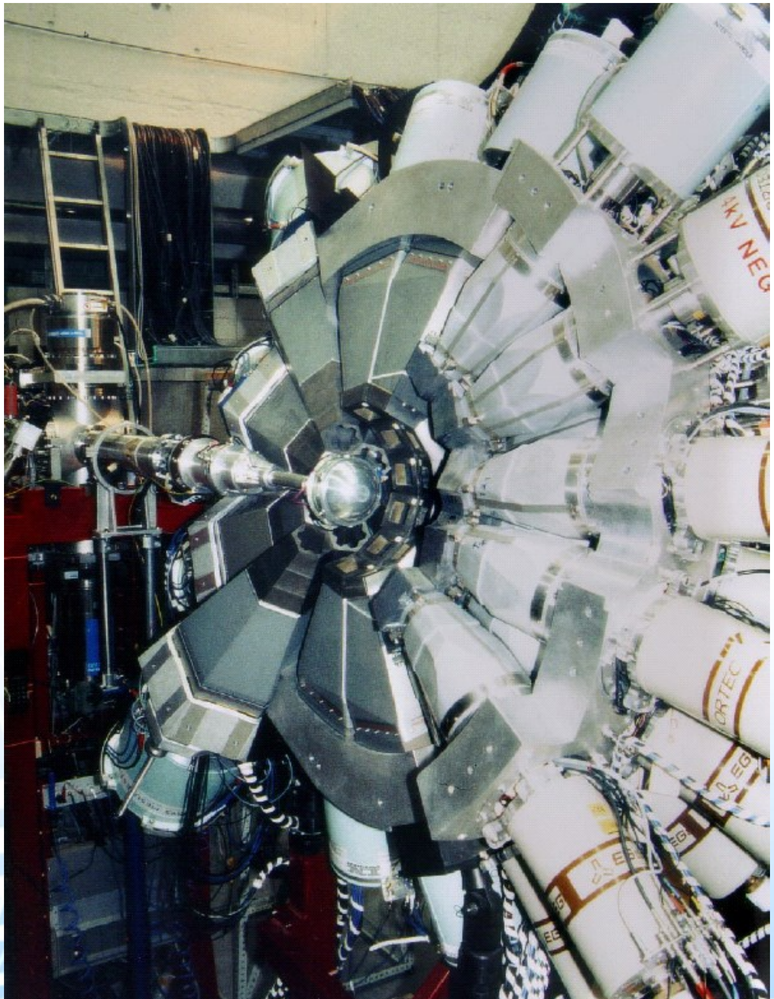
Velocity distribution of the recoils at the moment they leave the target, with and without evaporation



D. Tonev et. al., Phys. Rev. C 65 (2002) 034314.

fppt.com

Lifetime experiment:
Doppler-shift attenuation method

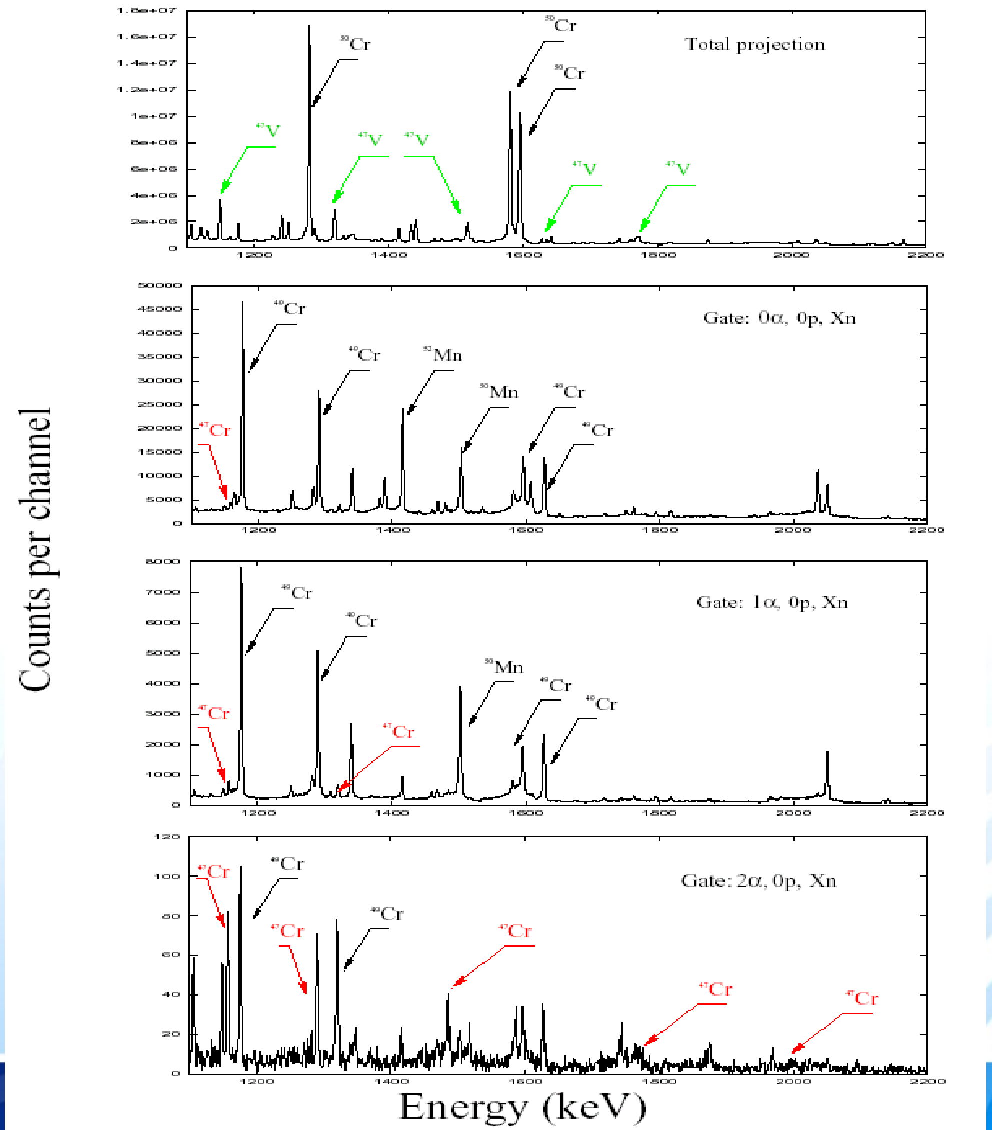


Details:

- Euroball experiment at LNL
- ISIS silicon ball and Neutron wall
- Reaction: (^{28}Si,^{28}Si)
- 2 α n channel → $^{47}Cr_{23}$
- 2 α p channel → $^{47}V_{24}$
- ^{28}Si beam with an energy of 110 MeV
- Target: 0.85 mg/cm^2 ^{28}Si (enriched to 99%) evaporated on a 15 mg/cm^2 ^{197}Au backing
- 7 days measurement
- v/c ~ 3.2 %

