

Sub-barrier transfer reactions and the nuclear Josephson effect

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Josephson effect

- recall of main concepts
- the proposed effect in nuclear physics

Sub-barrier transfer

- nucleon-nucleon correlations
- the challenging experimental needs

Data analysis

- the PRISMA-AGATA experiment
- the data analysis and interpretation

Int. ws on Many-body correlations, phase transitions and clustering: how to identify and quantify them?
CEA Saclay, Sept. 7-11, 2026

EXPERIMENT

G. Andreetta (INFN-LNL), L. Corradi (INFN-LNL), S. Szilner (RBI, Zagreb)
and Prisma+Agata collaboration

THEORY

F. Barranco (Univ. Seville), R. A. Broglia (NBI Copenhagen and Univ. Milano),
G. Potel (Univ. Seville), E. Vigezzi (Univ. Milano and INFN)

The pairing interaction: a micro-primer

The pairing interaction leads to the formation of:

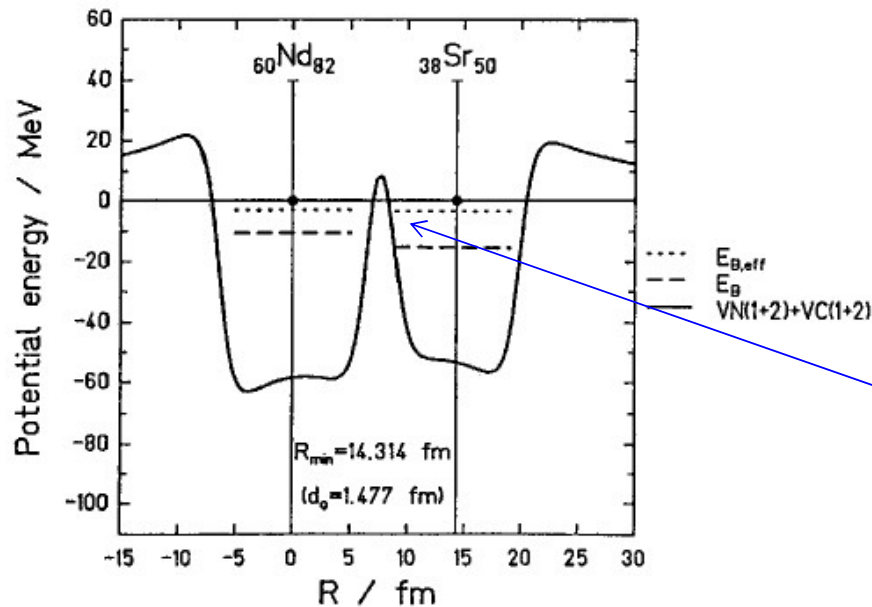
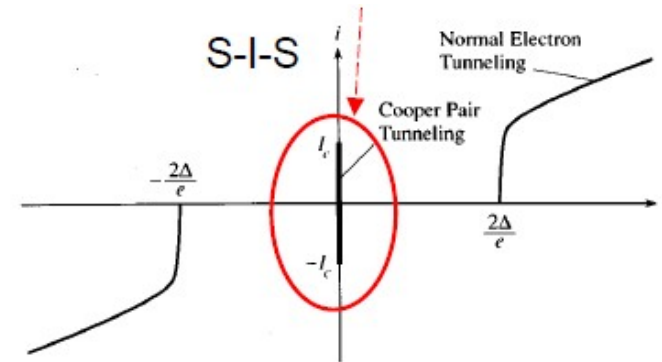
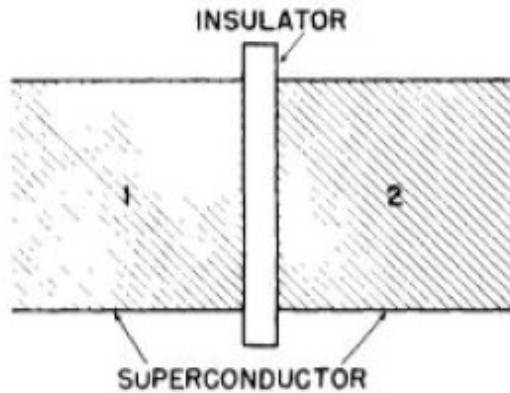
- the pairing gap Δ and corresponding modifications of the Fermi surface (BCS)
- Cooper pairs and associated outstanding phenomena of superconductivity

Main well known effects in nuclei:

- structure of low lying states (excitation energy levels in even-even nuclei)
- odd-even mass differences (binding energies)
- moment of inertia in open shell nuclei (different from that of a rigid body)
- enhanced cross sections in two nucleon transfer reactions
- mass distributions in fission reactions

Transfer reactions (especially two-nucleon transfer) are recognized to be (one of) the best tools to probe pairing correlations

Nuclear pair transfer viewed as Cooper pairs flow through a barrier



schematically, nucleon pairs play the role of electron Cooper pairs (bosons) tunnelling between superconductors through an isolator (represented by the barrier)

the tunnelling occurs through the inner potential barrier formed during the interaction

Nuclear Josephson effect

Theory – developed
mainly in the '70

Experiments – developed mainly in the '80,
with the advent of heavy ion accelerators
and related instrumentation

Theory – recent revival due to
advances in calculations

Experiments – major breakthrough due to the
development of large solid angle magnetic
spectrometers and large gamma arrays

K. Dietrich, Phys. Lett. B32(1970)428

K. Dietrich, Ann. of Physics 66(1971)480

K. Hara, Phys. Lett. B35(1971)198

M. Kleber and H. Schmidt, Z. Phys. 245(1971)68

R. A. Broglia et al., Phys. Lett. B73(1978)401

H. Weiss, Phys. Rev. C19(1979)834

[...]

R. Kunkel et al., Phys. Lett. B208(1988)355

R. Kunkel et al., Z. Phys. A336(1990)71

[...]

W. Von Oertzen and A. Vitturi, Rep. Prog. Phys. 64(2001)1247

[...]

G. Potel, F. Barranco, E. Vigezzi and R. A. Broglia,
Phys. Rev. C103(2021)L021601

P. Magierski, Physics 14(2021)27

[...]

PRISMA magnetic spectrometer

AGATA gamma ray spectrometer

when theories were being developed, there were poor experimental tools

when instruments were sufficiently developed, few theorists were working in the field

with the novel instrumentation and reached accuracy in calculations, one can now probe the Josephson effect much more coherently

Quantum entanglement in nuclear Cooper-pair tunneling with γ raysG. Potel ¹, F. Barranco,² E. Vigezzi,³ and R. A. Broglia^{4,5}¹*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*²*Departamento de Física Aplicada III, Escuela Superior de Ingenieros, Universidad de Sevilla, Camino de los Descubrimientos, Sevilla, Spain*³*INFN Sezione di Milano, Via Celoria 16, I-20133 Milano, Italy*⁴*The Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Blegdamsvej 17, Denmark*⁵*Dipartimento di Fisica, Università degli Studi di Milano, Via Celoria 16, I-20133 Milano, Italy*

(Received 13 October 2020; accepted 19 November 2020; published 25 February 2021)

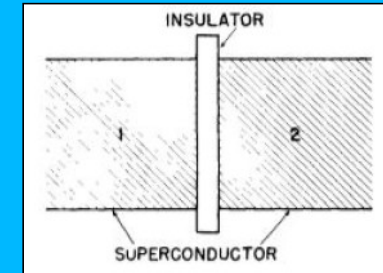
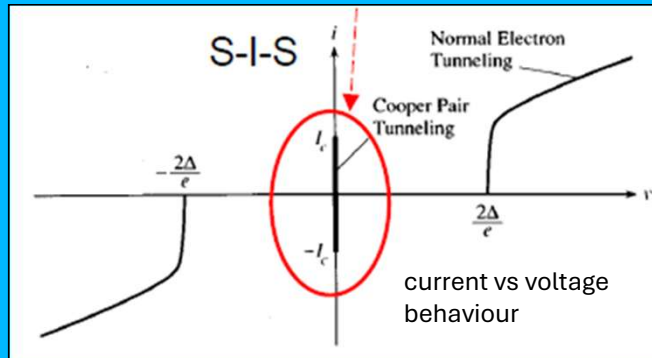
While Josephson-like junctions, transiently established in heavy-ion collisions ($\tau_{\text{coll}} \approx 10^{-21}$ s) between superfluid nuclei—through which Cooper-pair tunneling (Q -value Q_{2n}) proceeds mainly in terms of successive transfer of entangled nucleons—is deprived from the macroscopic aspects of a supercurrent, it displays many of the special effects associated with spontaneous symmetry breaking in gauge space (BCS condensation), which can be studied in terms of individual quantum states and of tunneling of single Cooper pairs. From the results of studies of one- and two-neutron transfer reactions carried out at energies below the Coulomb barrier we estimate the value of the mean-square radius (correlation length) of the nuclear Cooper pair. A quantity related to the largest distance of closest approach for which the absolute two-nucleon tunneling cross section is of the order of the single-particle one. Furthermore, emission of γ rays of (Josephson) frequency $\nu_J = Q_{2n}/h$ distributed over an energy range $\hbar/\tau_{\text{coll}}$ is predicted.

The Josephson effect: main features

DC Josephson

DC current present with a $V = 0$ voltage applied between two superconductors

$$J = J_c \sin 2\phi_{rel} \quad \phi_{rel} = \phi_2 - \phi_1$$

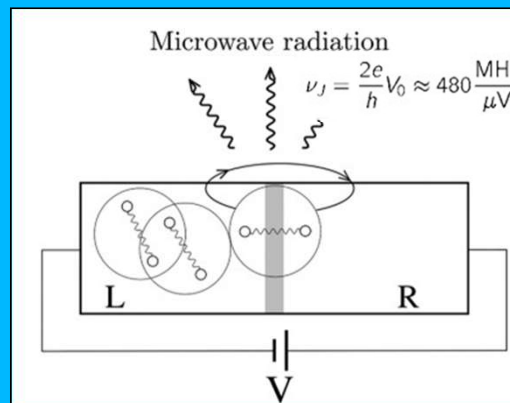


with no applied voltage a direct current flows across the link with a value defined by the relative gauge phase

AC Josephson

with $0 < V < 2\Delta$ (gap), the DC current $I = 0$ but an oscillating current appears, generating electromagnetic waves

$$J = J_c \sin \left(2\phi_{rel}(0) - \left(\frac{2eV}{\hbar} t \right) \right)$$

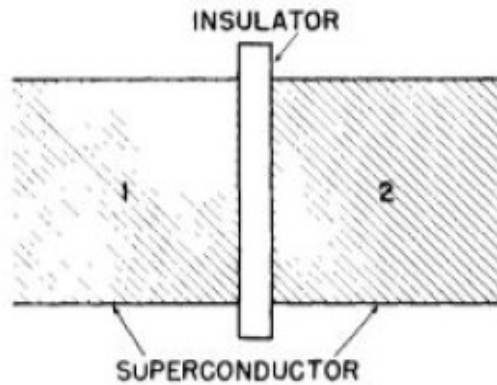


$$\phi_{rel}(t) = \phi_{rel}(0) - \frac{eV}{\hbar} t \quad \omega_J = \frac{2eV}{\hbar}$$

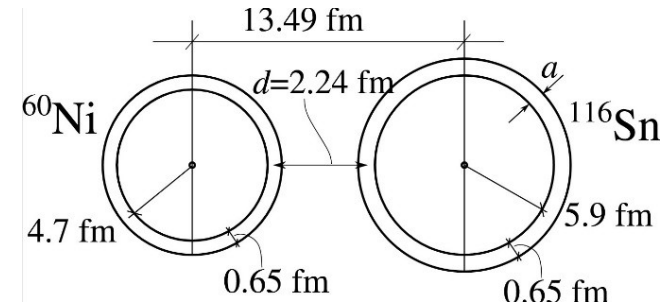
the voltage causes the phase difference across the junction to increase over time. Since phases which differ in 2π are equivalent, a linear phase growth produces an AC current and thus to emission of photons

B. D. Josephson, *The discovery of tunneling supercurrents*,
in Les Prix Nobel en 1973 (P. A. Norstedt and Sner, Stockholm, 1973), p. 104.

from macroscales to femtoscales

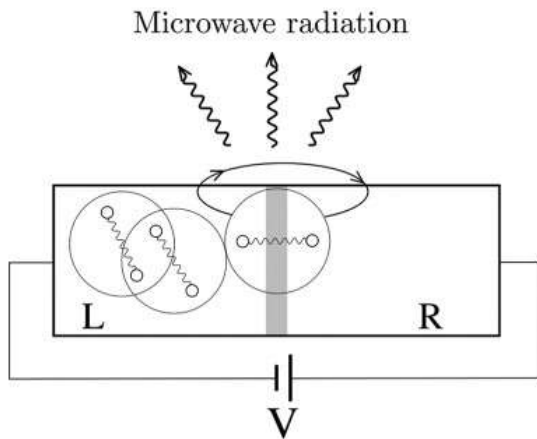


dielectric layer

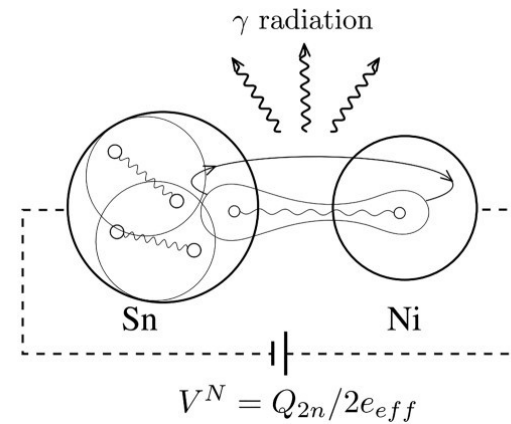


surface-surface distance of nuclei at the distance of closest approach

R. Broglia et al,
Nucl.Phys.News 31,4 (2021)



applied voltage

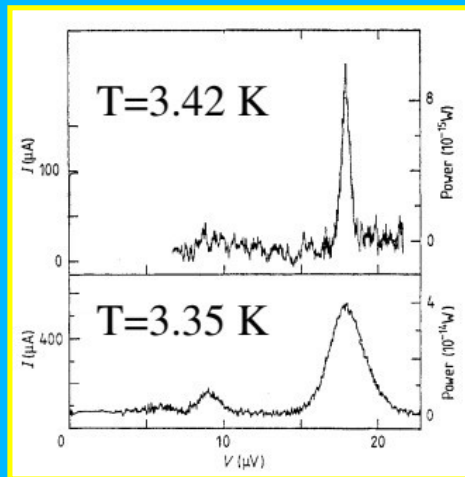


reaction Q-value divided by the effective charge of the tunneling Cooper pair

Possible Josephson-like effect in nuclear physics

$$\nu_J = \frac{2e}{h} V_0 \approx 480 \frac{\text{MHz}}{\mu\text{V}}$$

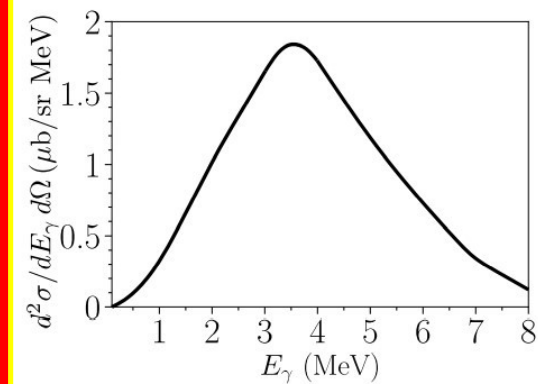
original spectrum obtained in the microwave region that confirms one of the main predictions of the AC Josephson effect



P.E.Lindelof, Rep.Prog.Phys.44:60,1981

The emission of EM waves in the region of MeV gamma rays is predicted. **The physical origin is in the dipole oscillations generated by the oscillating motion of the Cooper pairs between the interacting binary partners**

double differential cross section for γ emission

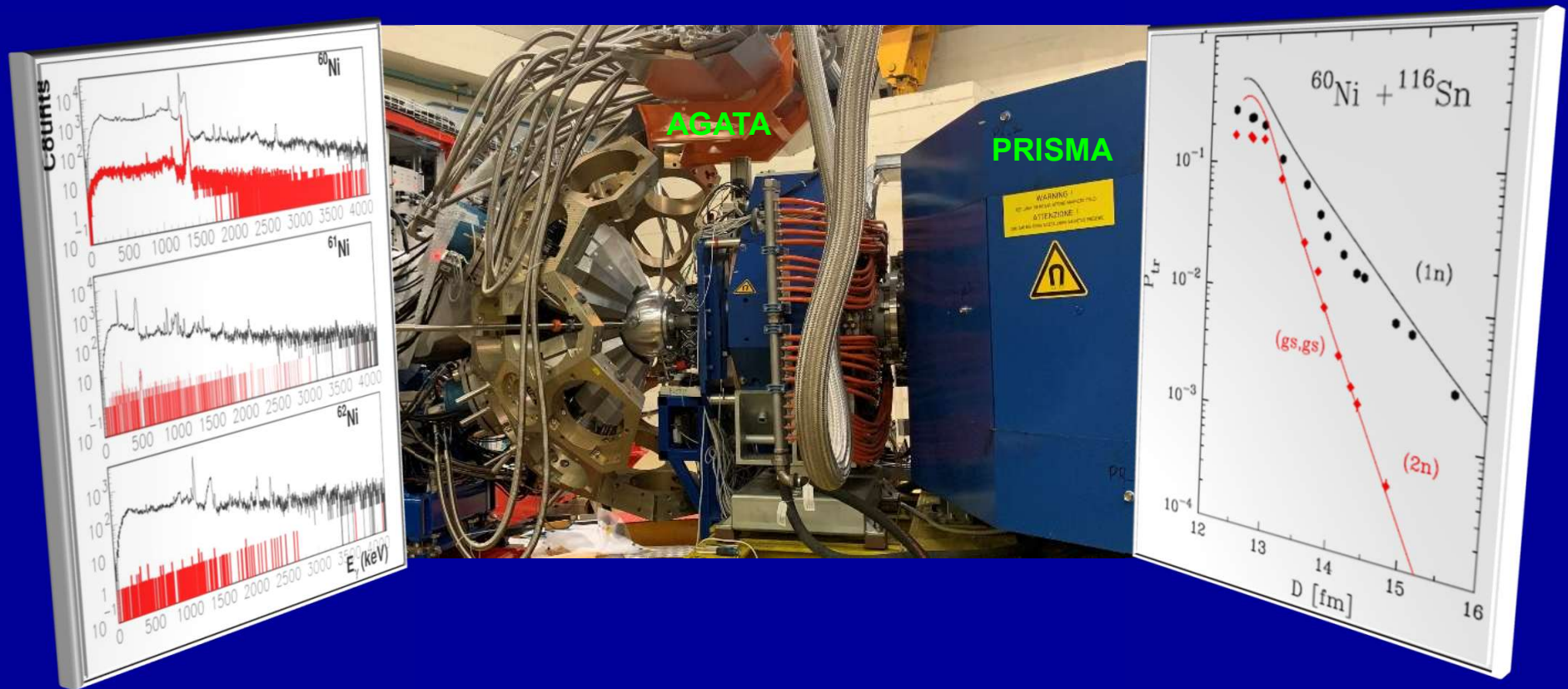


$$\frac{d^2\sigma}{d\Omega dE_\gamma} = \left(\frac{\mu_i \mu_f}{(2\pi\hbar^2)^2} \frac{k_f}{k_i} \right) \left(\frac{8\pi}{3} \frac{E_\gamma^2}{(\hbar c)^3} \right) \times |T_{m_\gamma}(\mathbf{k}_f, \mathbf{k}_i)|^2 \delta(E_\gamma + E_f - (E_i + Q))$$

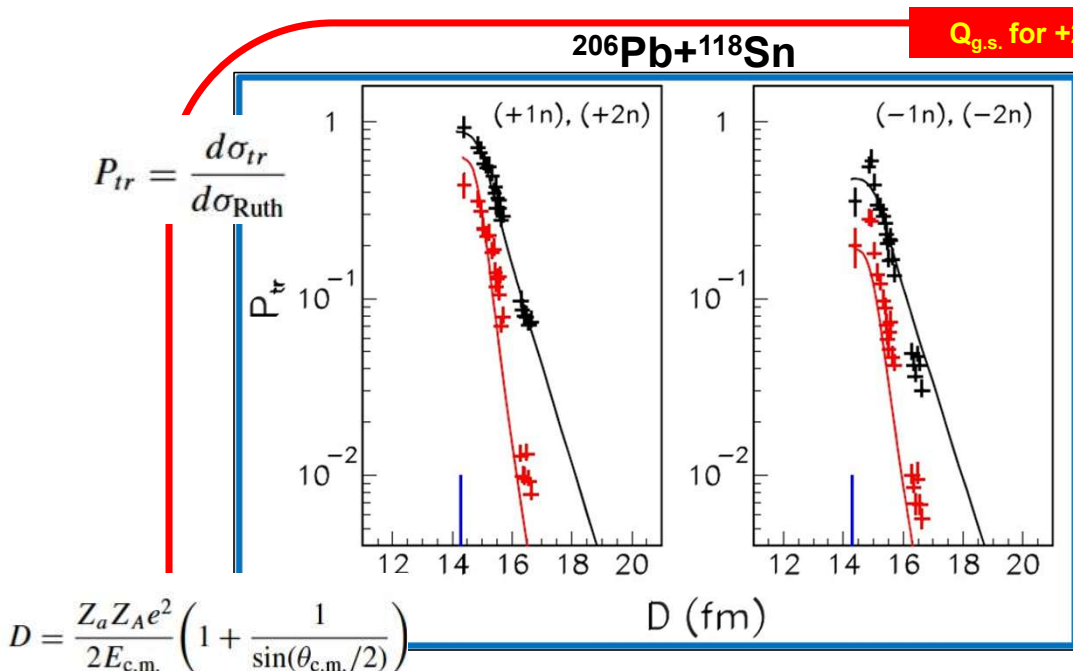
G.Potel, F. Barranco, E. Vigezzi and R. A. Broglia,
Phys. Rev. C103(2021)L021601

To reveal possible signatures of a nuclear Josephson effects we were in an ideal situation:

availability of data for the $^{60}\text{Ni} + ^{116}\text{Sn}$ system in a wide energy range
availability of the tracking spectrometer PRISMA (high A, Z, Q resolution and efficiency)
availability of the AGATA gamma array

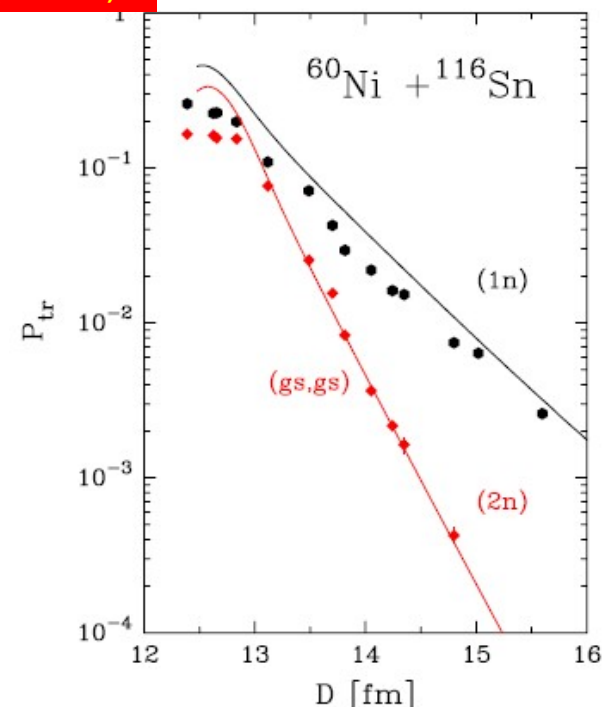


Near- and sub-barrier excitation functions for transfer channels with the PRISMA epectrometer



Measured with PRISMA a complete excitation function for neutron transfers at several bombarding energies. Data have been compared with the GRAZING code. Slopes are well reproduced. Differences in absolute scale are less than a factor 2, that can be justified as an effect of pairing vibrations in Pb isotopes.

S.Szilner, L.Corradi, J.Diklic, T.Mijatovic et al,
PRL133(2024)202501



The experimental transfer probabilities are well reproduced in absolute values, for the first time with heavy ion reactions, by microscopic calculations which incorporate a successive transfer process and a microscopic optical potential.

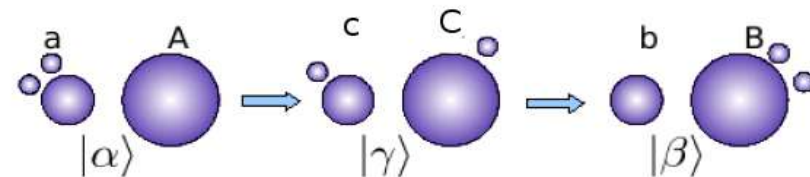
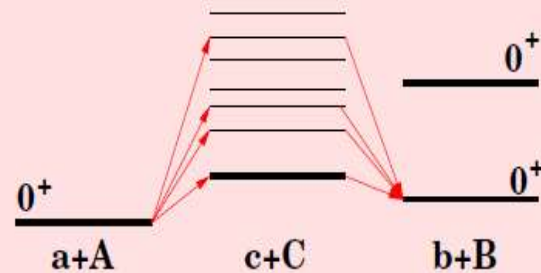
D.Montanari, L.Corradi, S.Szilner, G.Pollarolo et al,
PRL113(2014)052501

Two particle transfer (semiclassical theory, microscopic calculations)

$$c_{\beta}(\ell) = c_{\beta}^{(1)} + c_{\beta}^{ort} + c_{\beta}^{succ}$$

3 terms : simultaneous, orthogonal and successive

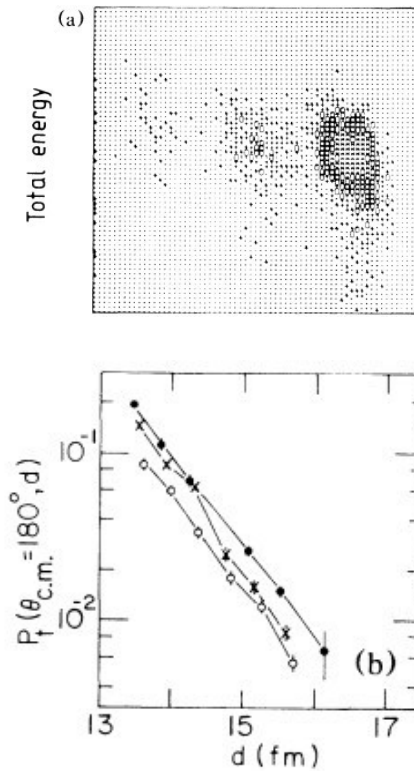
only the successive term contributes to the transfer amplitude



$$\begin{aligned} (c_{\beta})_{succ} = & \frac{1}{\hbar^2} \sum_{a_1, a'_1} B^{(A)}(a_1 a_1; 0) B^{(a)}(a'_1 a'_1; 0) 2 \frac{(-1)^{j_1 + j'_1}}{\sqrt{(2j_1 + 1)} \sqrt{(2j'_1 + 1)}} \sum_{m_1 m'_1} (-1)^{m_1 + m'_1} \\ & \times \int_{-\infty}^{+\infty} dt f_{m_1 m'_1}(\mathcal{R}) e^{i[(E_{\beta} - E_{\gamma})t + \delta_{\beta\gamma}(t) + \hbar(m'_1 - m_1)\Phi(t)]/\hbar} \\ & \times \int_{-\infty}^t dt f_{-m_1 - m'_1}(\mathcal{R}) e^{i[(E_{\gamma} - E_{\alpha})t + \delta_{\gamma\alpha}(t) - \hbar(m'_1 - m_1)\Phi(t)]/\hbar} . \end{aligned}$$

Measurements of transfer reactions at sub-barrier energies: a long and challenging history