fppt.com

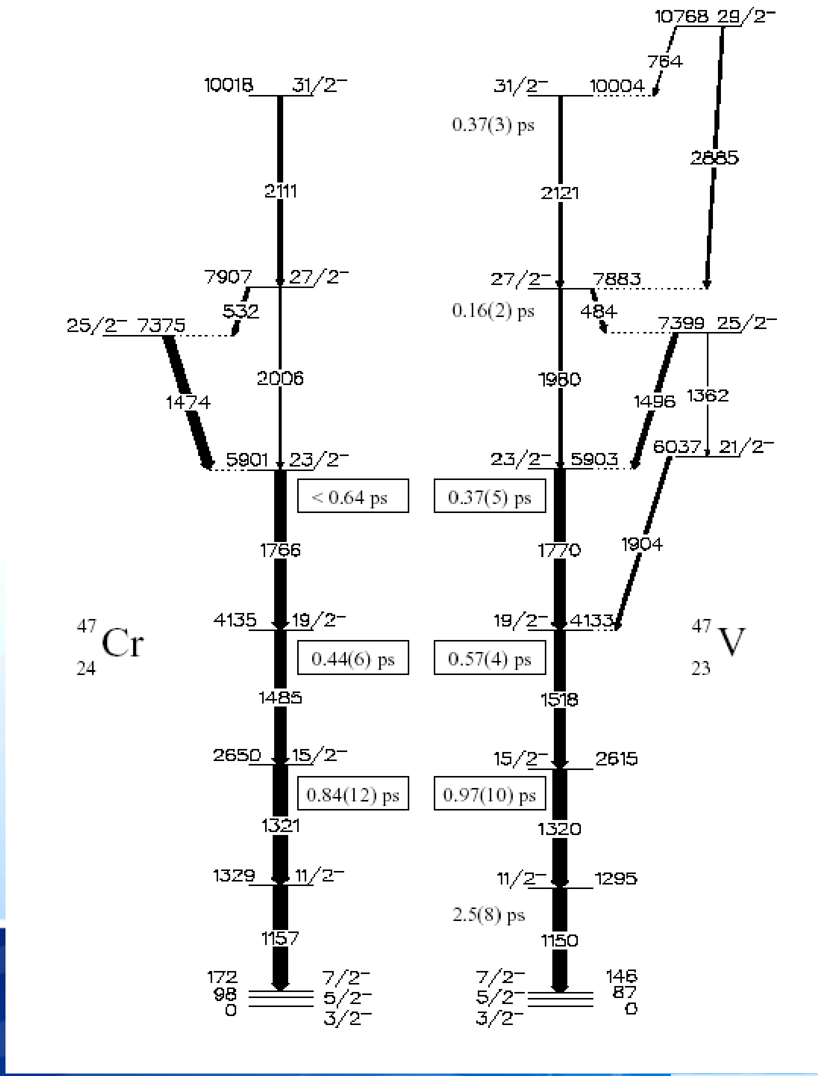
Reaction channel selection



D. Tonev et. al., Phys. Rev. C 65 (2002) 034314.

fppt.com

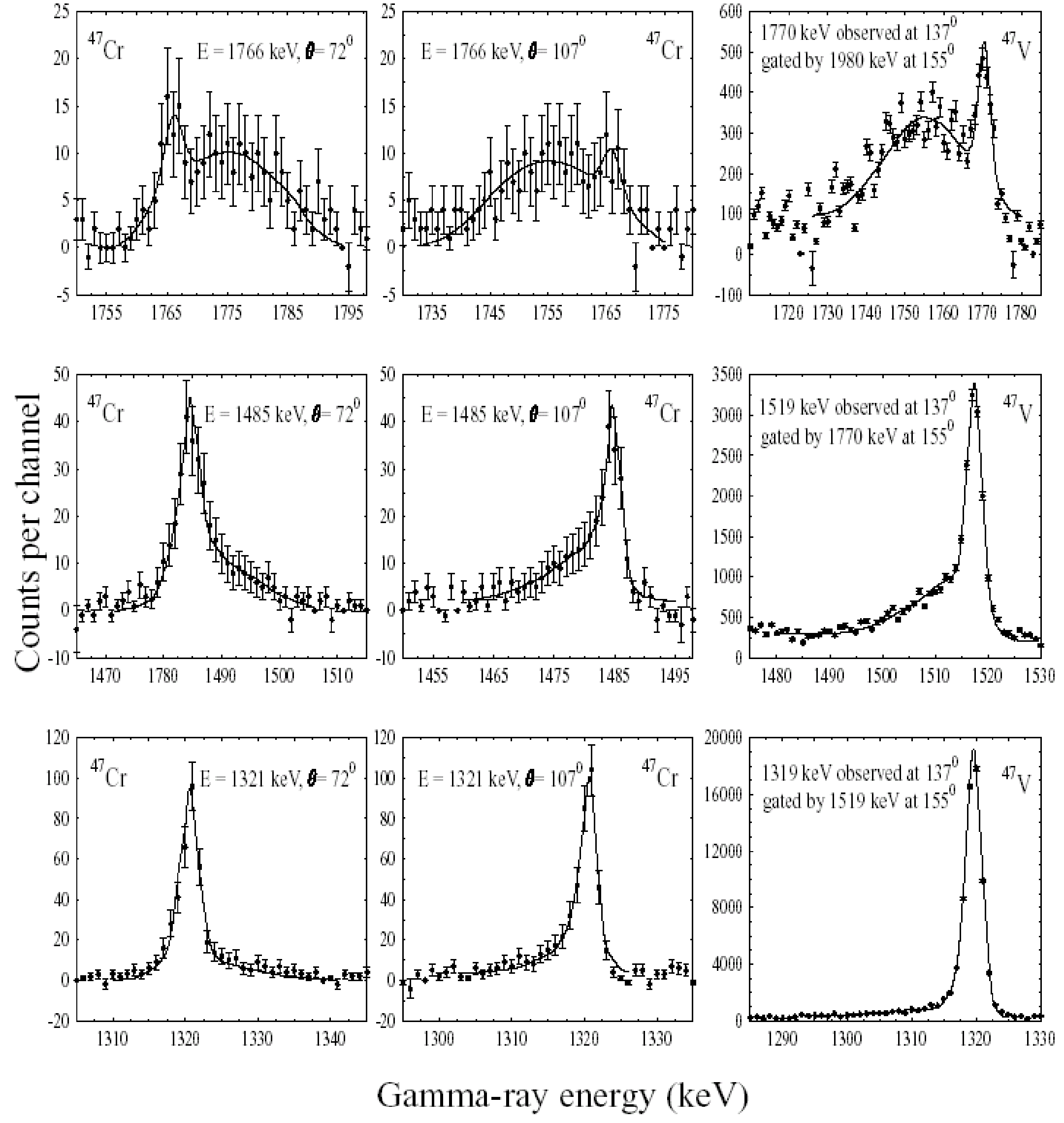
Partial level scheme of the mirror nuclei with determined lifetime



D. Tonev et. al., Phys. Rev. C 65 (2002) 034314.

fppt.com

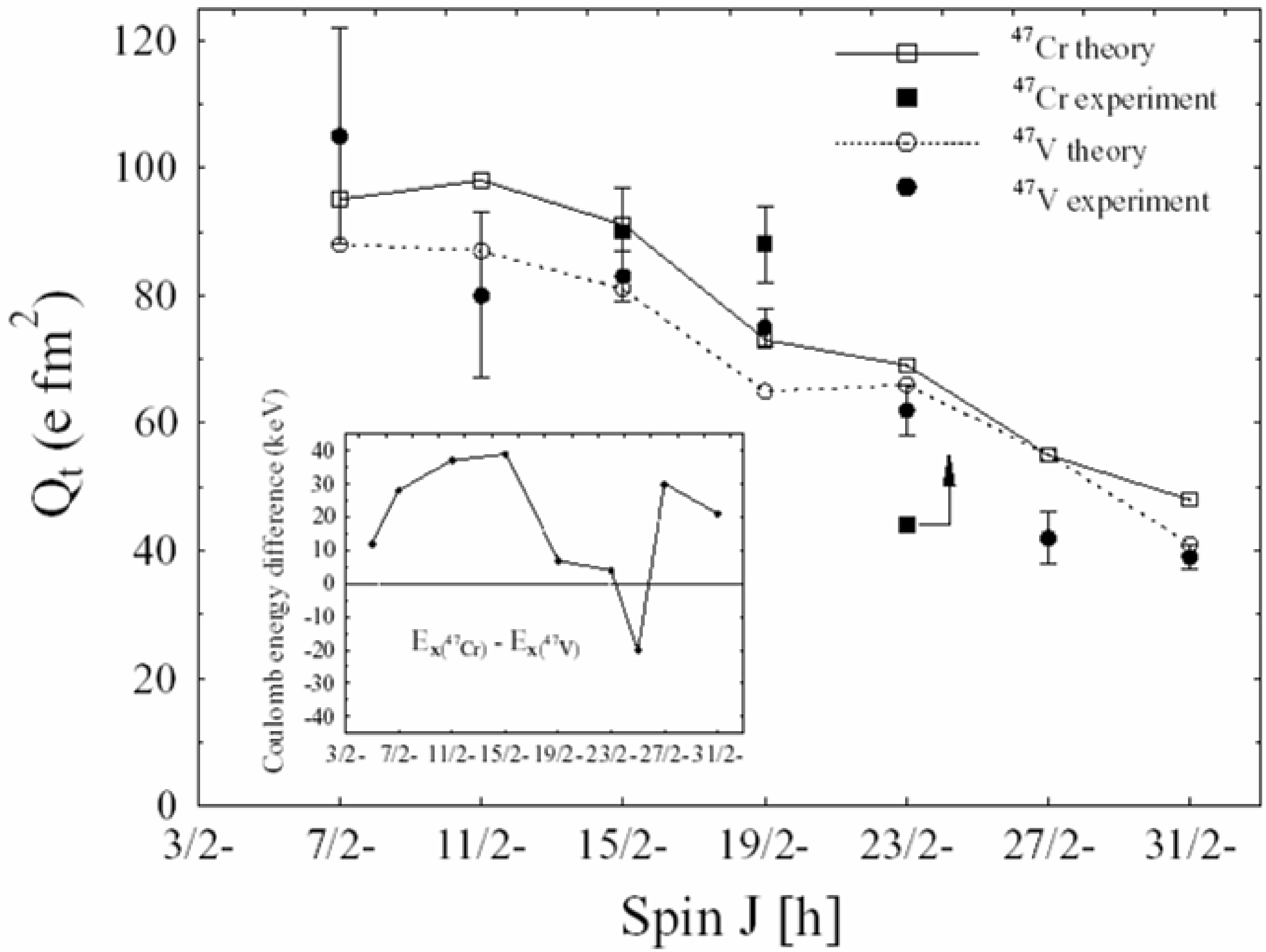
Fits of the lineshapes



D. Tonev et. al., Phys. Rev. C 65 (2002) 034314.

fppt.com

Qt values



D. Tonev et. al., Phys. Rev. C 65 (2002) 034314.

fppt.com

Comparison with theoretical predictions

- The behaviour of Qt values are compared with the predictions reported by G. Martines-Pinedo, A. P. Zuker, A. Poves, and E. Caurier, ”Full *pf* shell study of *A*=47 and *A*=49 nuclei”, Phys. Rev. C 55, 187 (1997).

- The behaviour of the Qt determined in the present DSAM experiment in ^{47}V show systematic decrease with increasing spin. The data for ^{47}Cr are less conclusive, but they exclude the increase of Qt’s.