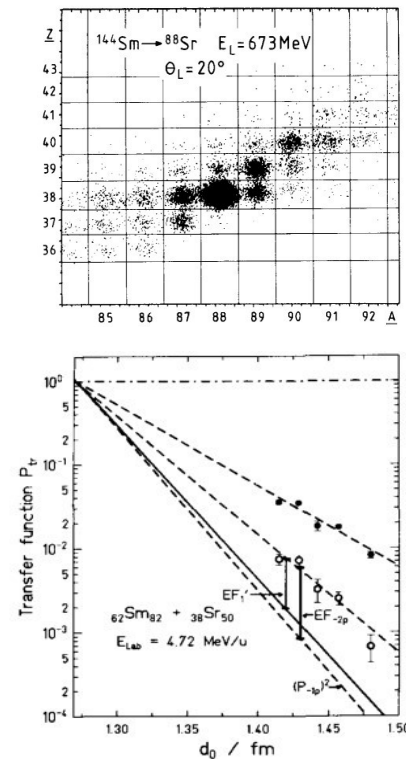
Daresbury RMS



direct
kinematics

R.Betts et al.,
PRL59(1987)978

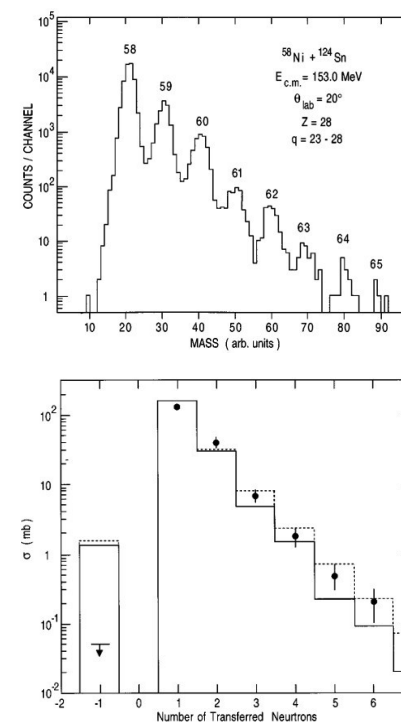
GSI magnetic
spectrometer



direct/inverse
kinematics

R.Kunkel et al.,
PLB208(1988)355

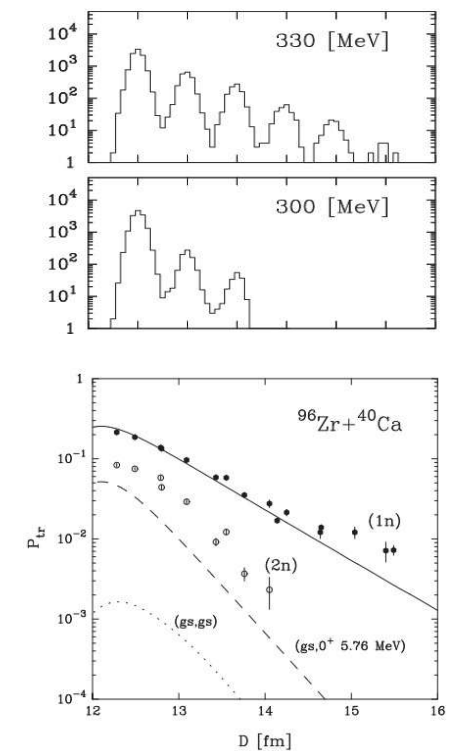
Argonne
split pole



inverse
kinematics

C.L.Jiang et al.,
PRC57(1998)2393

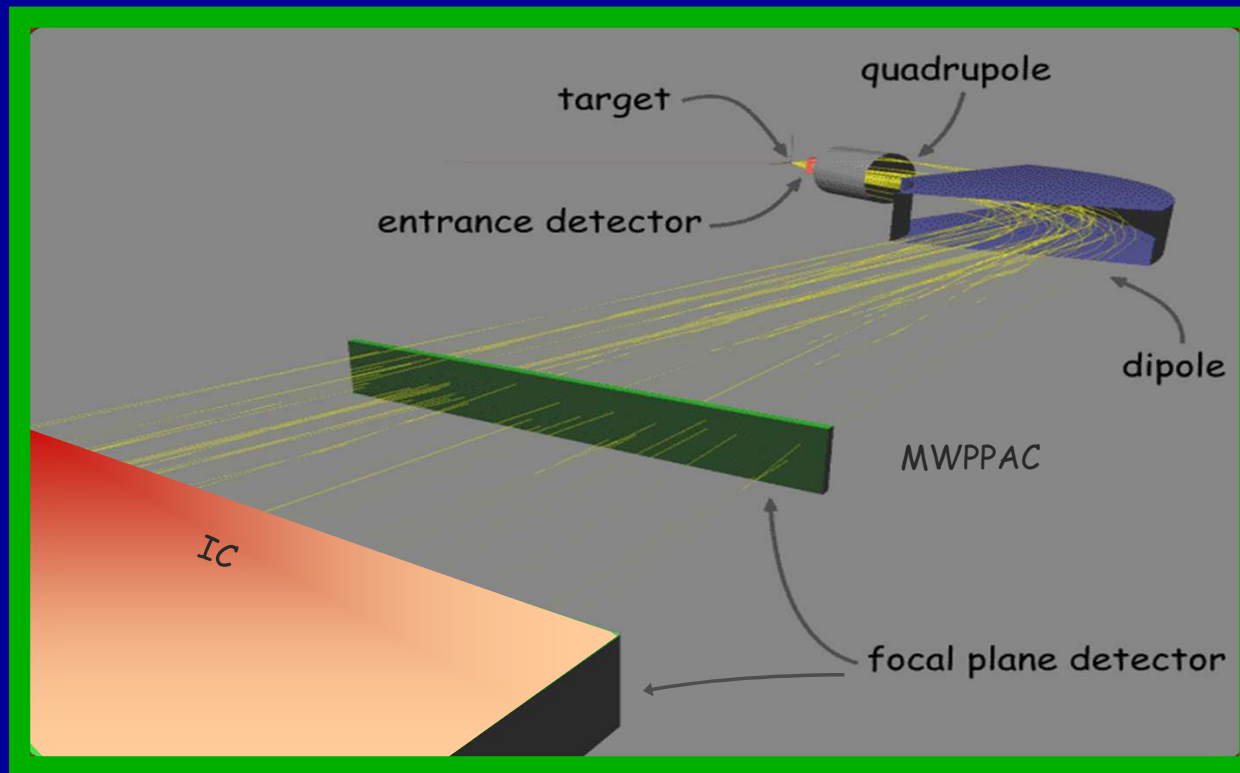
LNL tracking
spectrometer



inverse
kinematics

L.Corradi et al.,
PRC84(2011)034603

PRISMA spectrometer - trajectory reconstruction



$$T = \frac{S(\theta, \phi)}{v}$$

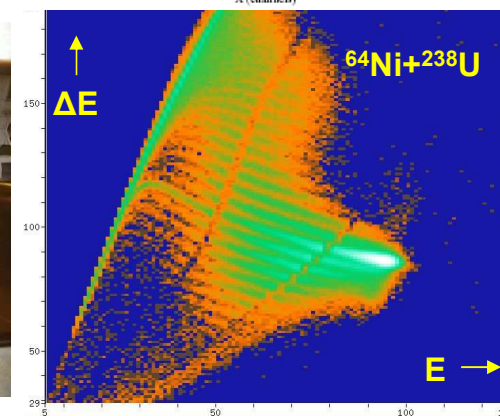
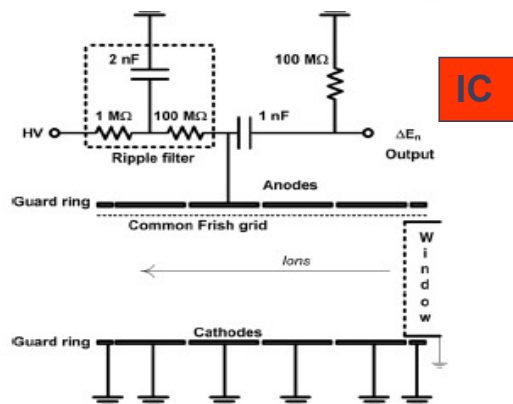
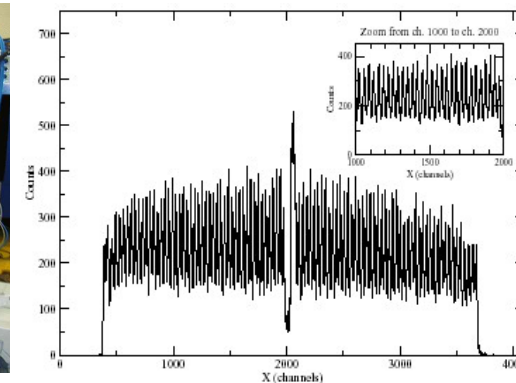
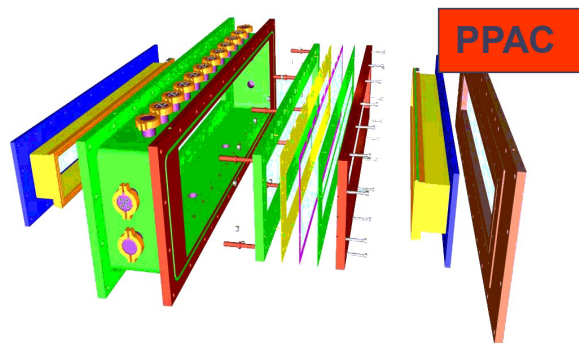
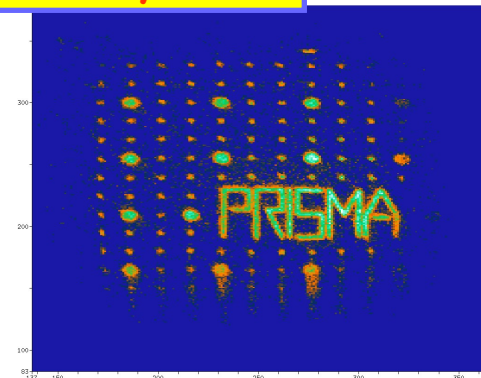
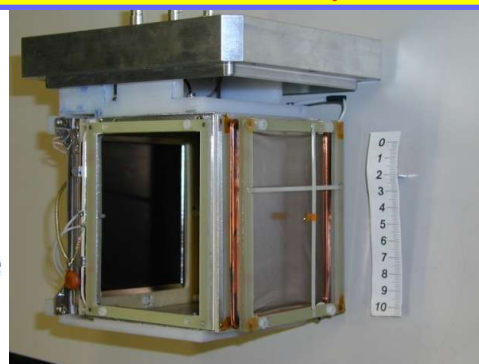
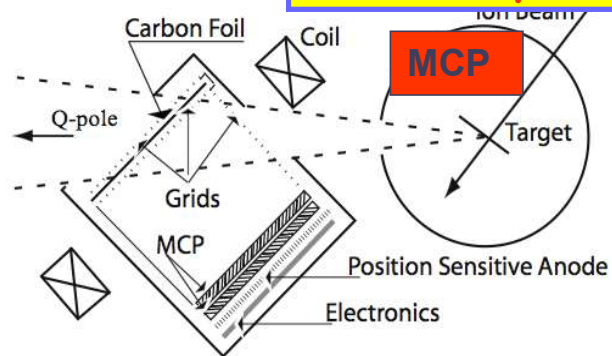
A physical event is composed by the parameters:

- | | |
|-------------------------------|--------------|
| • position at the entrance | x, y |
| • position at the focal plane | X, Y |
| • time of flight | TOF |
| • energy | DE, E |

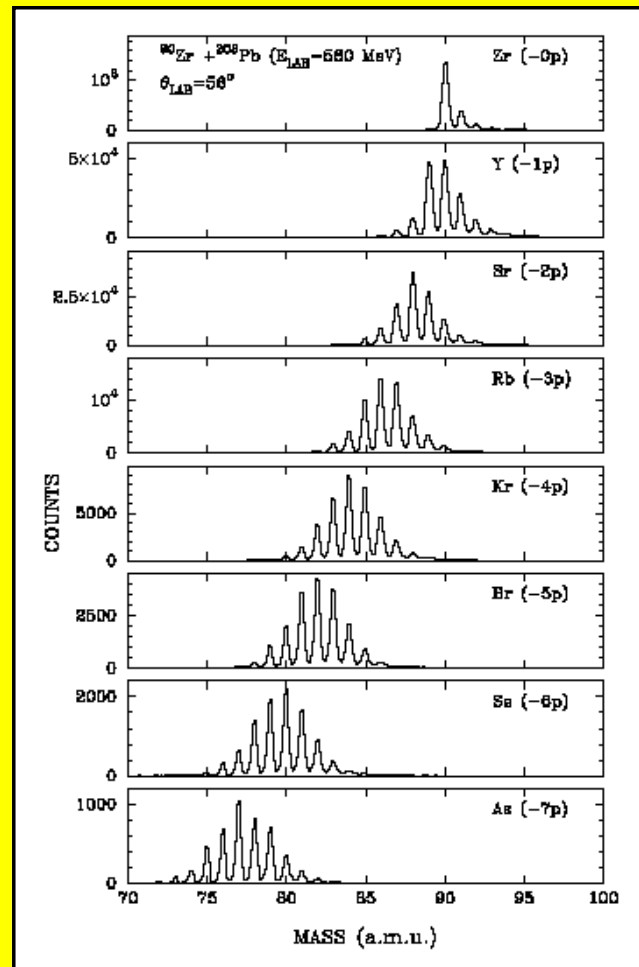
$$B\rho = A \cdot \frac{v}{q} \propto X$$

$$q = \frac{2}{S(\theta, \phi)} \cdot \frac{E \cdot T}{B\rho(\theta, \phi)}$$

PRISMA spectrometer - a complex detector system

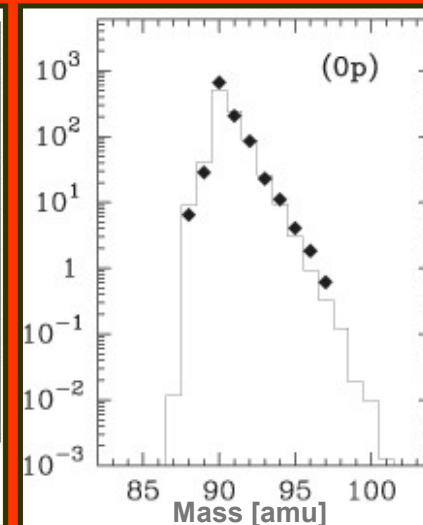
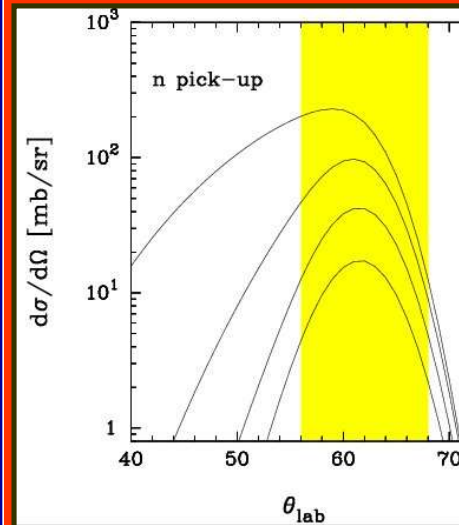


Multineutron and multiproton transfer channels near closed-shell nuclei



$^{90}\text{Zr} + ^{208}\text{Pb}$ $E_{\text{lab}} = 560$ MeV

pure neutron pick-up channels

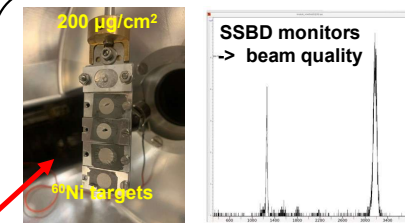
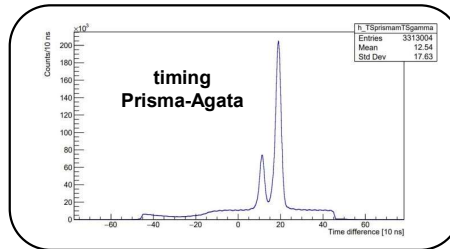


PRISMA spectrometer data

GRAZING code calculations

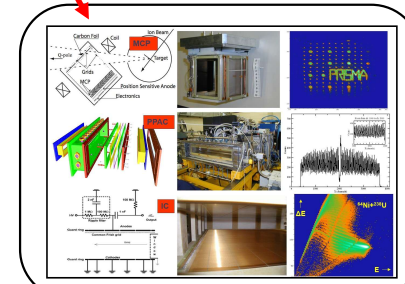
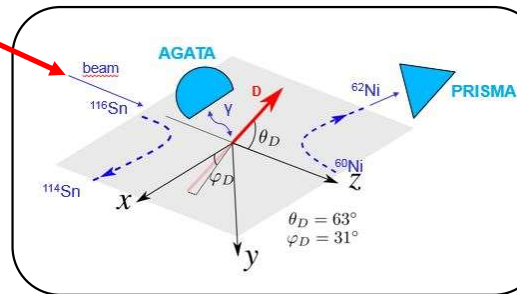
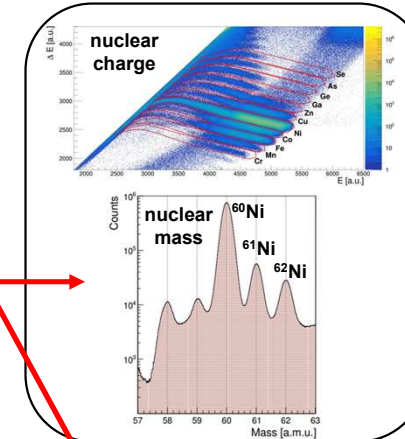
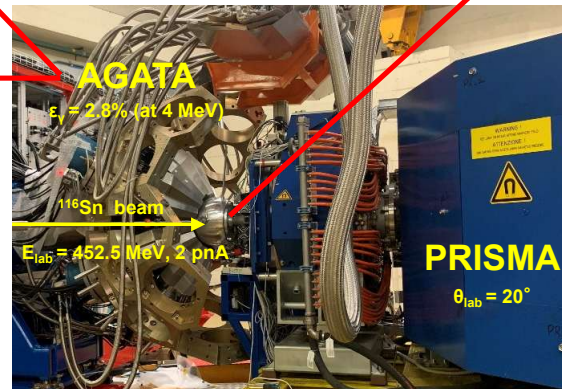
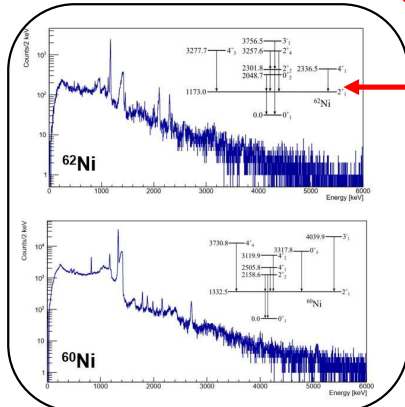
S.Szilner et al, Phys.Rev.C76(2007)024604

Search for a nuclear Josephson effect - PRISMA-AGATA experiment Feb. 2023



Theoretical $d\sigma/d\Omega$
= 30.36 $\mu\text{b/sr}$

expected few
tens/day
 γ coincidences
with ^{62}Ni ions



PRISMA

AGATA

SIMULATIONS

THEORY

PRISMA

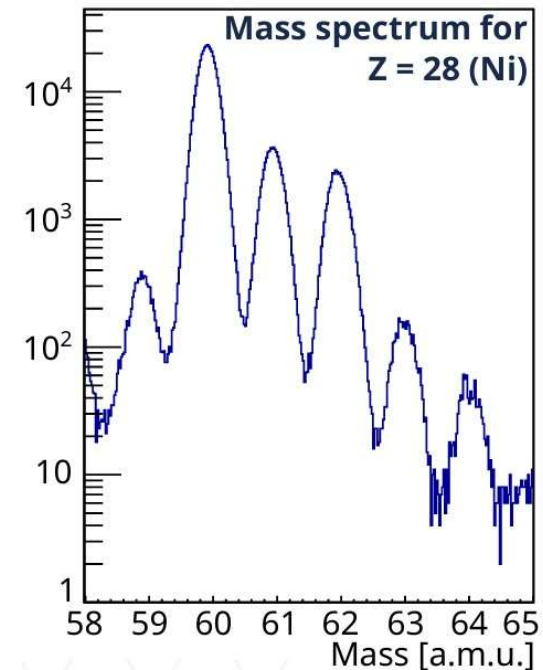
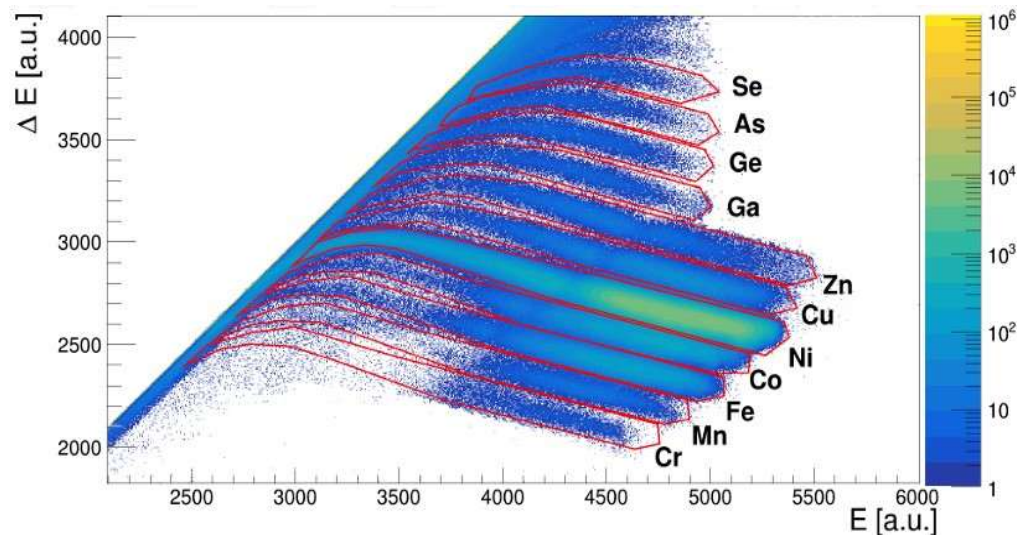


AGATA

SIMULATIONS

THEORY

Nuclear charge and mass determination

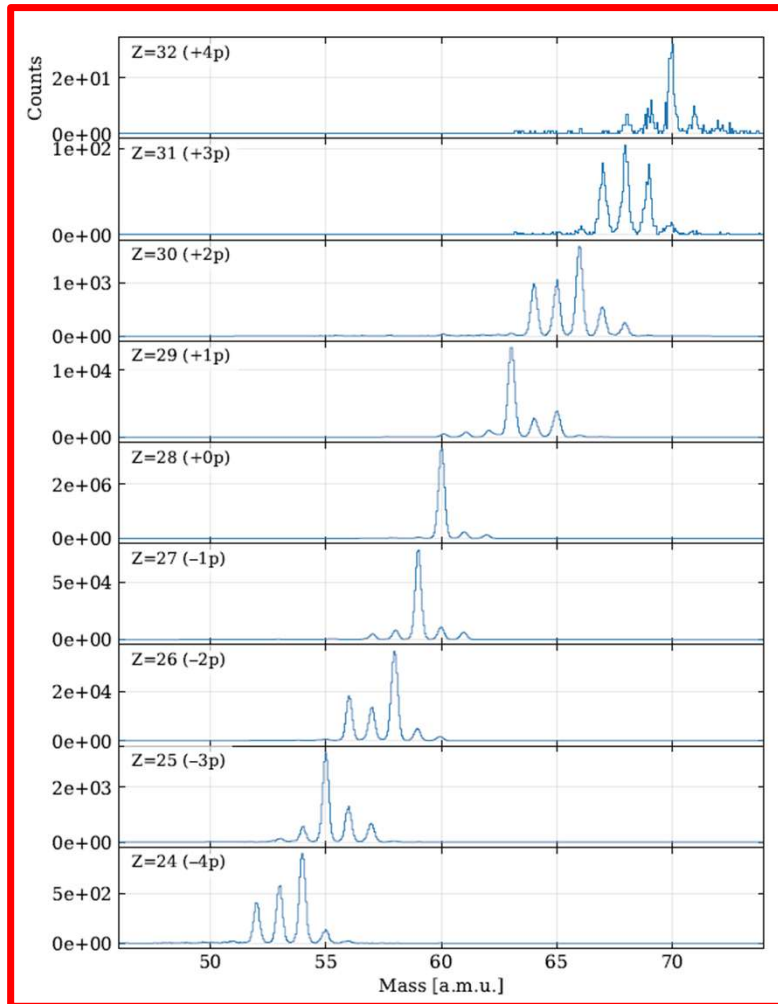


The high Z and A resolutions allowed to well distinguish the multitude of neutron and proton transfer channels at energies below the Coulomb barrier

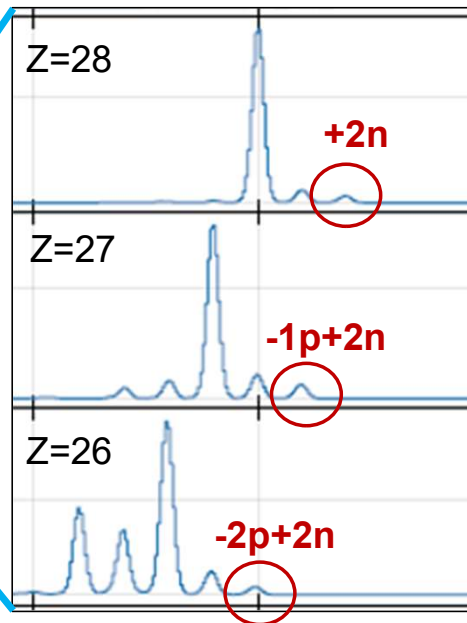
The accumulated statistics allowed to make bins of 1-2 degrees in the angular distributions, so one could extract the transfer probabilities in a wide D range encompassing the critical region near the correlation length 13.2-13.5 fm

Data analysis by G.Andreetta (PhD)

Neutron and proton mass determination



The high efficiency of PRISMA allowed to extract, also at sub-barrier energies, the cross sections for multineutron and multiproton transfers



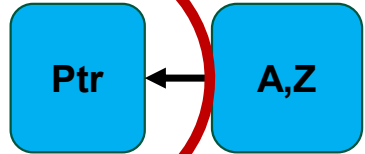
thus, for example, one can study to what extent the one and two neutron pick-up act independently from proton stripping

PRISMA

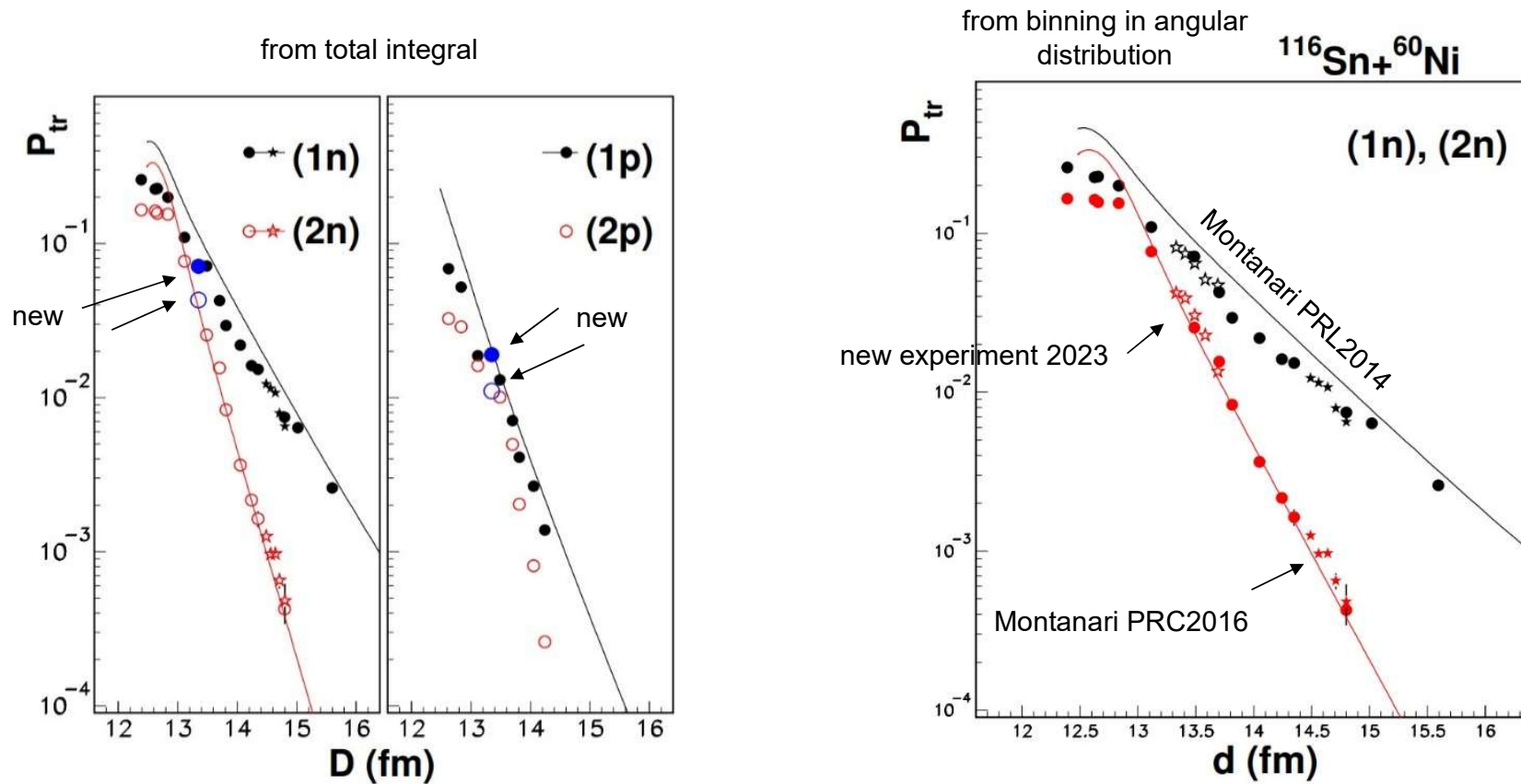
AGATA

SIMULATIONS

THEORY

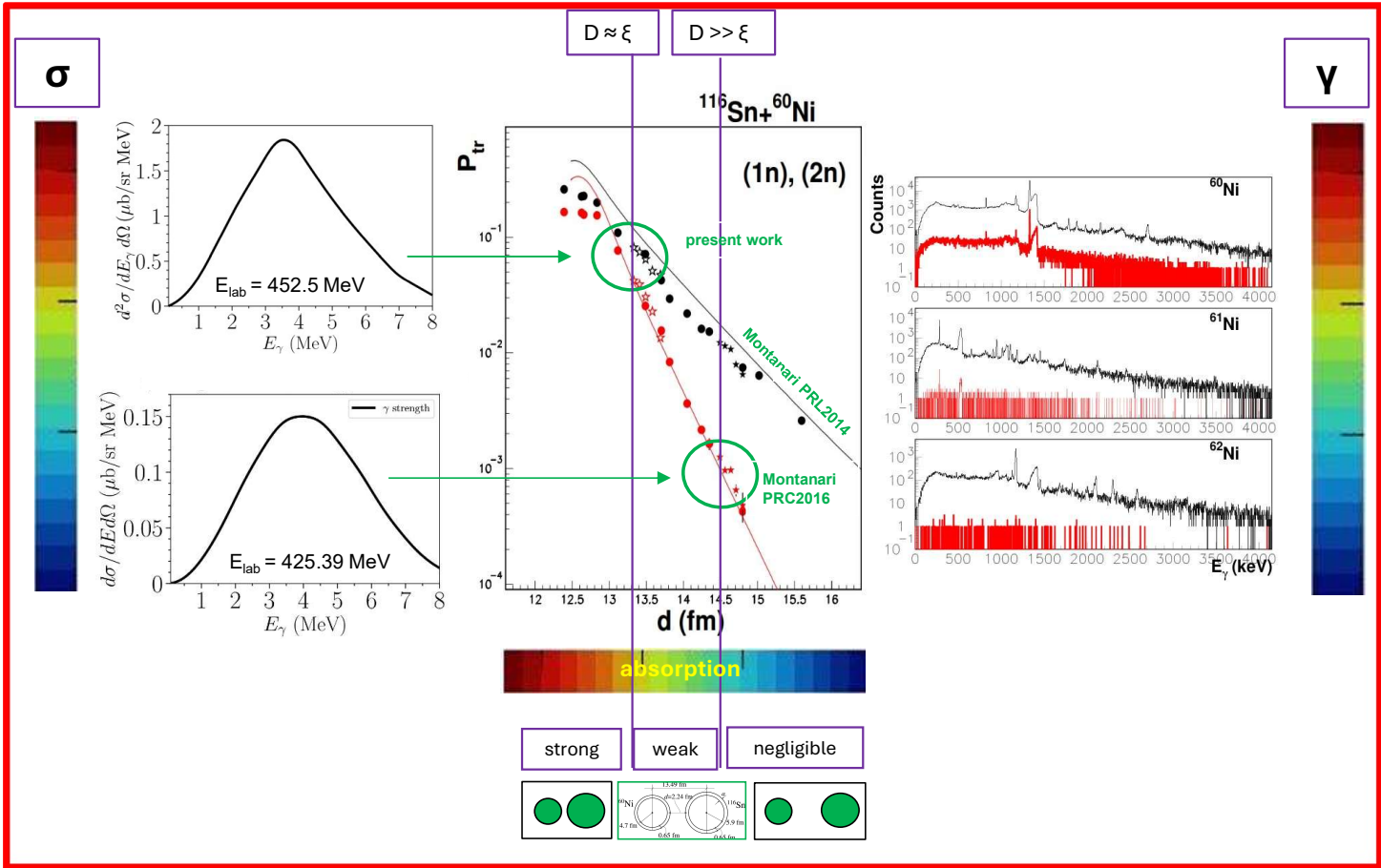


Extraction of transfer probabilities



The transfer probabilities for the one and two neutron pick-up channels well agree in 3 different experiments

Excellent consistency of cross sections and gamma yields measured in the previous and present experiment

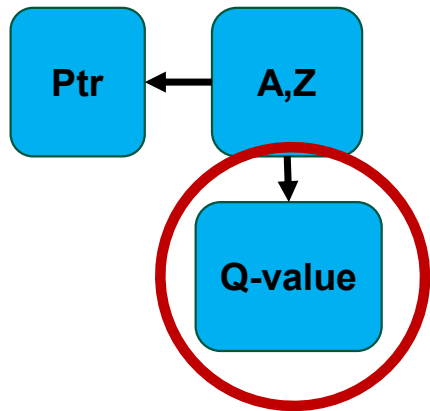


PRISMA

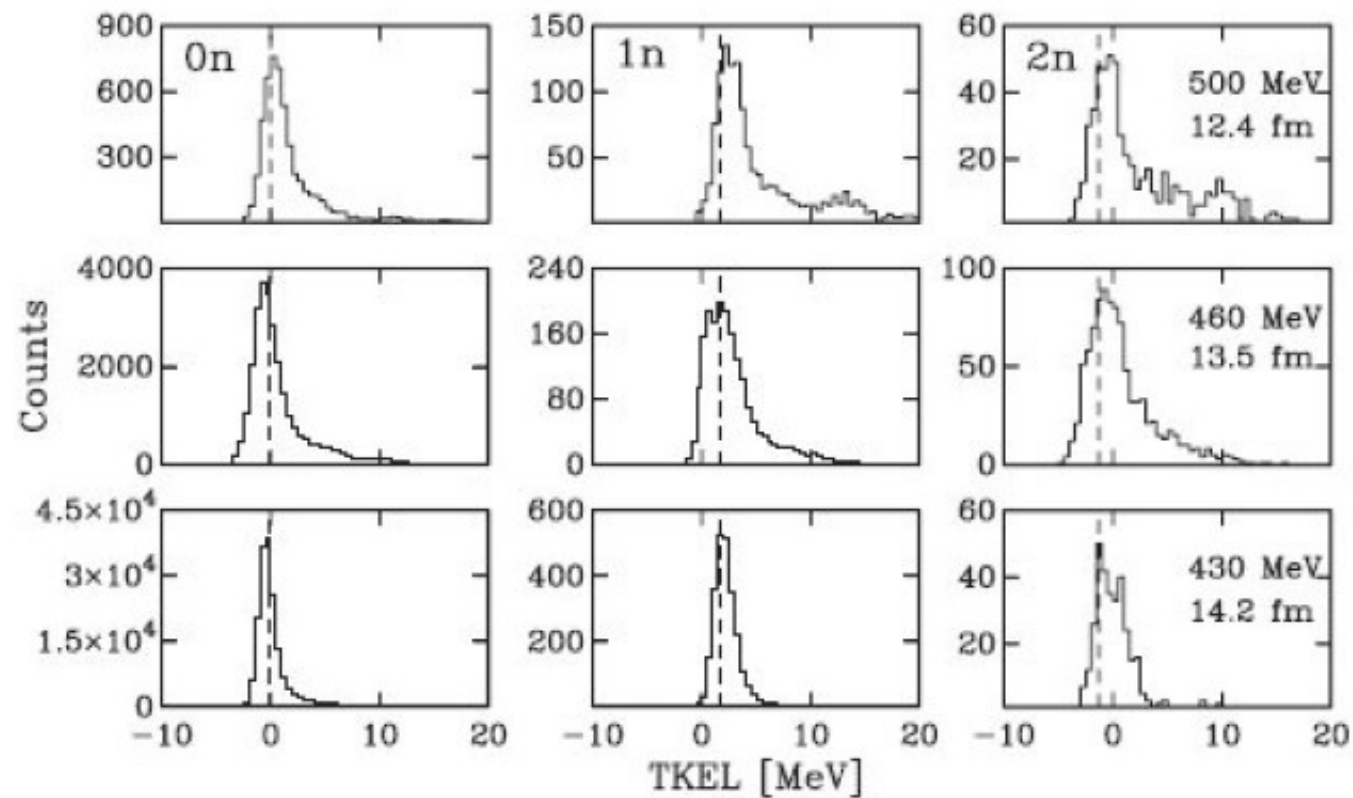
AGATA

SIMULATIONS

THEORY



Total Kinetic Energy Loss distributions



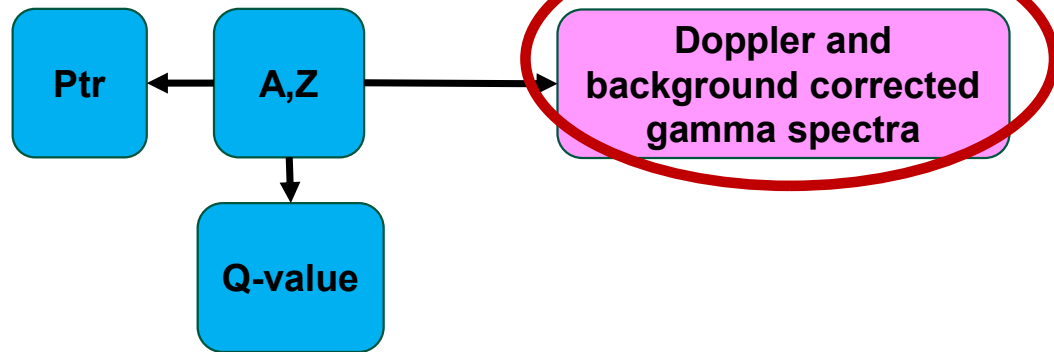
At sub-barrier energies the TKEL become narrower and larger energy loss tails strongly diminish

PRISMA

AGATA

SIMULATIONS

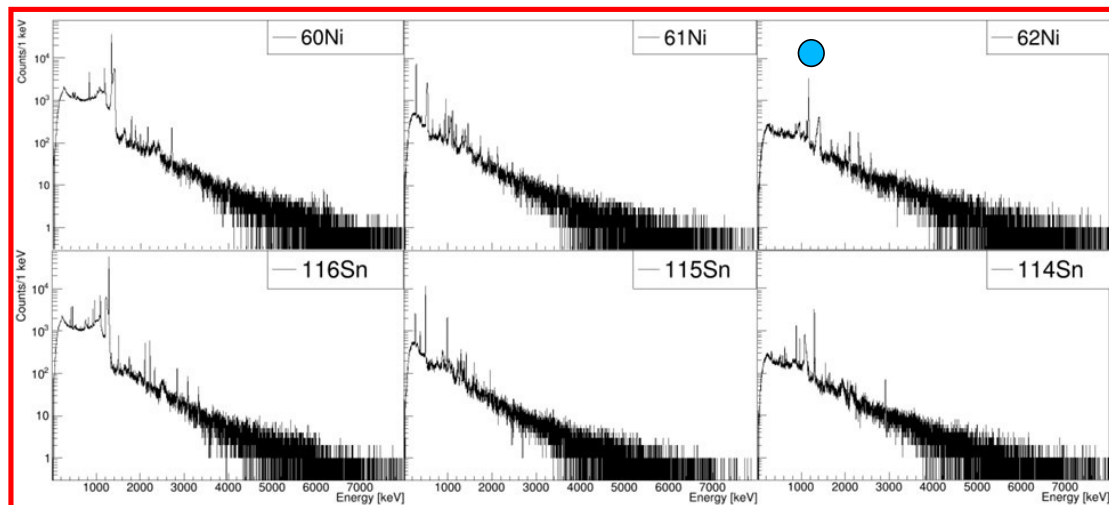
THEORY



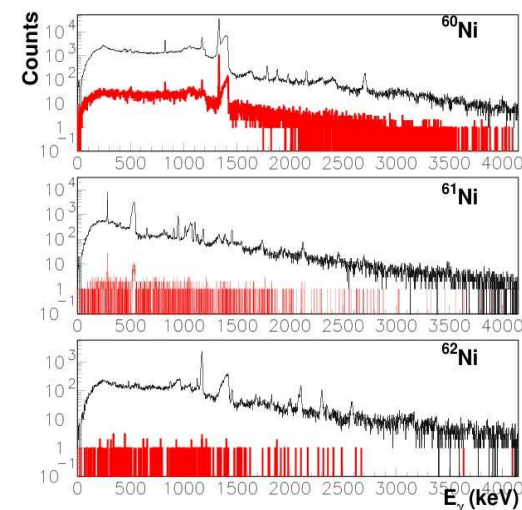
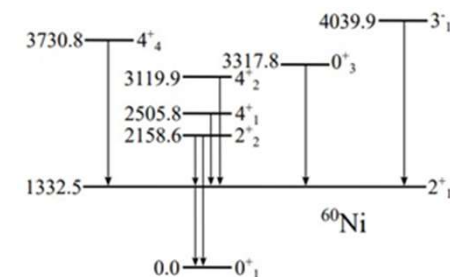
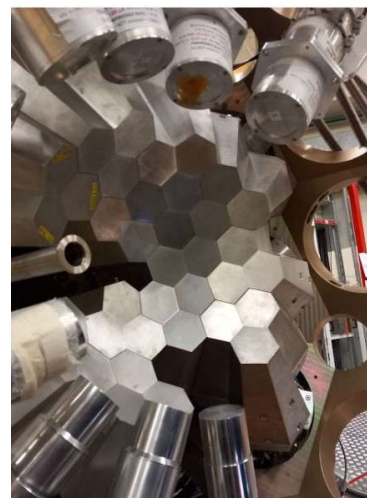
Gamma spectra from AGATA obtained in coincidence with $^{60,61,62}\text{Ni}$ isotopes identified with PRISMA