- Our Qt values characterize levels at which substantial changes in Coulomb Energy Difference (CED) occur.

- The effect is explained by M. Bentley in Phys. Lett. B 437, 243 (1998) as an evidence for changes in the underlying nuclear structure and the nuclear shape. The effect is explained by an alignment of a pair of protons in ^{47}Cr around spin $19/2^-$, which leads to a reduction of their spatial correlations and thus of the Coulomb energy. This energy is not affected in ^{47}V where two neurons align.

fppt.com

Conclusions:

- First determination of subpicosecond lifetimes of high-spin states in mirror nuclei from the 1 $f_{7/2}$ shell.
- The presented lifetimes in ^{47}Cr are determined for the first.
- Agreement between experimental and calculated shell model values of transition probabilities.
- The behaviour of transition quadrupole moments Q_t's with spin may be is associated with the nuclear structure changes inferred earlier by observation of the trend of the Coulomb energy differences (CED).
- Proofs for symmetry in the transition probabilities in the mirror nuclei ^{47}Cr and ^{47}V.
- The first practical application of the new method for lifetime determination using coincidence DSAM data.

fppt.com

Electromagnetic transitions and the Isospin

Electromagnetic operators have an Isovector part and an Isoscalar part:
$M(\sigma L) = M^{(1)}(\sigma L) + M^{(0)}(\sigma L)$
The matrix elements of the two parts combine with opposite sign in mirror nuclei:
$\langle a, T, -T_3 | M(\sigma L) | b, T, -T_3 \rangle = (-1)^{K+2T_3} \langle a, T, T_3 | M(\sigma L) | b, T, T_3 \rangle$

In the long-wavelength limit, the isoscalar part of M(E1) vanishes.
As a consequence, at this limit:

(1) In nuclei with N=Z, E1 transitions with $\Delta T=0$ are forbidden

(2) In mirror nuclei, analogue E1 transitions have equal strength

$<10^{-6}$ W.u.

Both rules are to some extent violated:

Due to the small isoscalar term $M^{(0)}(E1)$, no longer zero outside the limit $kR \to 0$

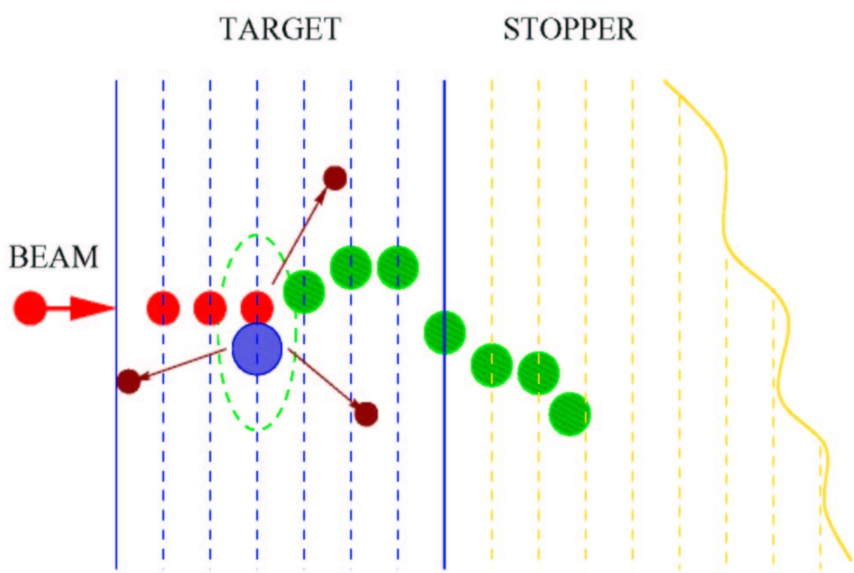
Owing to the effect of Coulomb interactions on the level wavefunctions

The isoscalar part is hindered (~1/10) with respect to the vector part:

In all M1 transition amplitudes

In ML single-particle amplitudes with $\Delta j = L$

Lifetime experiment: Doppler-shift attenuation method

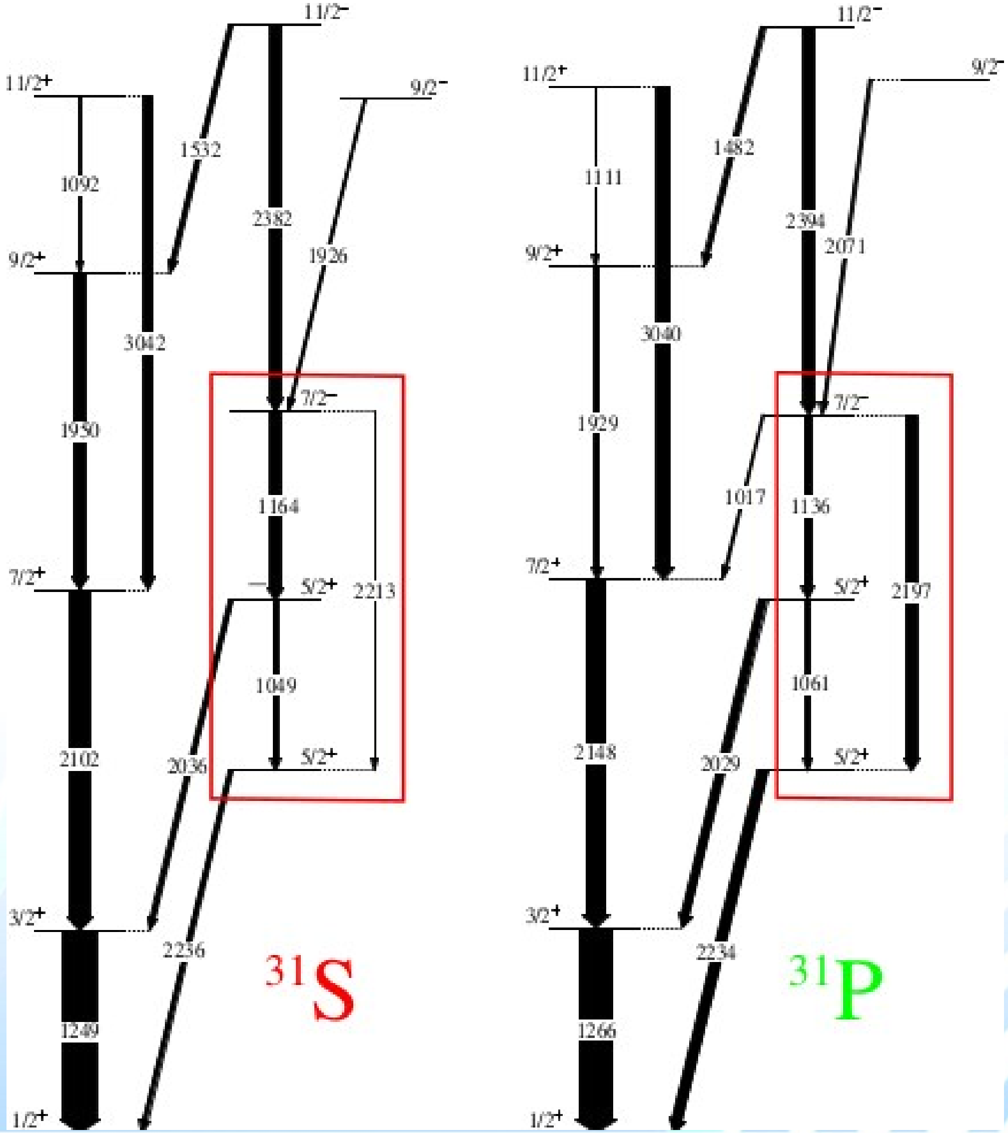


Details:

- GASP spectrometer, LNL
- Reaction channels of interest: $^{20}Ne(^{12}C,1n)^{31}S$; $^{20}Ne(^{12}C,1p)^{31}P$
- ^{20}Ne beam has been provided for the first time with Piave-Alpi accelerator with an energy of 33 MeV
- Target: 0.75 mg/cm^2 ^{12}C onto a 8.0 mg/cm^2 Au backing
- 5 days measurement
- v/c ~ 2.8 %
- Beam intensity 9 pnA
- Euclides charged particle detector
- Gate on the shifted part of the feeding transition
- Stopping Powers are precisely checked