L.Corradi, S.Szilner et al., PRISMA+AGATA exp 2023

$D = 13.5 \text{ fm} \approx \xi$

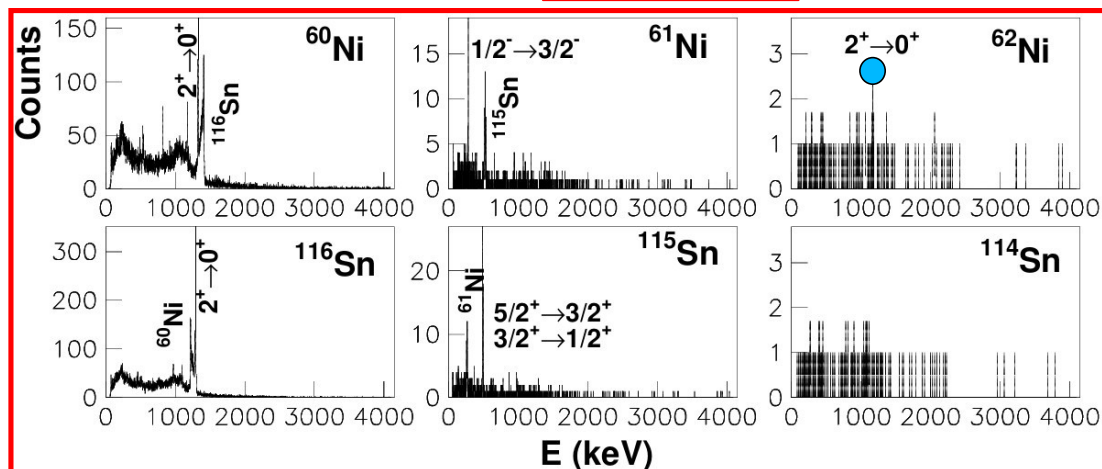


AGATA 2023 - 37 crystals

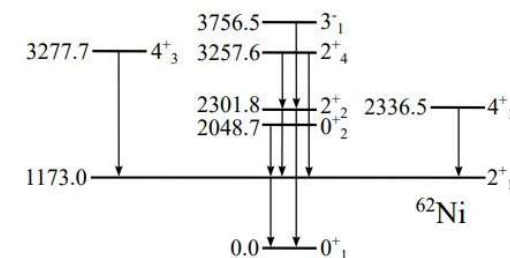


D.Montanari et al, PRC93(2016)054623

$D = 14.5 \text{ fm} > \xi$



AGATA 2012 - 12 crystals

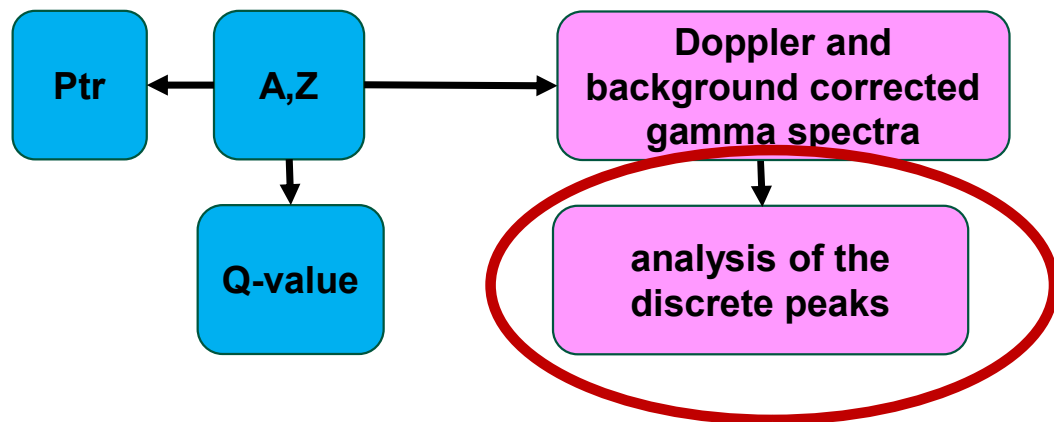


PRISMA

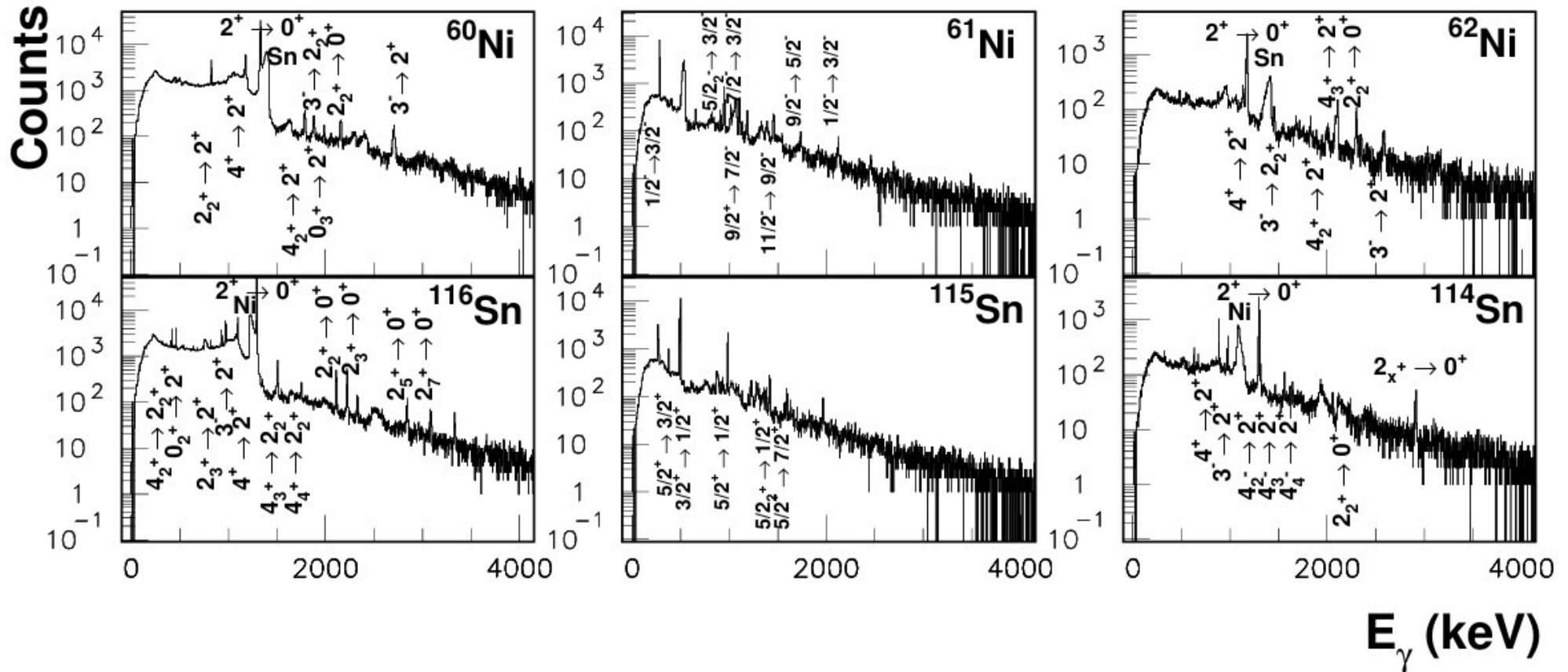
AGATA

SIMULATIONS

THEORY

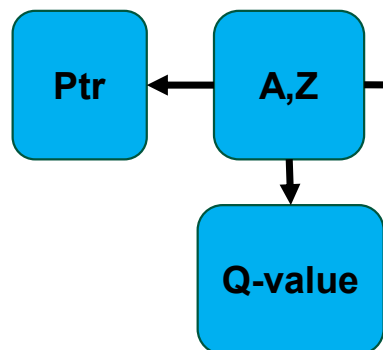


Doppler corrected gamma spectra

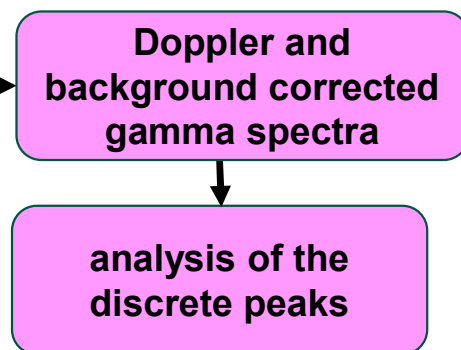


In the single spectra one can observe a wealth of discrete gamma peaks, even at high energies and with intensities about 10^{-3} those of the main lowest transitions

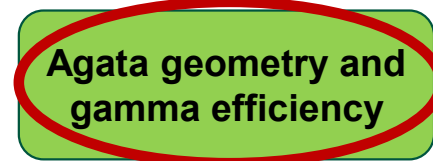
PRISMA



AGATA

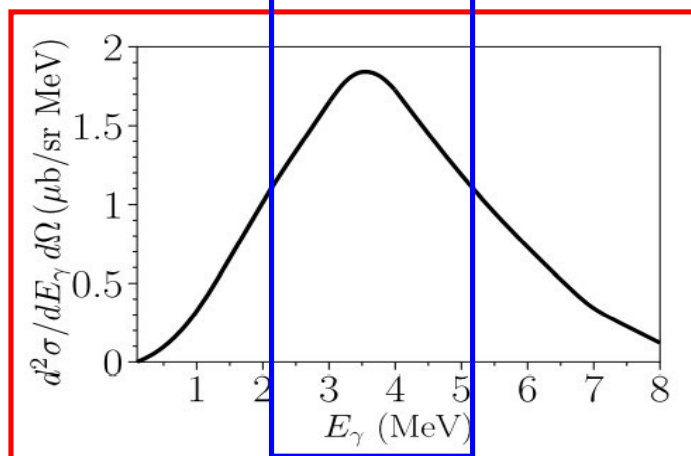
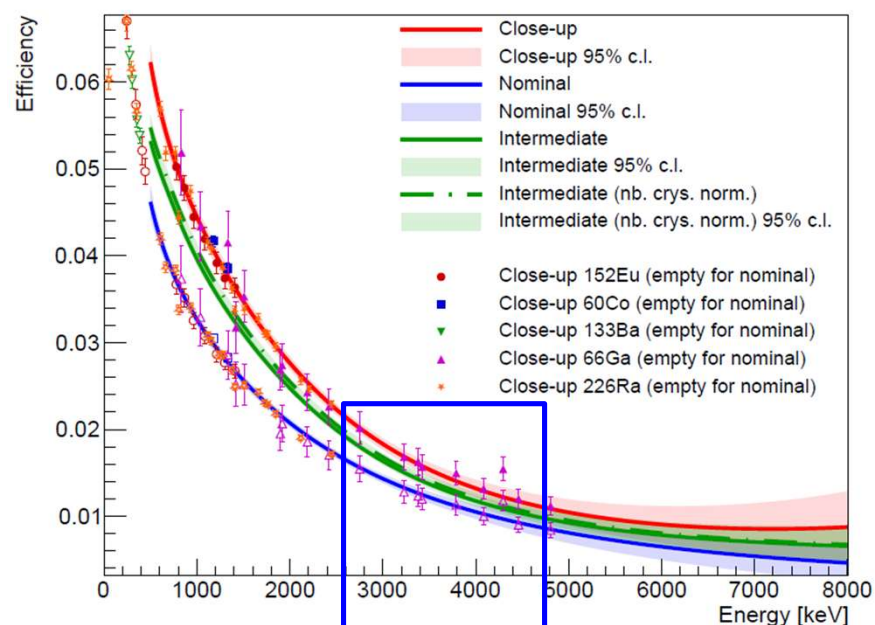


SIMULATIONS



THEORY

Courtesy by G.Andreetta and M.Balogh

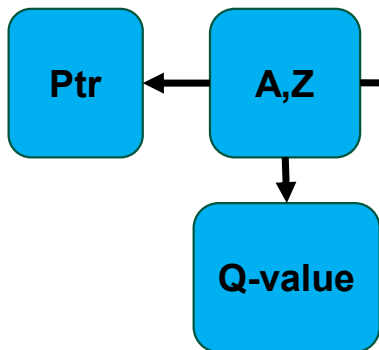


AGATA efficiency

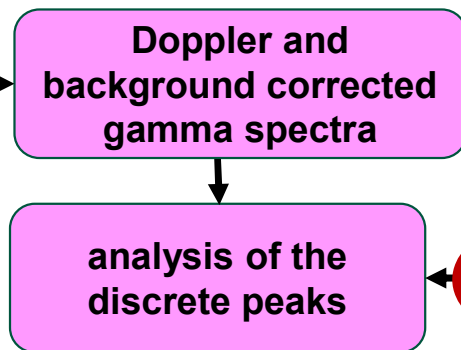
Gamma ray detection efficiency has been extracted by a fitting procedure of data from suitable sources and nuclear reactions. Final values are taken by analysis in calorimetric mode

Evaluation of gamma ray detection efficiency is very important, taking into account that the main Josephson strength is predicted around 3-4 MeV

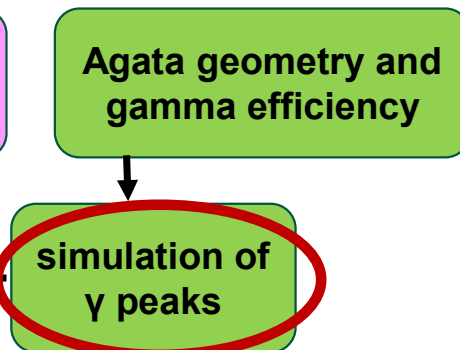
PRISMA



AGATA

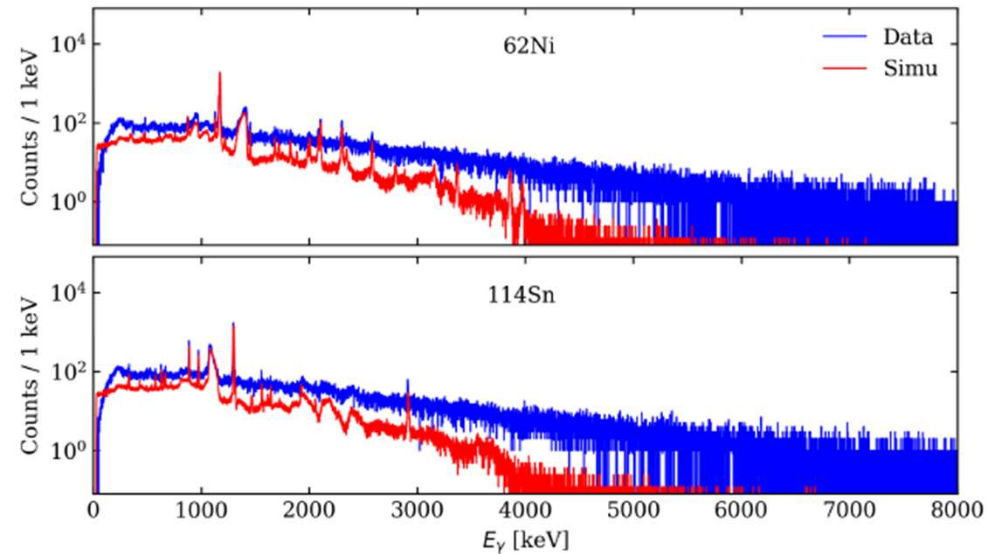
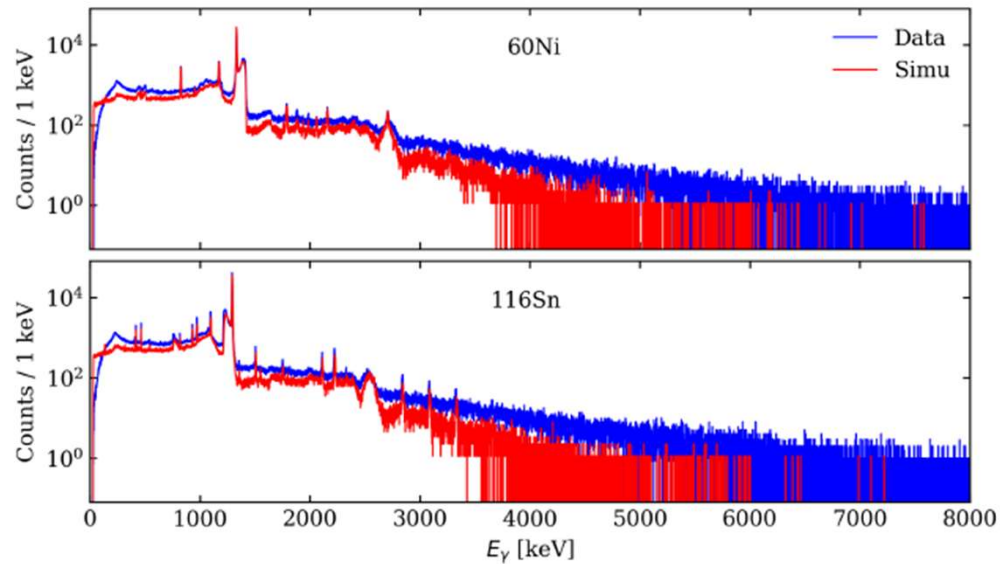


SIMULATIONS

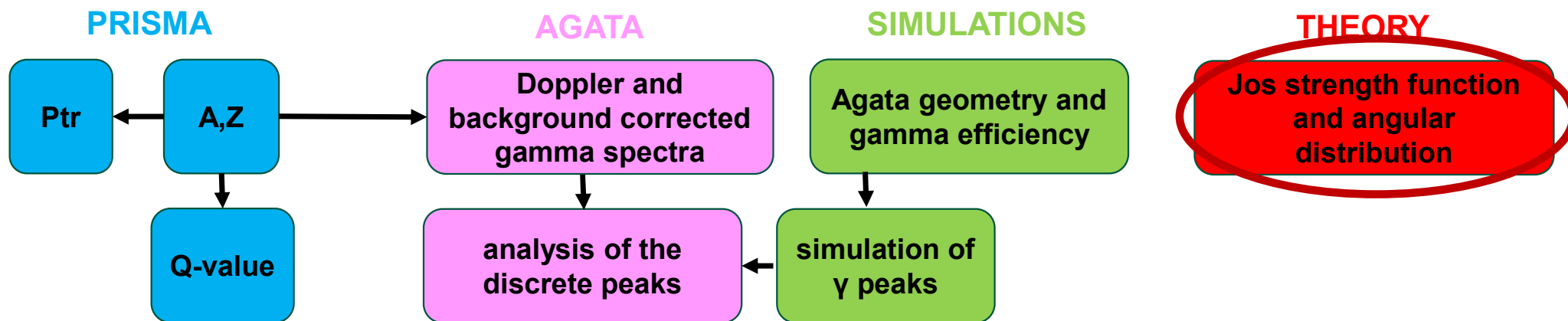


THEORY

Experimental and simulated gamma spectra



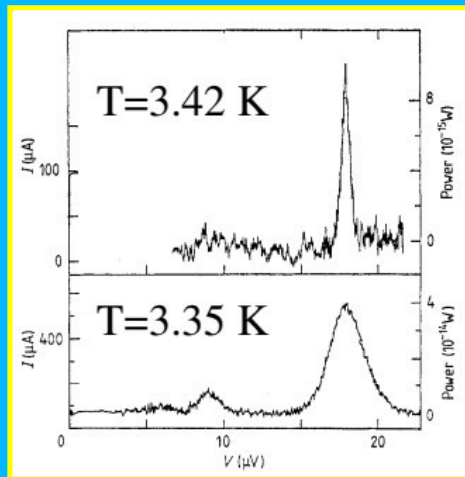
Simulations do not include exponential tails, normally used to fit the background, since the searched Josephson events may be embedded into it. In this way we avoid to bias the subtraction procedure later adopted



Possible Josephson-like effect in nuclear physics

$$\nu_J = \frac{2e}{h} V_0 \approx 480 \frac{\text{MHz}}{\mu\text{V}}$$

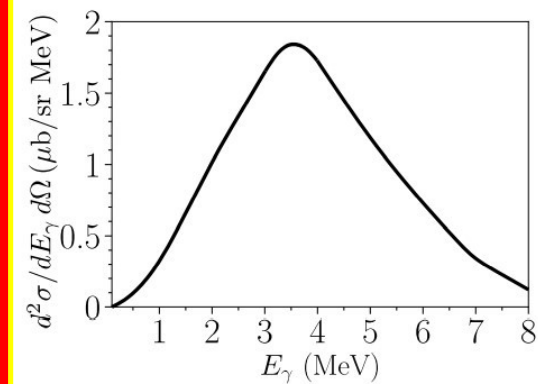
original spectrum obtained in the microwave region that confirms one of the main predictions of the AC Josephson effect



P.E.Lindelof, Rep.Prog.Phys.44:60,1981

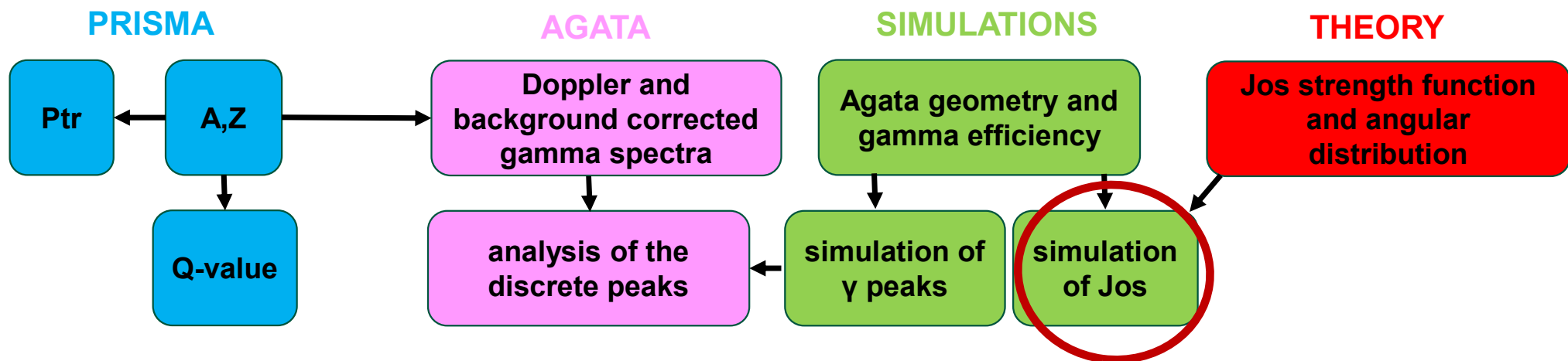
The emission of EM waves in the region of MeV gamma rays is predicted. **The physical origin is in the dipole oscillations generated by the oscillating motion of the Cooper pairs between the interacting binary partners**

double differential cross section for γ emission



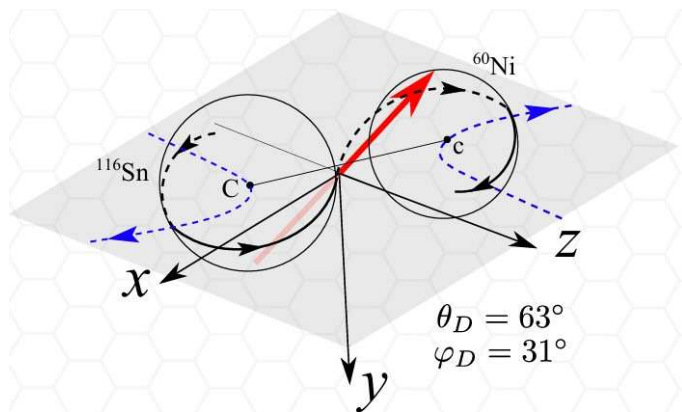
$$\frac{d^2\sigma}{d\Omega dE_\gamma} = \left(\frac{\mu_i \mu_f}{(2\pi\hbar^2)^2} \frac{k_f}{k_i} \right) \left(\frac{8\pi}{3} \frac{E_\gamma^2}{(\hbar c)^3} \right) \times |T_{m_\gamma}(\mathbf{k}_f, \mathbf{k}_i)|^2 \delta(E_\gamma + E_f - (E_i + Q))$$