fppt.com

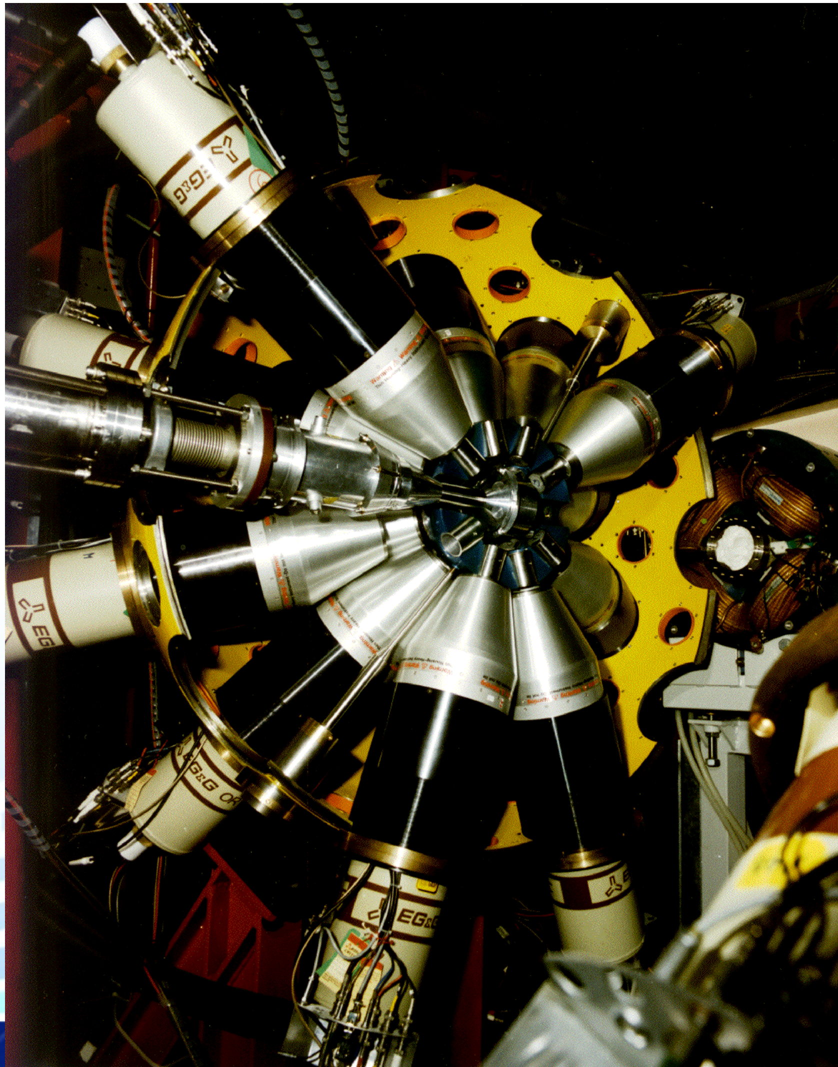
Partial level schemes of A=31 mirror couple



Partial level scheme of ^{31}P and ^{31}S from the work of D.G. Jenkins et al.. PRC 72 (2005) 031303(R). The different pattern of the decay of the $7/2_1^-$ states in the mirror couple is clearly seen (levels surrounded by rectangles).

fppt.com

Angular correlation analysis



GASP Spectrometer

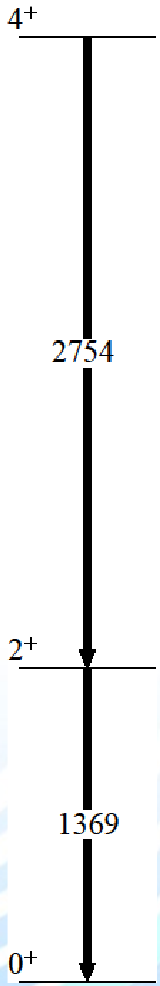
Details:

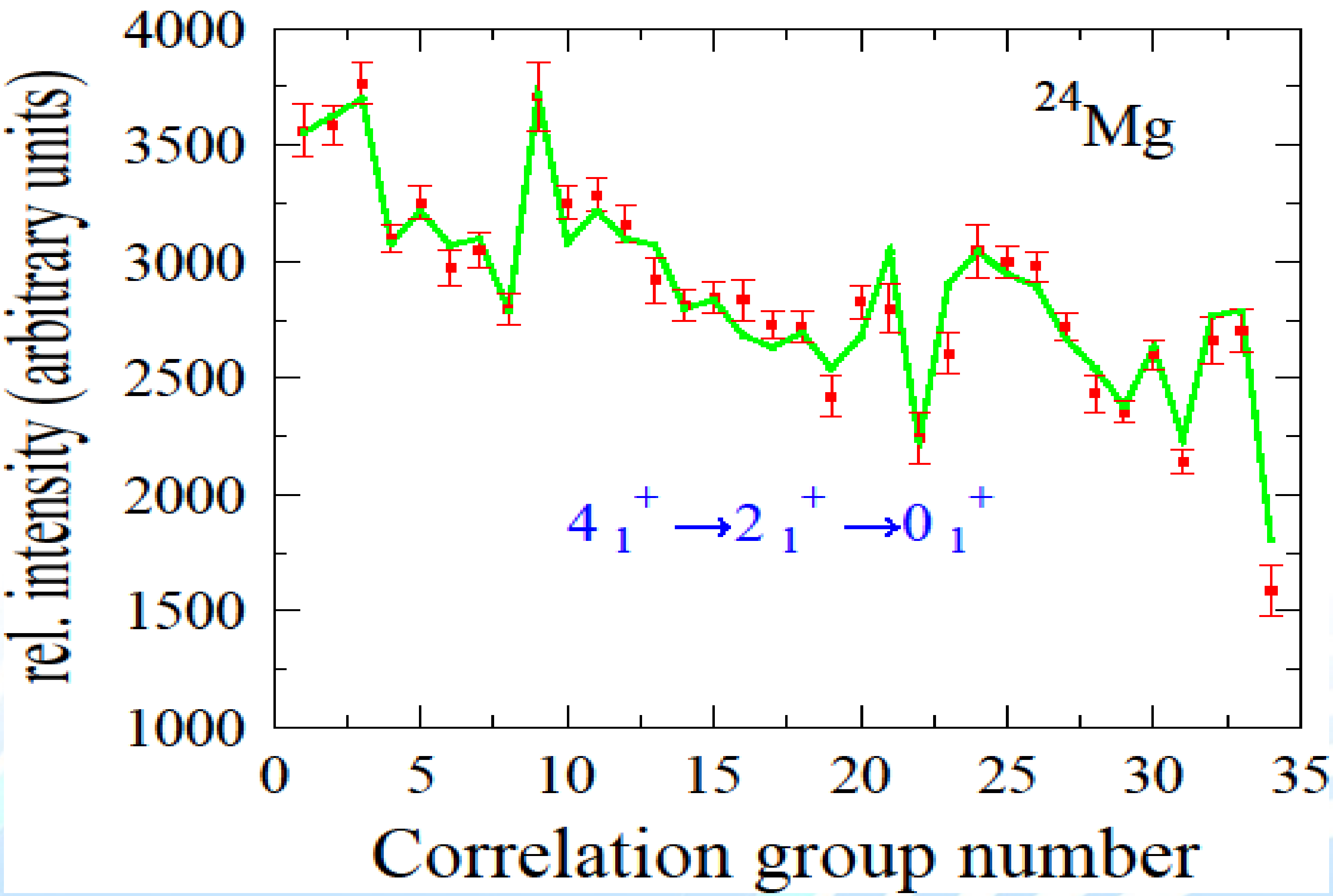
- Detectors of GASP spectrometer are grouped in 34 correlation groups
- The symmetries of the coincident radiation event of the gamma-rays lead to symmetries of the function $W(\theta_{1,}\theta_{2,}\phi)$
- They can be used to establish independent angular correlations groups for a given setup
- For a given spin hypothesis, the data analysis consists of fitting the intensity of the cascade by adjusting the parameter σ characterizing the distributions of the magnetic sub-states *m* of the spin of the first oriented level and $\delta 1$ and $\delta 2$ of the two successive transitions.