G.Potel, F. Barranco, E. Vigezzi and R. A. Broglia, Phys. Rev. C103(2021)L021601

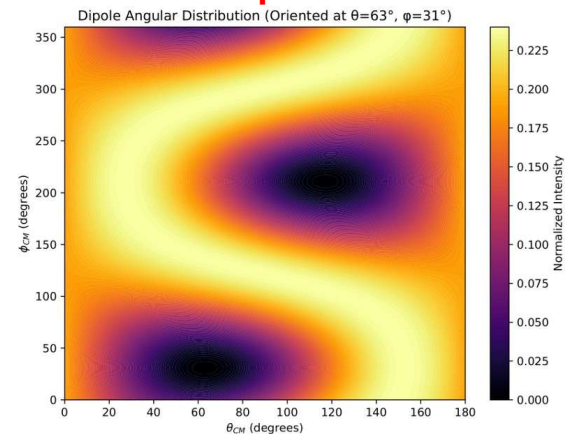


Josephson dipole gamma ray angular distributions

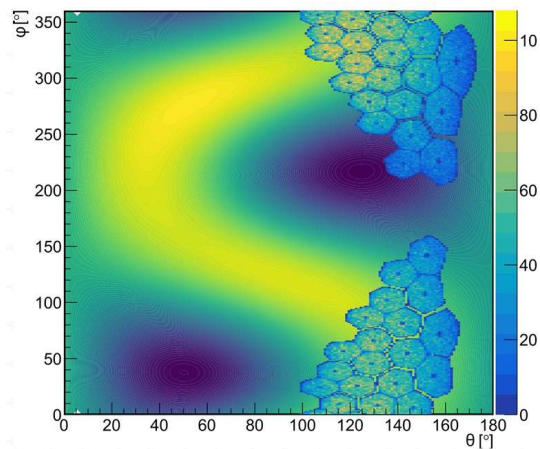
scheme of the reaction



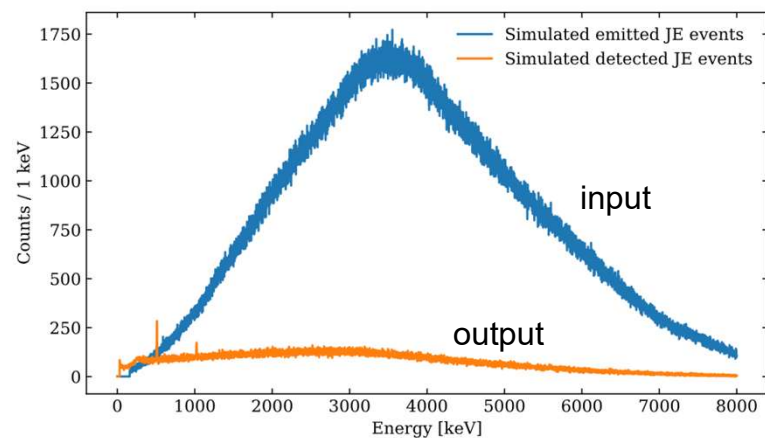
theoretical predictions

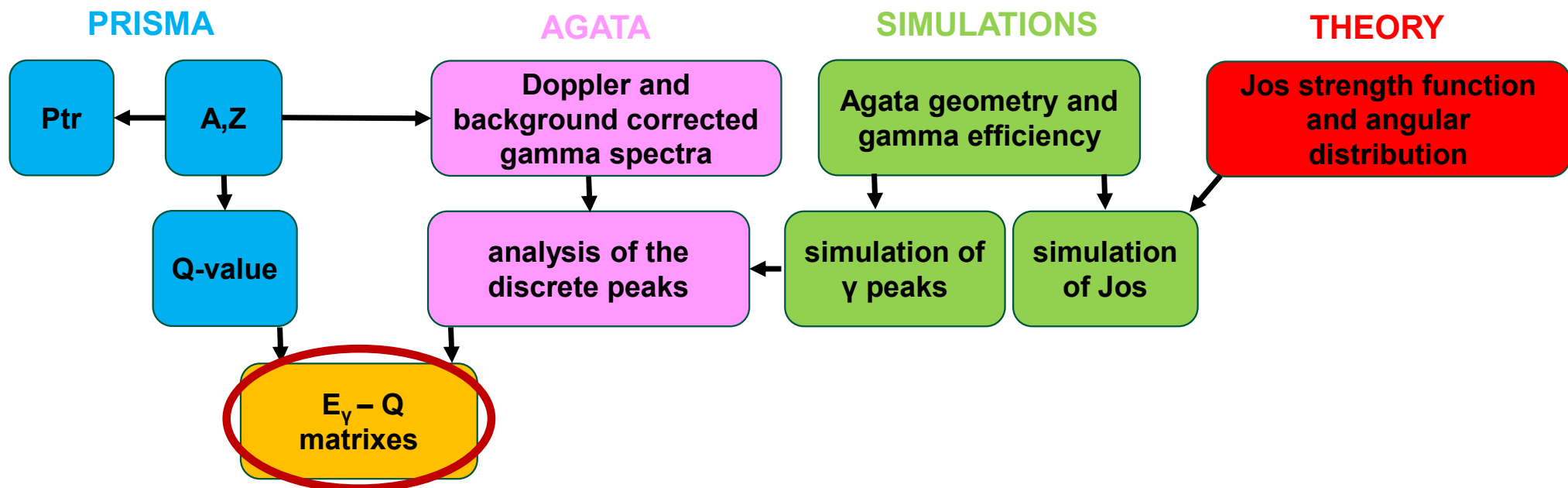


overlap with AGATA geometry

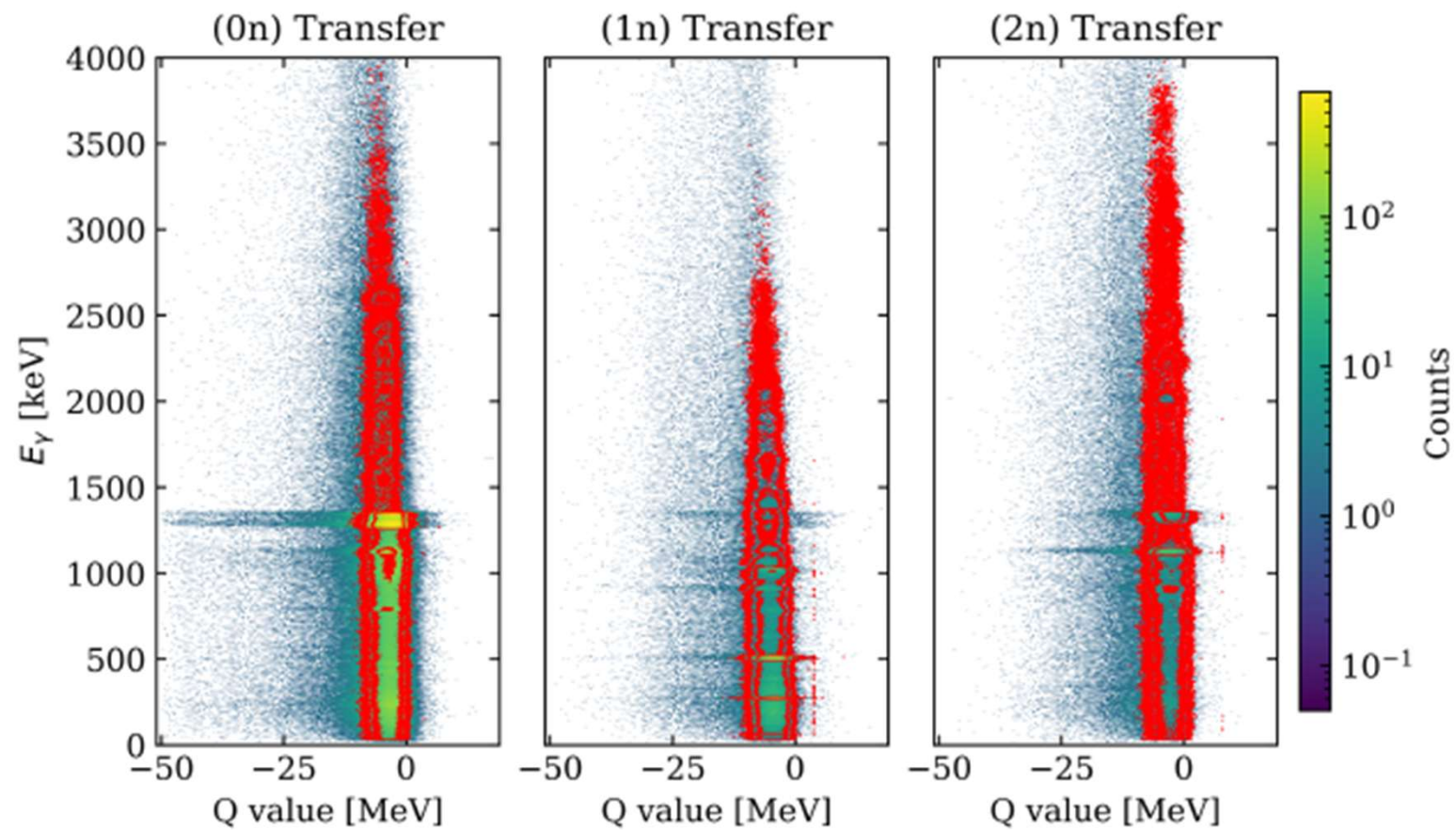


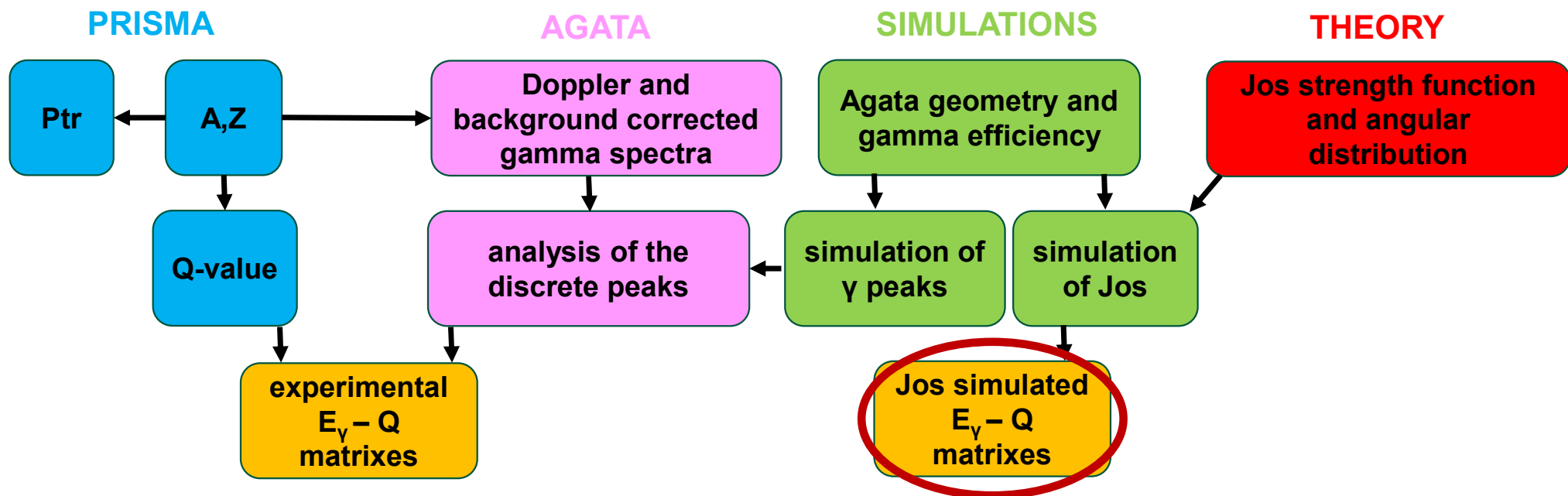
simulations





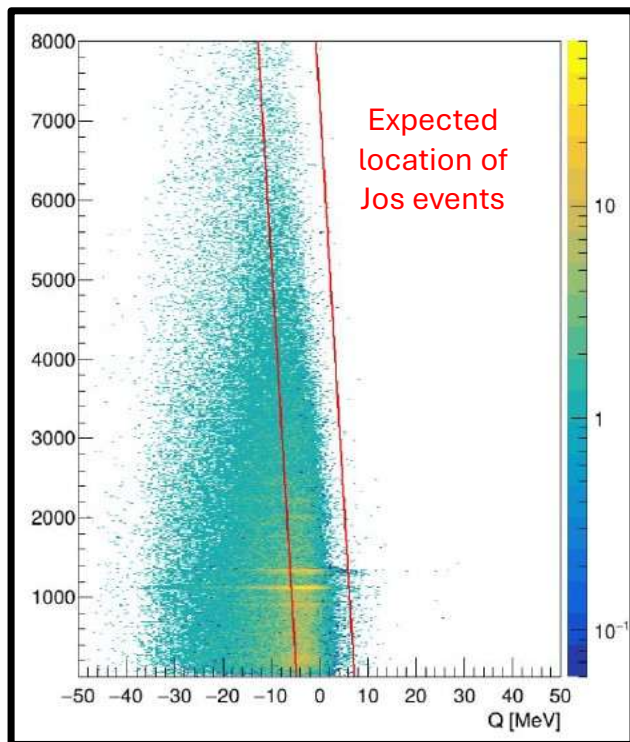
E_γ vs Q-value matrixes: data compared with simulations for the discrete lines



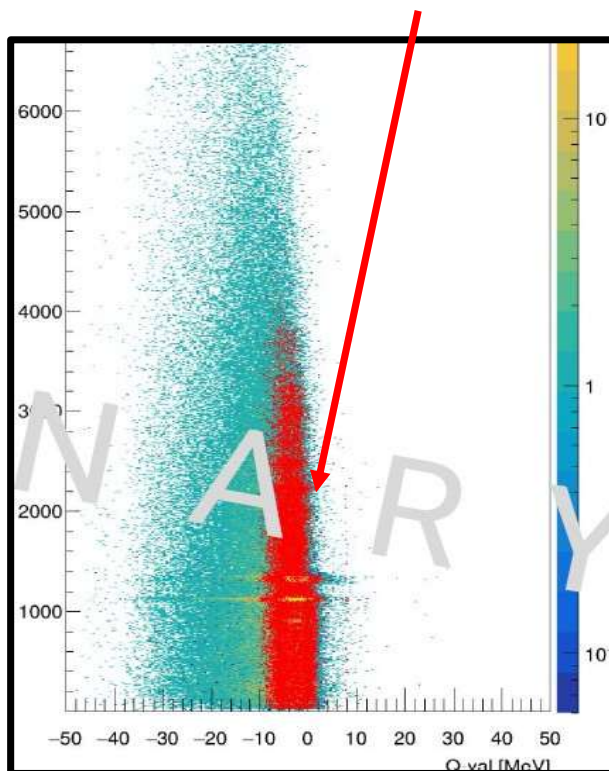


Experimental and simulated E_γ vs Q matrixes for the $2n$ transfer channel

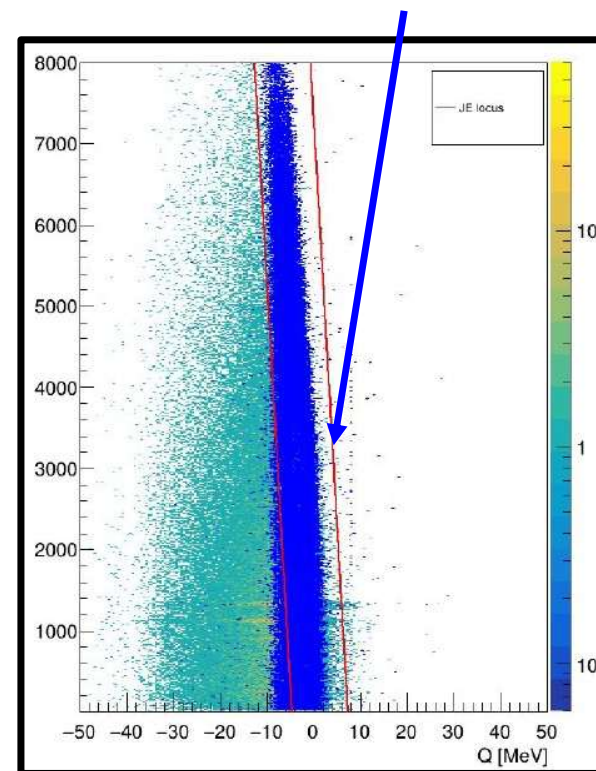
Experimental event distribution



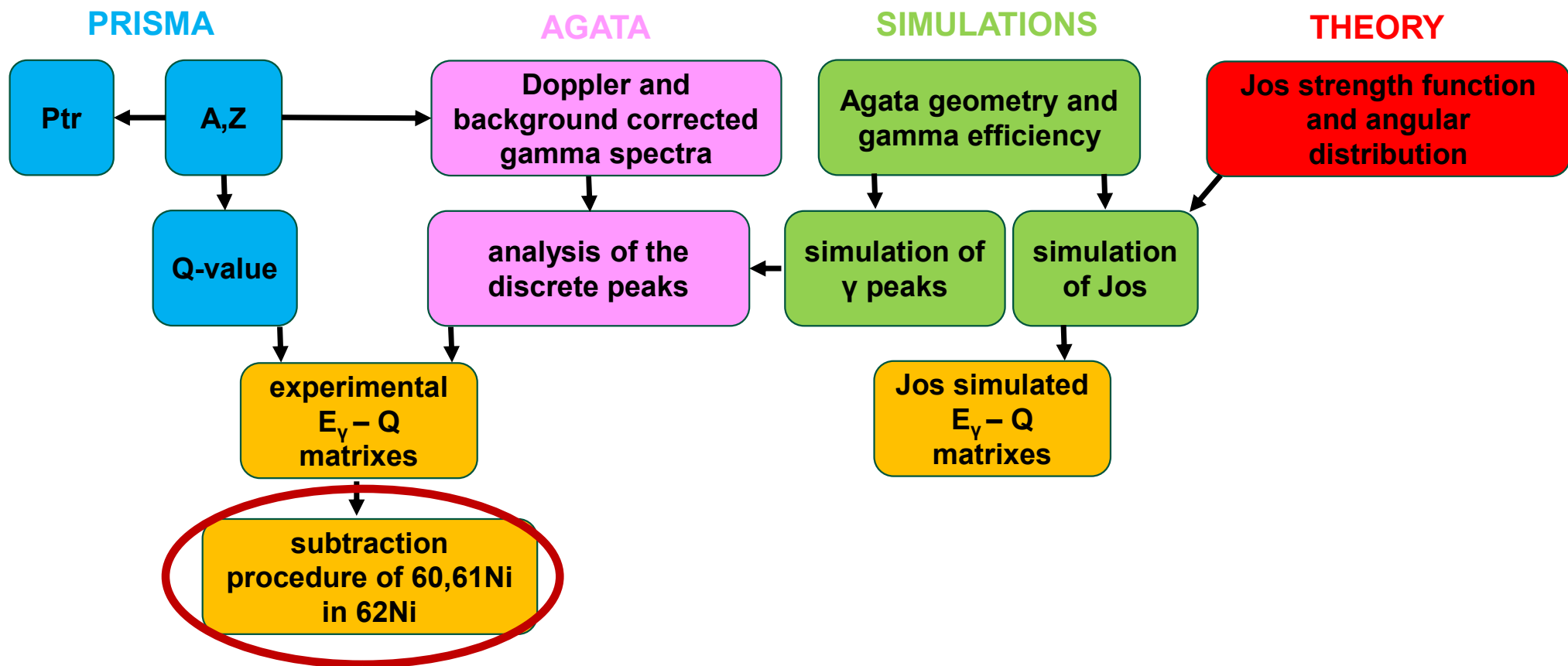
+ Simulation of discrete lines



+ Simulation of Josephson events ($\times 10^3$)



The Jos simulation defines a band in the Q - E_γ matrix of the $2n$ channel



the subtraction idea

The tree scheme of the subtraction procedure

$$S_y = S_{tr} + S_{inel}$$

$$= S(0n) \cdot (N2/N0)$$

$$S_{tr} = S_{tr-corr} + S_{tr-uncorr}$$

$$= 2 \cdot S(1n)_{tr} \cdot (N2/N1)$$

$$= 2 \cdot [S(1n) - S(0n) \cdot (N1/N0)] \cdot (N2/N1)$$

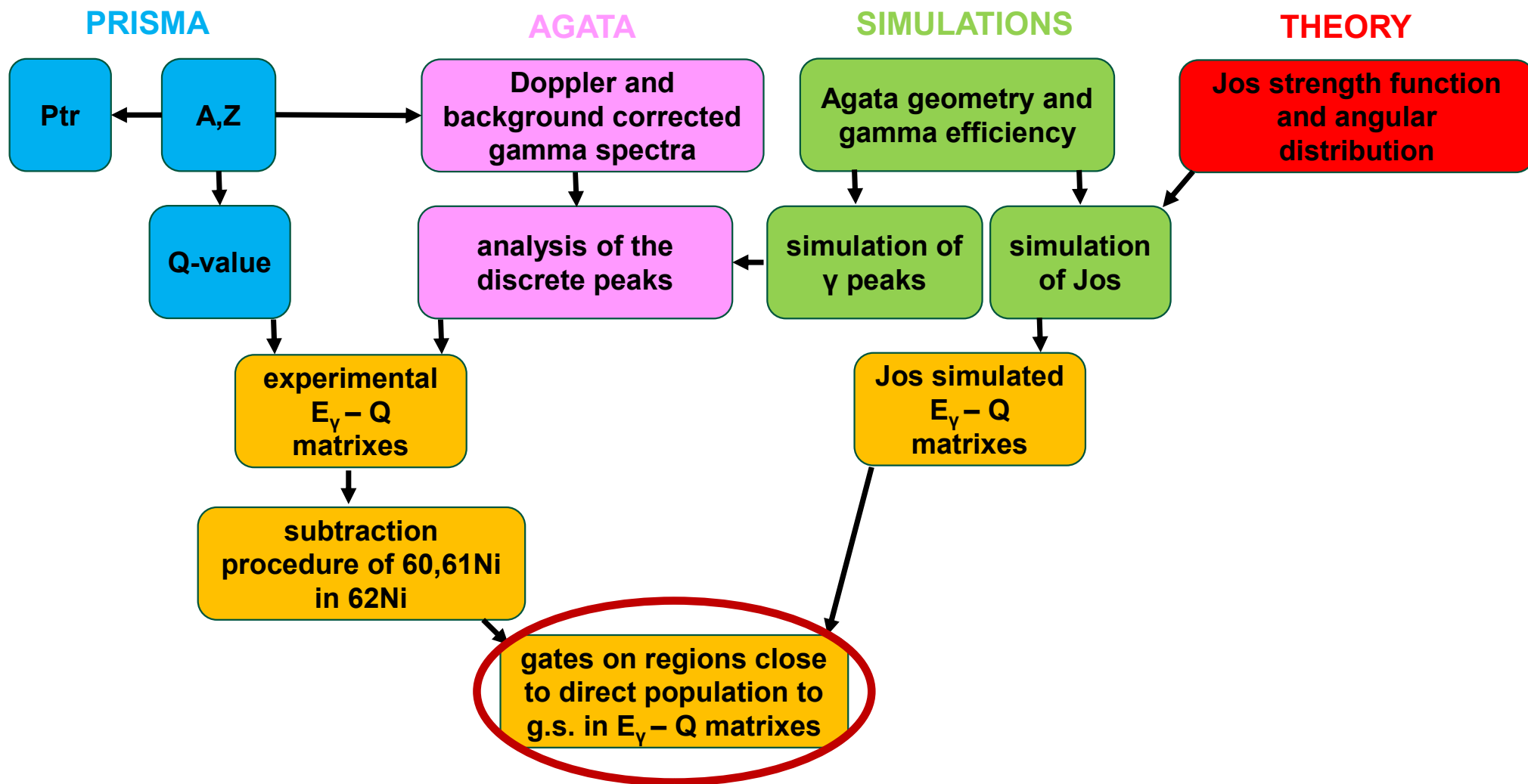
$$= S_y - 2 \cdot S(1n) \cdot (N2/N1) + S(0n) \cdot (N2/N0)$$

$S_{tr-corr}$ represents the sum of all possible contributions involving 2n correlations, among which may be those from Josephson effect

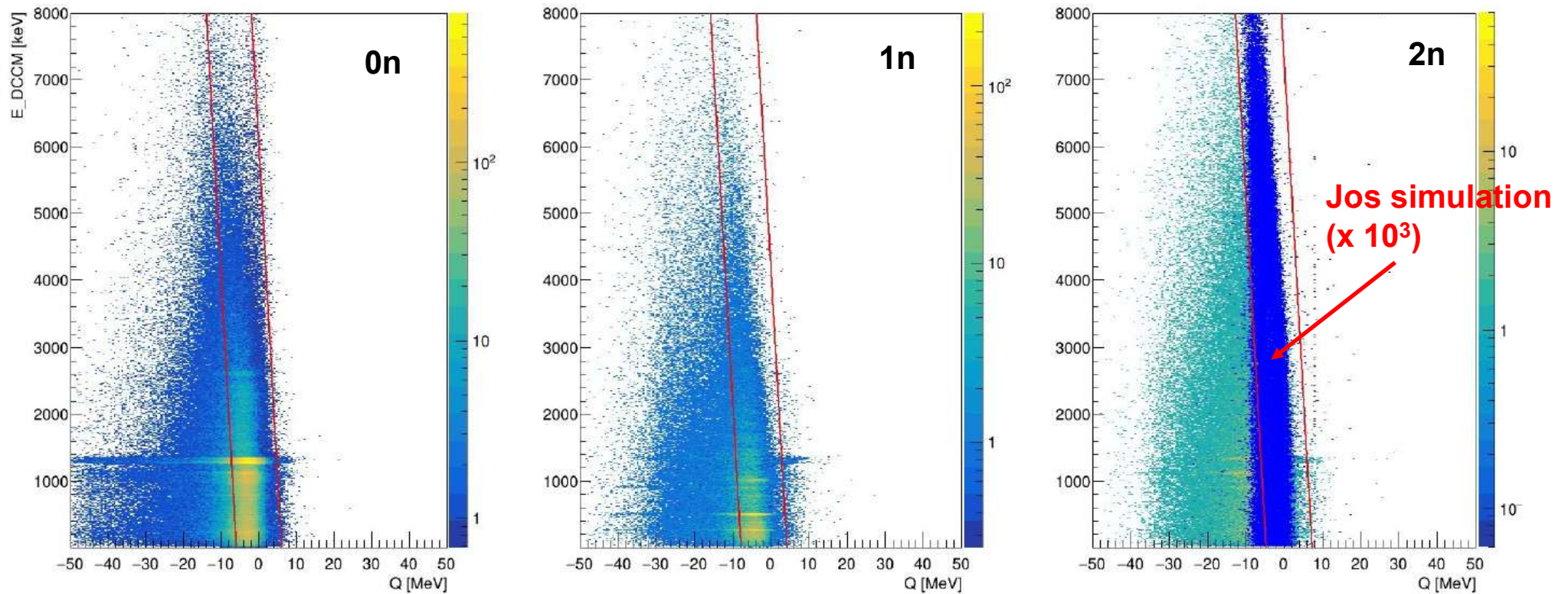


the inelastic part of ^{62}Ni is evaluated by rescaling the mass yields of ^{60}Ni