I. Wiedenhover et al., PRC **58**(1998) 721.

fppt.com

Angular correlation analysis for an E2-E2 cascade in ^{24}Mg

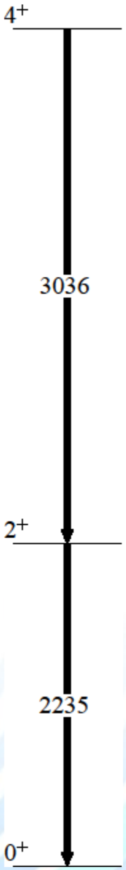


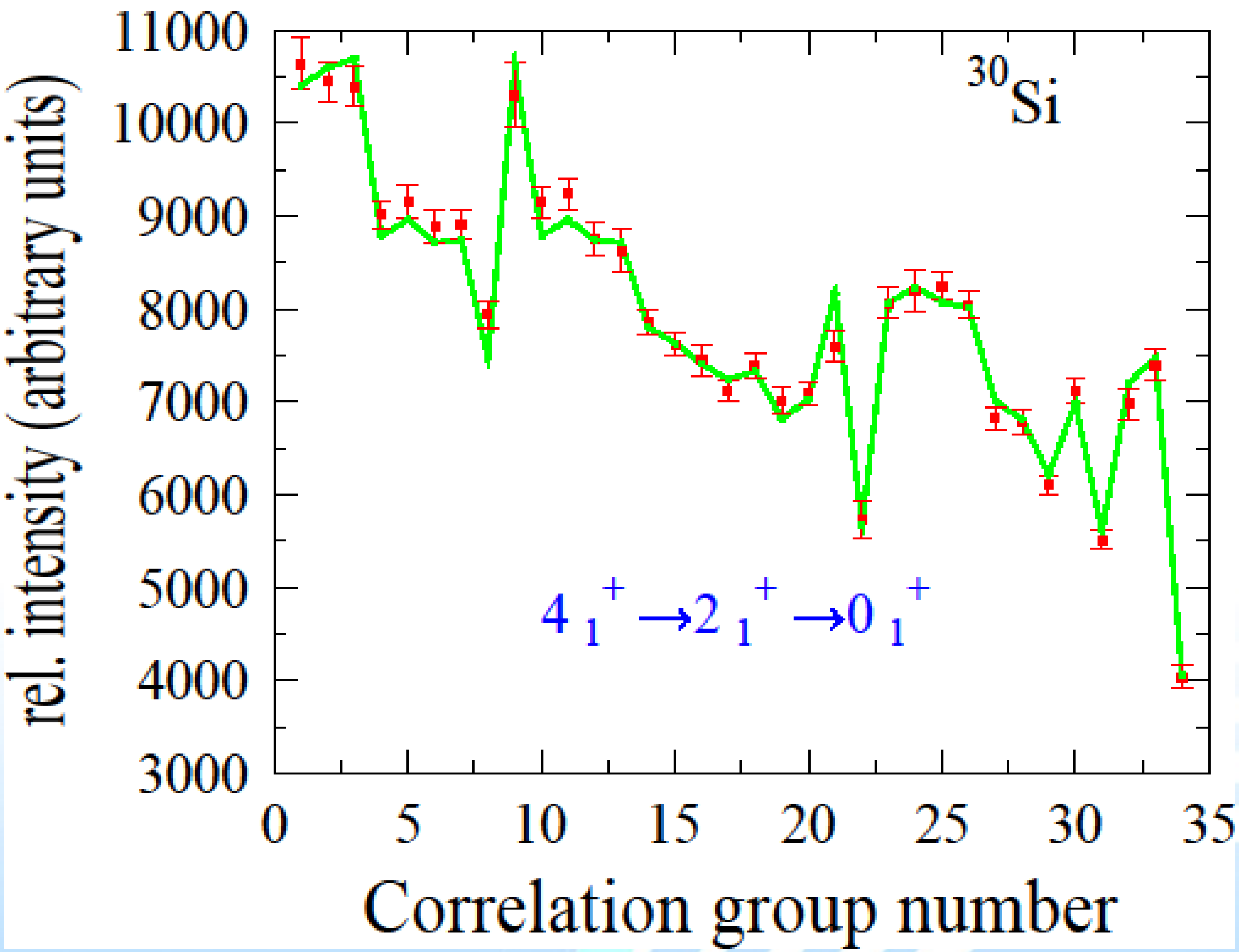


Analysis performed with the program ***CORLEONE****, by I. Wiedenfover*

fppt.com

Angular correlation analysis for an E2-E2 cascade in ^{30}Si

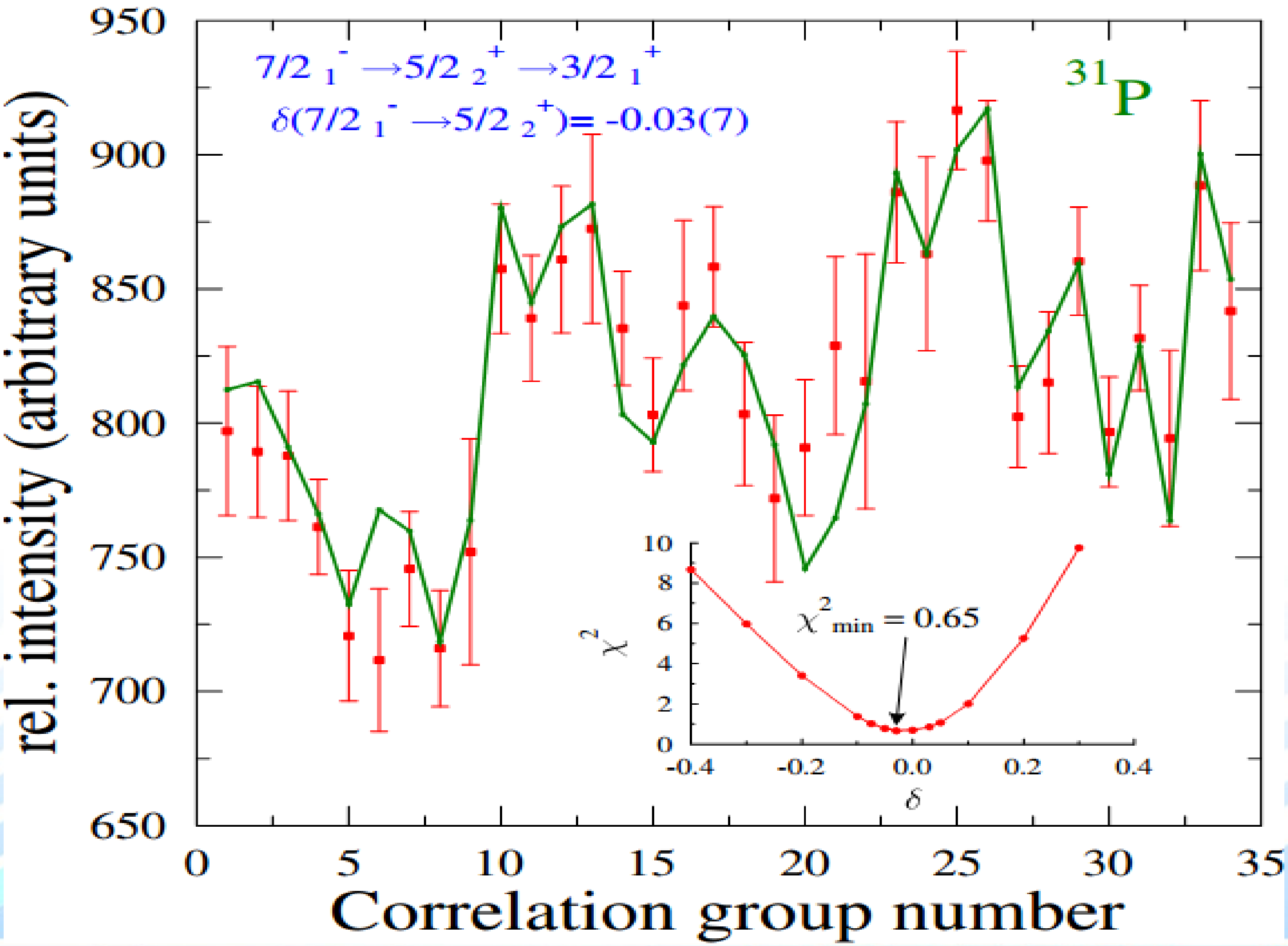




Analysis performed with the program ***CORLEONE****, by I. Wiedenfover*

fppt.com

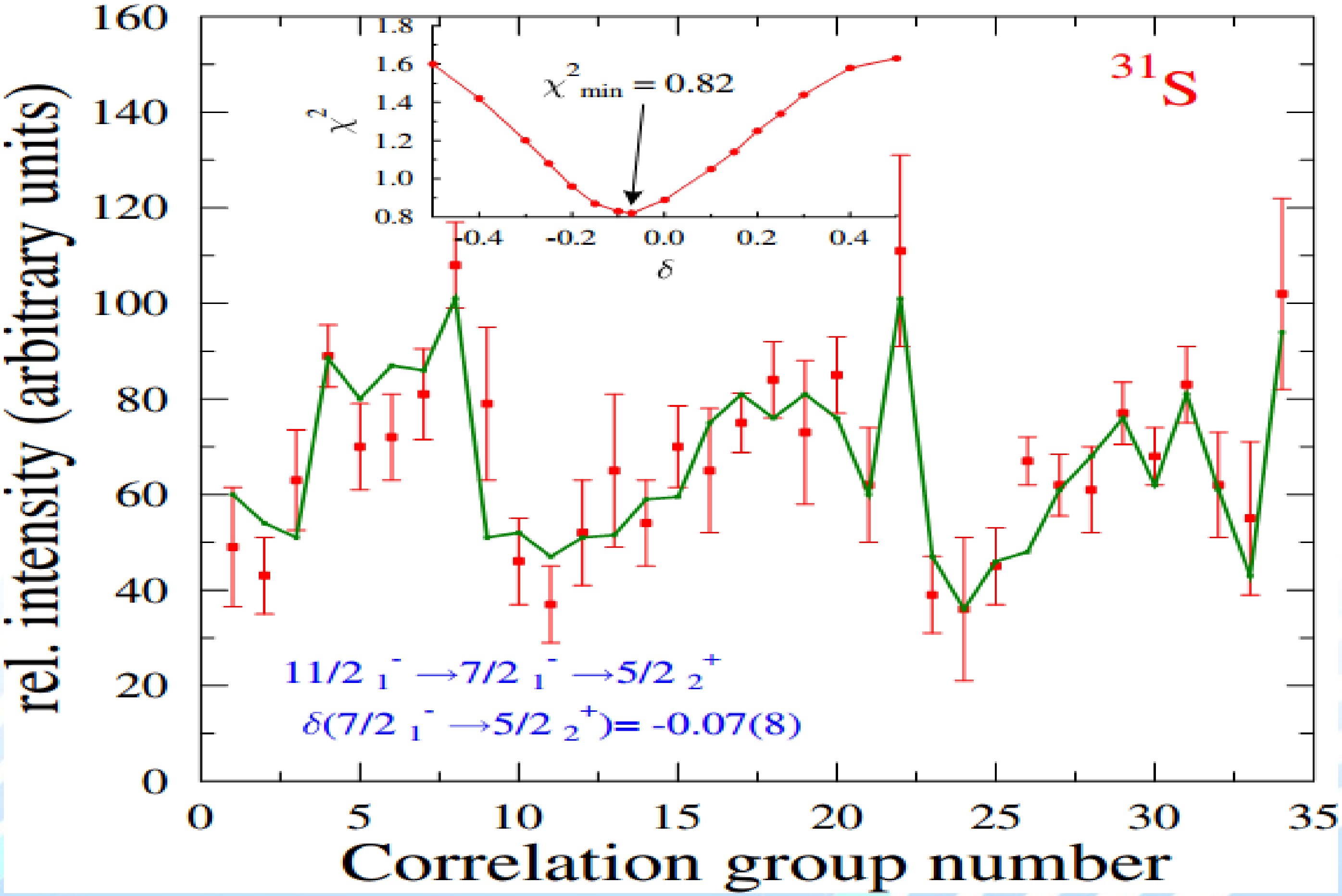
Angular correlation analysis for the cascade in interest in ^{31}P