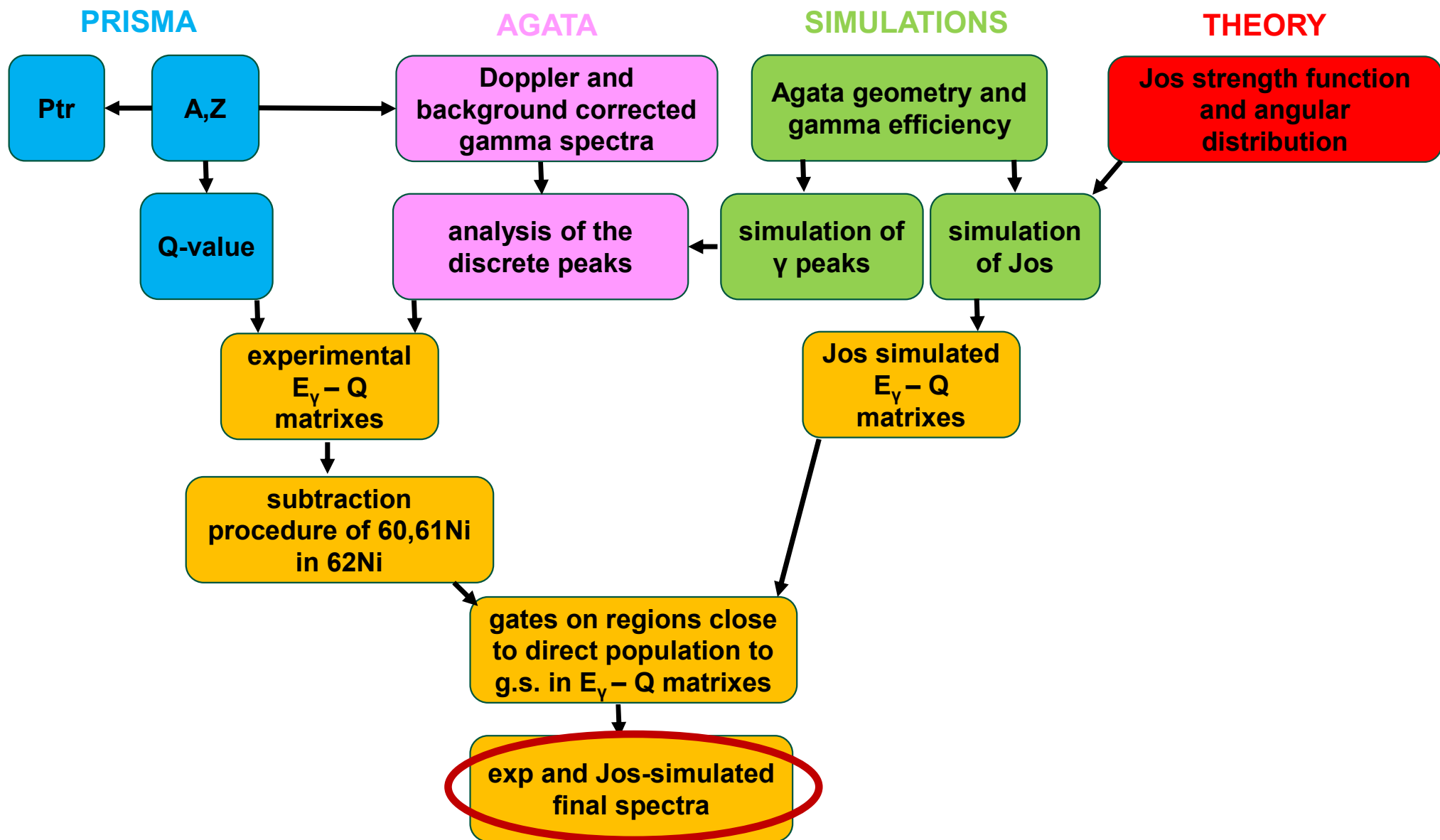
the uncorrelated part of ^{62}Ni is evaluated first subtracting from ^{61}Ni the mass rescaled ^{60}Ni part, and then rescaling x2 the residual ^{61}Ni strength



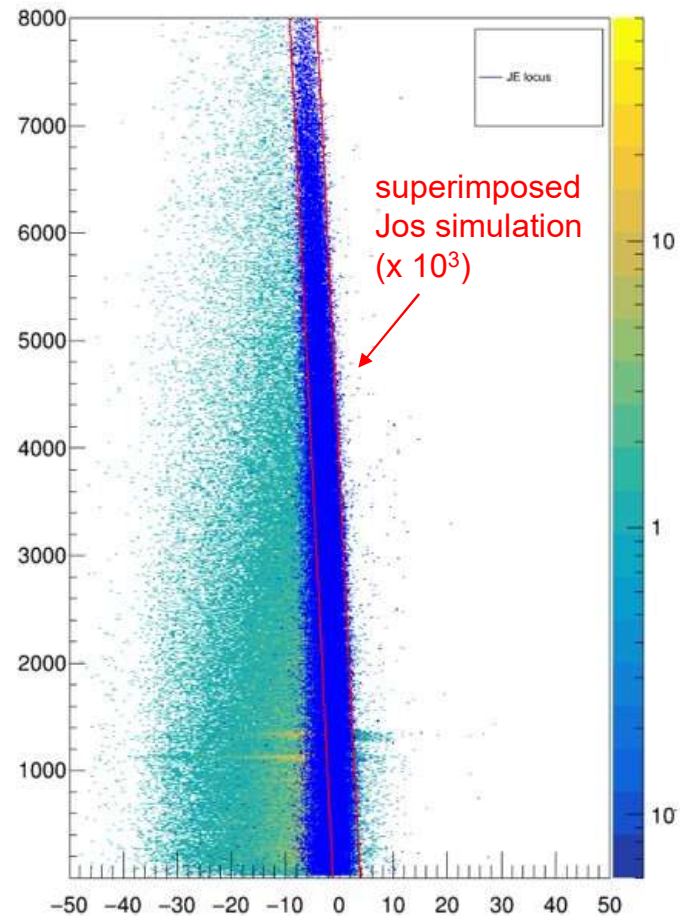
Experimental and simulated Q-Egamma matrixes



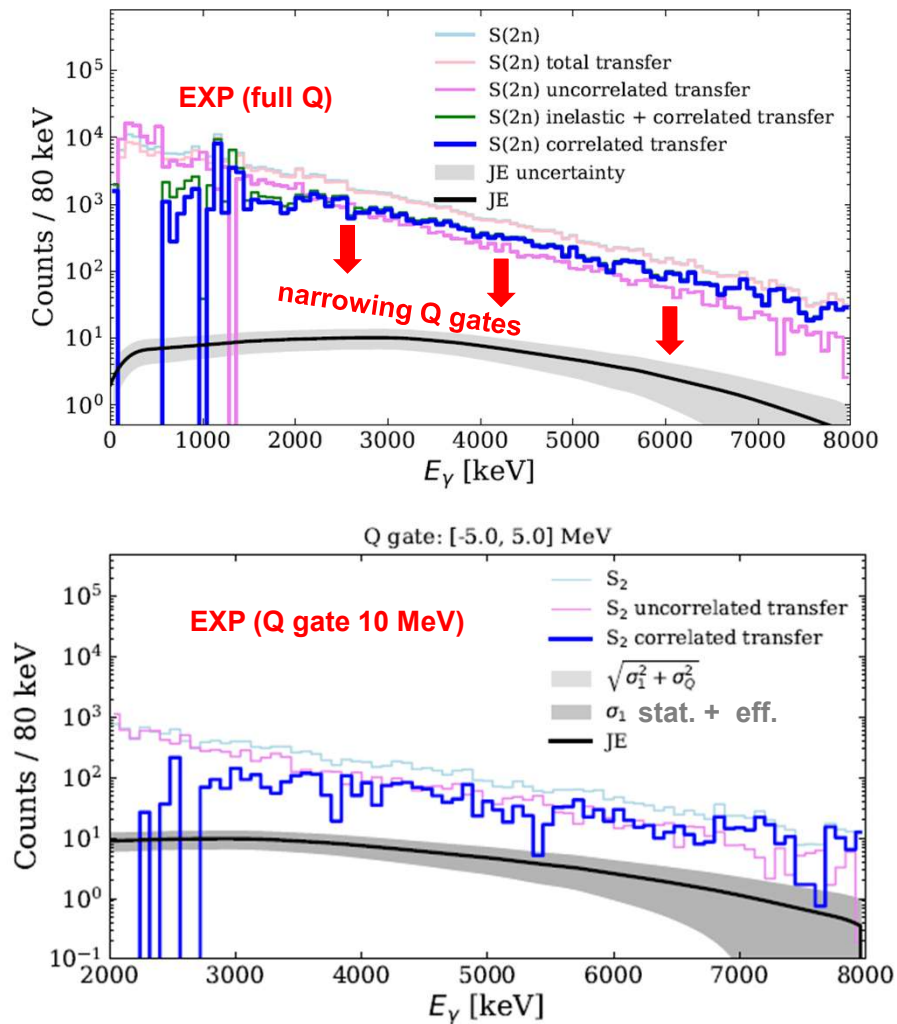
The Jos simulation defines a band in the Q-Egamma matrix of the 2n channel. To attribute the experimental events in the same region to a true effect we implemented a special subtraction procedure by scaling (for the cross section ratios) the events inside similar bands for the 0n and 1n channels



Gating on Q-Egamma matrixes

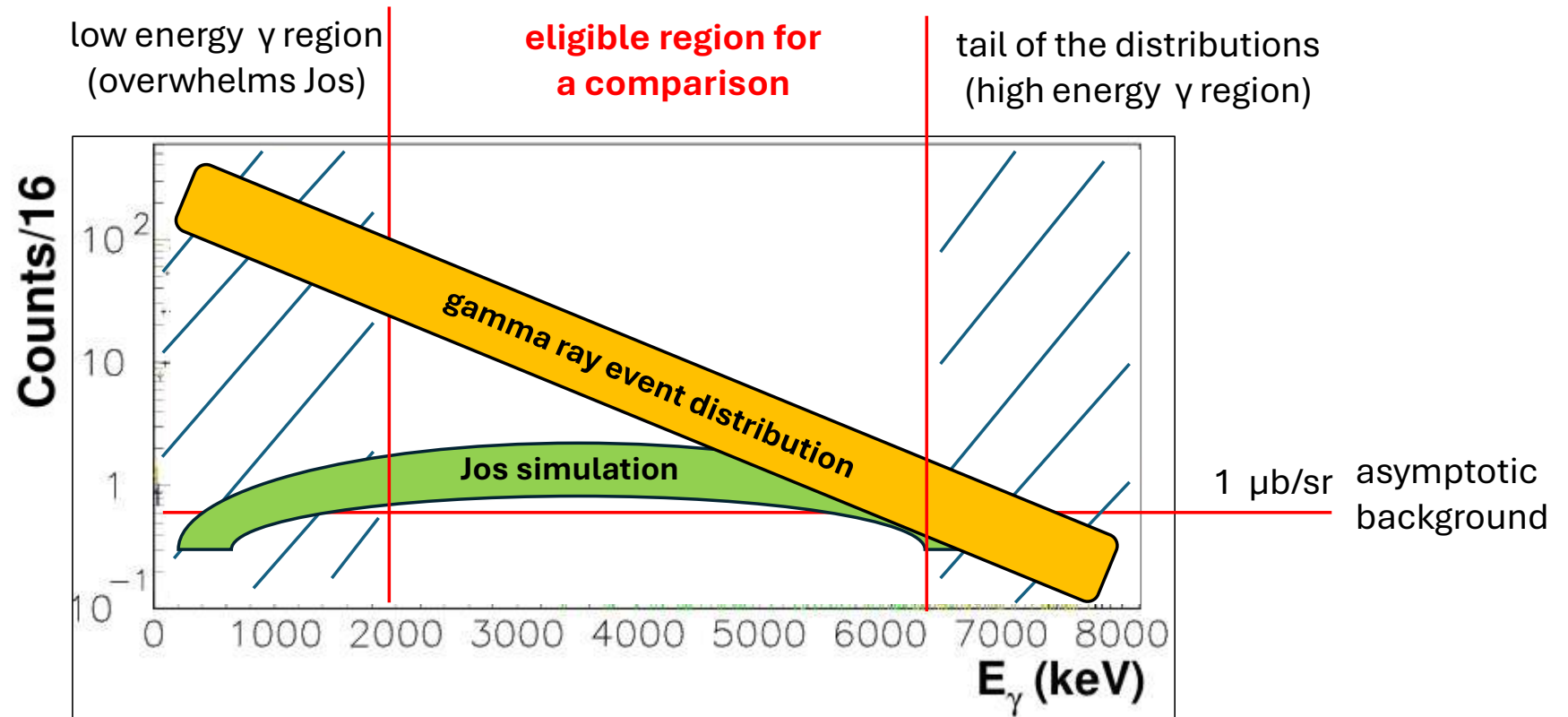


Data analysis by G.Andreetta (PhD)



analysis is in progress to extract the final distributions and to characterize the statistical significance of the obtained results

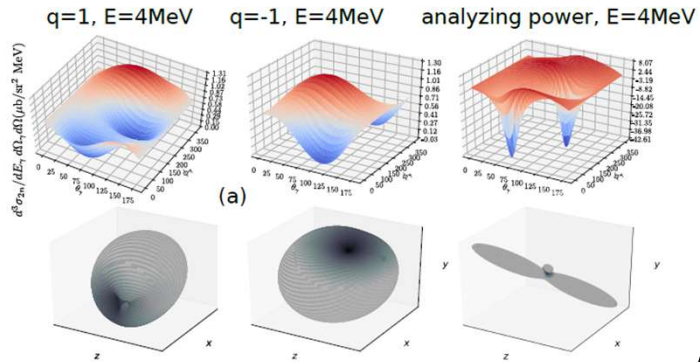
Summary : schematic overview of present situation



analysis is in progress to extract the final distributions and characterize the statistical significance of the obtained results

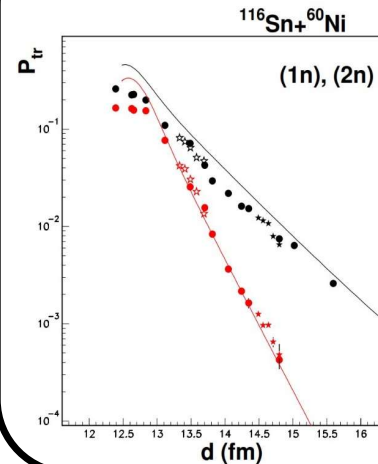
Revealing clear-cut features of a nuclear Josephson effect calls for new important measurements

detailed gamma ray angular distributions

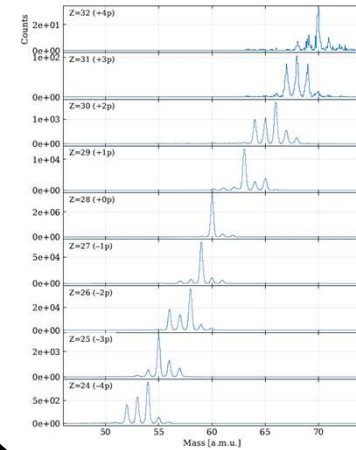


G.Potel et al, arXiv:2206.05351v2 [nucl-th] 17 Jun 2022

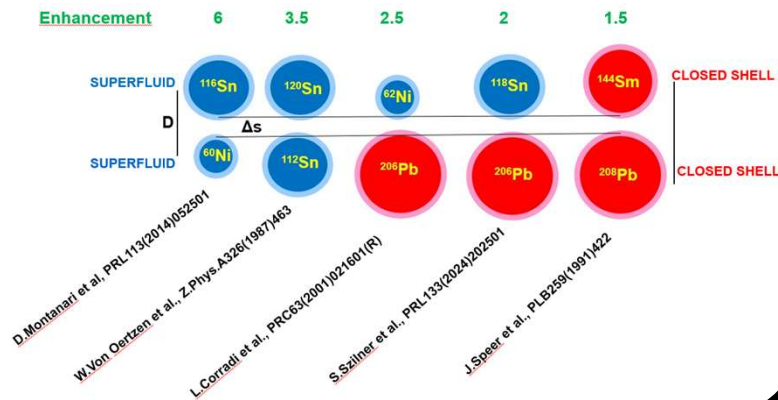
different energies



other channels



other nuclei with different structure



different set-ups (different background)