Angular correlation pattern for the cascade involving $7/2_1^- \rightarrow 5/2_2^+ \rightarrow 3/2_1^+$ transitions of ^{31}P.

fppt.com

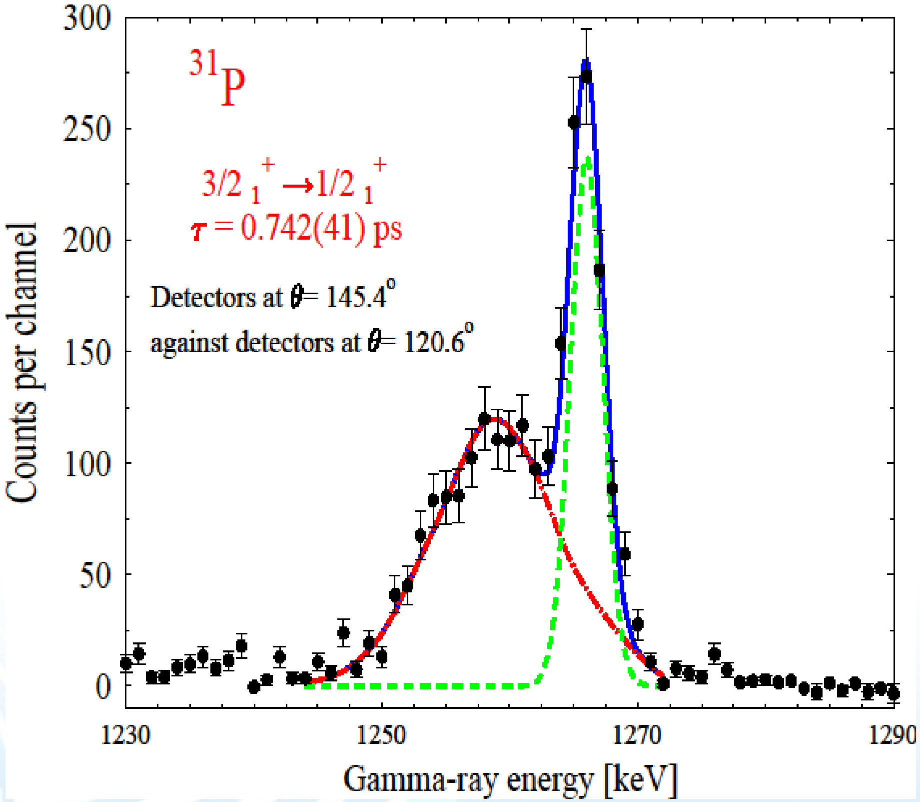
Angular correlation analysis for the cascade in interest in ^{31}S

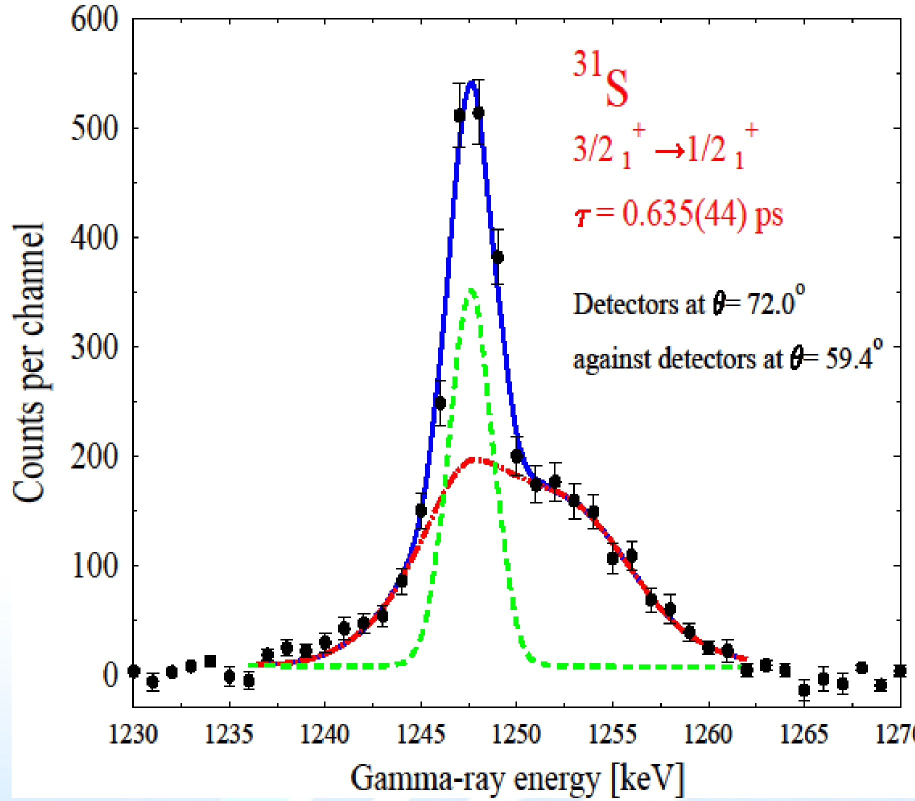


Angular correlation pattern for the cascade involving $11/2_1^- \rightarrow 7/2_1^- \rightarrow 5/2_2^+$ transitions of ^{31}S.

fppt.com

Line shape analysis of the $3/2_1^+ \rightarrow 1/2_1^+$ transitions of the analogue transitions in the mirror couple ^{31}P and ^{31}S, according to DDCM.



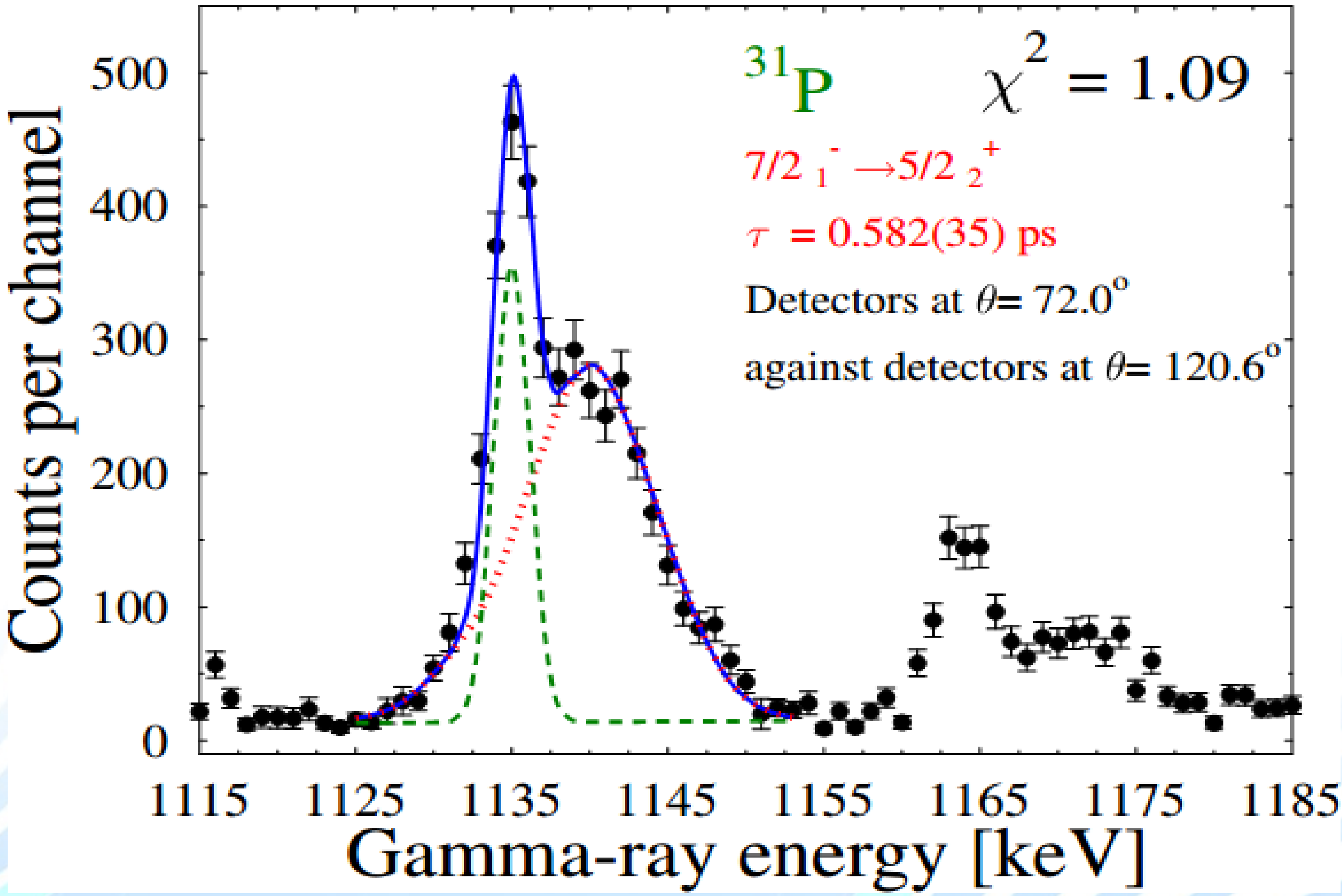


P.M. Endt, Nucl Phys. A 633, 1, 1998
Previously measured τ = 0.745 (35) ps
Our result: 0.736 (24) ps

R.Engmann et al., Nucl Phys. A 162, 295, 1971
Previously measured τ = 0.720 (180) ps
Our result: 0.624 (24) ps

D. Tonev, G. de Angelis, I. Deloncle, N. Goutev, G. De Gregorio, et. al., Phys. Lett. B 821 (2021) 136603.

Line shape analysis of the $7/2_1^- \rightarrow 5/2_2^+$ transitions of the analogue transitions in the mirror couple ^{31}P, according to DDCM.



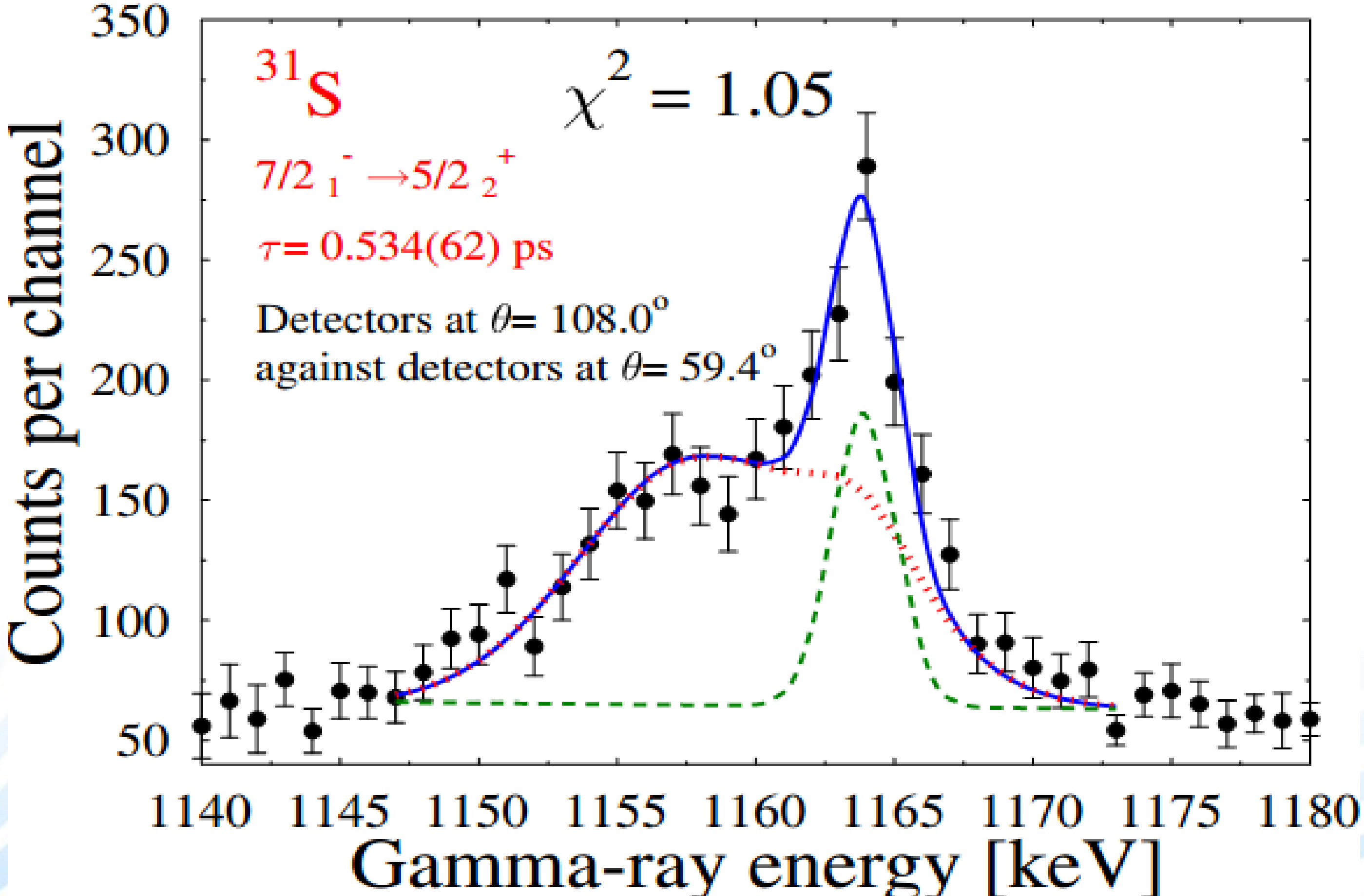
P.M. Endt, Nucl Phys. A 633, 1, 1998

Previously measured $\tau = 0.600\ (100)$ ps

Our result: 0.597(26) ps

D. Tonev, G. de Angelis, I. Deloncle, N. Goutev, G. De Gregorio, et. al., Phys. Lett. B 821 (2021) 136603.

Line shape analysis of the $7/2_1^- \rightarrow 5/2_2^+$ transitions of the analogue transitions in the mirror couple ^{31}P and ^{31}S, according to DDCM.



N.S. Pattabiraman, Phys. Rev. C 78, 024301, 2008

Previously measured ^{31}S τ = 1.030 (210) ps

Our result for ^{31}S is: τ = 0.543(49) ps

The result for ^{31}P is: τ = 0.597(45) ps

D. Tonev, G. de Angelis, I. Deloncle, N. Goutev, G. De Gregorio, et. al., Phys. Lett. B 821 (2021) 136603.

Violation of the E1 symmetry rule in A=31 mirror couple?

^{31}P

$\tau = 0.597\ (45)$ ps

$7/2_1^- \rightarrow 5/2_2^+$: B(E1) = 2.7(2) x 10^{-4} e^2fm^2

$7/2_1^- \rightarrow 5/2_1^+$: B(E1) = 0.58(4) x 10^{-4} e^2fm^2

^{31}S

$\tau = 0.543\ (49)$ ps

$7/2_1^- \rightarrow 5/2_2^+$: B(E1) = 7.2(7) x 10^{-4} e^2fm^2

$7/2_1^- \rightarrow 5/2_1^+$: B(E1) = $<2.2(4)$ x 10^{-4} e^2fm^2

IS/IV ~ 0.24

fppt.com

Theoretical calculations

- The behaviour of B(E1) we try to describe within the Equation of Motion Phonon Model (EMPM), which generates an orthonormal basis of multiphonon states whose constituents are the Tamm-Dankoff Approximation phonons.

- The method does not rely on any approximation and takes into full account the Pauli principle. A self consistent calculation was performed using a Hamiltonian composed on an intrinsic kinetic operator and the chiral potential NNLOsat, which includes the contribution of the three body forces.

- The calculated B(E1) strengths are in excellent agreement for two mirror transitions $7/2_1^- \rightarrow 5/2_2^+$ and in reasonable accordance (the same order of magnitude) for 7/21- → 5/21+.

- Calculations have been performed by G. de Gregorio, Naples University.

fppt.com

Violation of the E1 symmetry rule in A=31 mirror couple?

^{31}P

$\tau = 0.597\ (45)$ ps

$7/2_1^- \rightarrow 5/2_2^+$: B(E1) = 2.7(2) x $10^{-4}\ e^2fm^2$

$7/2_1^- \rightarrow 5/2_1^+$: B(E1)th = 2.2 x $10^{-4}\ e^2fm^2$

$7/2_1^- \rightarrow 5/2_2^+$: B(E1) = 0.58(4) x $10^{-4}\ e^2fm^2$

$7/2_1^- \rightarrow 5/2_1^+$: B(E1)th = 2.4 x $10^{-4}\ e^2fm^2$

^{31}S

$\tau = 0.543\ (49)$ ps

$7/2_1^- \rightarrow 5/2_2^+$: B(E1) = 7.2(7) x $10^{-4}\ e^2fm^2$

$7/2_1^- \rightarrow 5/2_2^+$: B(E1)th = 7.9 x $10^{-4}\ e^2fm^2$

$7/2_1^- \rightarrow 5/2_1^+$: B(E1) = <2.2(4) x $10^{-4}\ e^2fm^2$

$7/2_1^- \rightarrow 5/2_1^+$: B(E1)th = 6.9 x $10^{-4}\ e^2fm^2$

IS/IV ~ 0.24

IS/IVth ~0.27

fppt.com

Coherent enhancement

- Contribution from mixing with higher lying states are, individually, even smaller. Their combined effect, however, can be large if each one of the mixing matrix element is, to some extent, coherent in phase with the E1 amplitude involving the same level. Most of the contribution to the mixing can, therefore, be associated to the isovector giant monopole resonance built over the state considered.

- The good agreement of our theoretical approach with the experimental data confirms that. The breaking of the isospin symmetry originates from the violation of the charge symmetry of the two- and three-body parts of the chiral potential adopted, which includes the Coulomb interaction. This isospin violation terms yield assymetric wavefunctions and, therefore, asymmetric B(E1) for ^{31}S and ^{31}P.

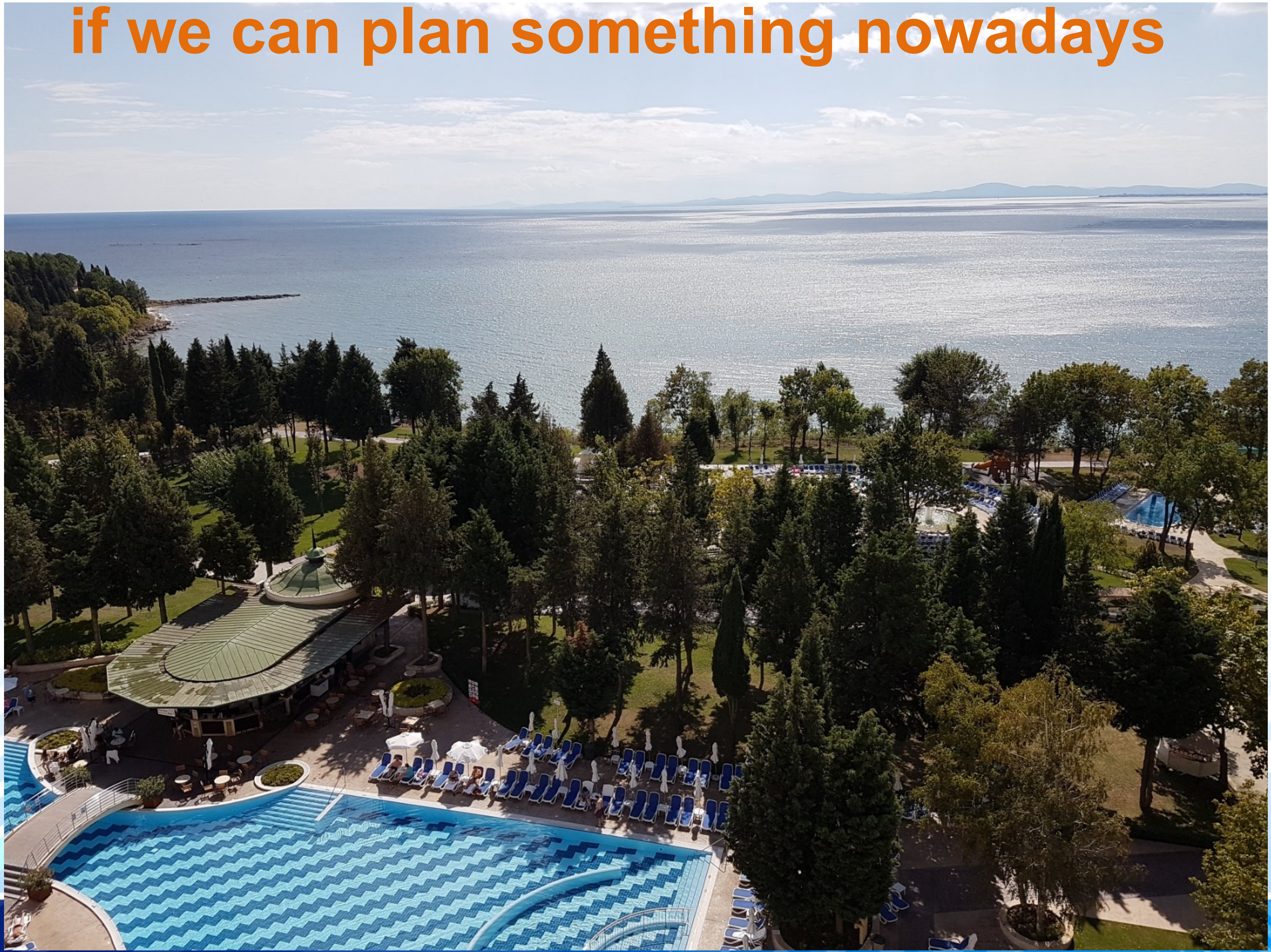
fppt.com

Conclusions:

- DSAM lifetimes experiments were performed at the LNL with Piave-Alpi accelerator using GASP spectrometer (Configuration II).
- Using advanced methods for lifetime analysis 4 lifetimes in the both mirror nuclei ^{31}P and ^{31}S are determined.
- Angular correlation analysis were performed in order to investigate multiple mining ratios of the candidate E1 transitions.
- The difference between the B(E1) values of the analogue transitions in A=31 mirror couple is an indication for a violation of the E1 symmetry rule.
- The behaviour of B(E1) we try to describe within the Equation of Motion Phonon Model.

fppt.com

An invitation for Varna school in September 2025, if we can plan something nowadays



Thank you very much!!!

fppt.com

$\gamma\gamma$ Angular correlation analysis

$$W(\theta_1, \theta_2, \phi) = \sum_{\lambda_1, \lambda, \lambda_2} B_{\lambda_1}(I_1) A_{\lambda}^{\lambda_1 \lambda_2}(\gamma_1) A_{\lambda_2}(\gamma_2) H_{\lambda_1, \lambda, \lambda_2}(\theta_1, \theta_2, \phi)$$

where

$$H_{\lambda_1, \lambda, \lambda_2} = \frac{4\pi}{2\lambda_2+1} \sum_{q=-\lambda'}^{q=\lambda'} \langle \lambda_1 0 \lambda q | \lambda_2 q \rangle Y_{\lambda q}(\theta_1 \phi) Y^{*}_{\lambda_2 q}(\theta_2 \phi),$$

$$\lambda' = min(\lambda, \lambda_2)$$

The detector effciency is fitted with five parameter function

$$\epsilon(E_\gamma) = A * (E_\gamma - C + D * e^{-E * E_\gamma})^B$$

fppt.com

Induced isoscalar term

What can give rise to *a* non-zero isoscalar term?

- Including terms neglected in the long-wavelength (Siegert) approximation
  - Higher *powers* of kR, from *the* series expansion of $j_1(kR)$
  - Magnetic terms

However only VERY SMALL effects

IS/IV ~ 10-^{4}

A=67 mirror couple

$^{67}Se_{33}$ and $^{67}As_{34}$

Two pairs of analogue $9/2^+ \rightarrow 7/2^-$ transitions

$\tau(^{67}Se) = 1.5(6)$ ns; $\tau(^{67}As) = 0.7(2)$ ns

IS/IV = 0.35(20)

R. Orlandi, G. de Angelis, P.G. Bizzetti et. al., Phys. Rev Lett. 103 (2009) 052501.

fppt.com

Why a new interest for Isospin?

- New experimental results on nuclei with Z >N
- Shell model codes for model spaces as large as the full f-p shell

Relevant observables:

Coulomb Energy Differences in Isospin Multiplets:

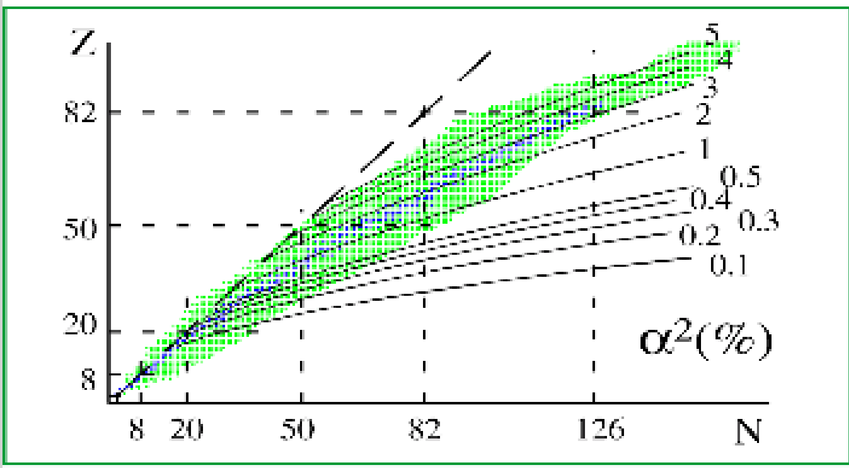
A sort of microscope to evidence tiny effects in nuclear structure

Electromagnetic strengths of “analogue” transitions:

Possible signature of Isospin mixing

Estimated isospin mixing via the IVGMR

G. Colò et al., Phys. Rev. C 52, R1175 (1995)



α^2 in the ground state of even-even N=Z nuclei

$$\alpha^2 = \frac{1}{2}\langle Z = N \mid T_{-}T_{+} \mid Z = N \rangle$$

Isospin mixing increases for N=Z nuclei.