Sub-barrier transfer reactions and search for signatures of a nuclear Josephson effect with PRISMA+AGATA: the $^{60}Ni+^{116}Sn$ system

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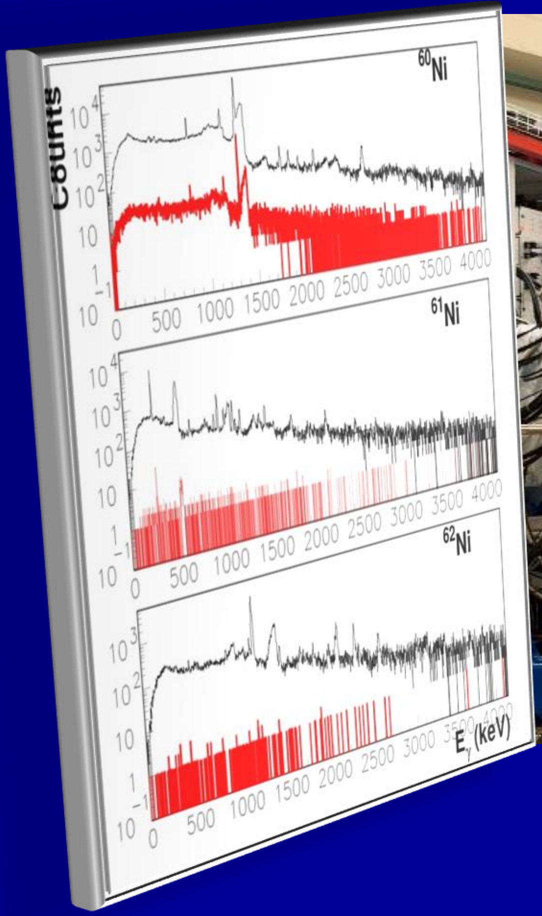
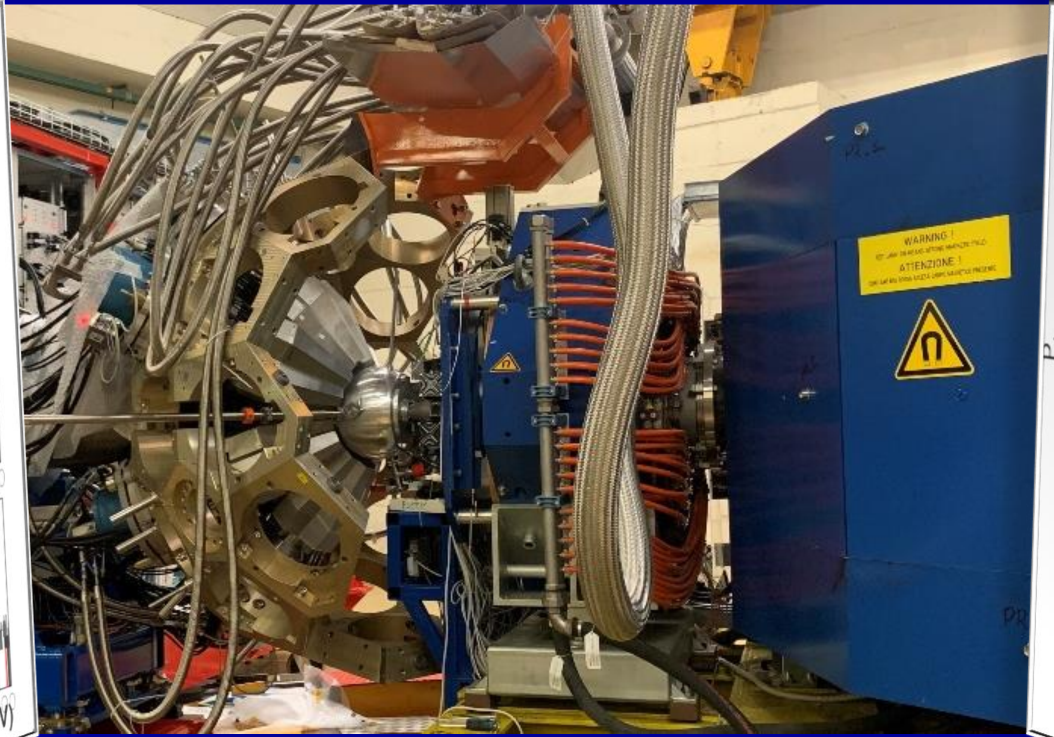
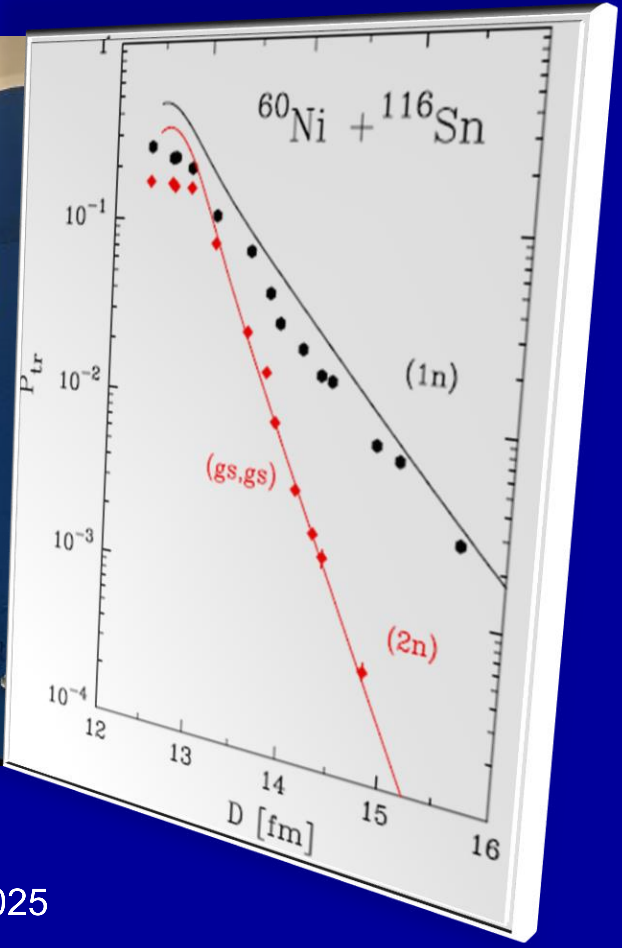






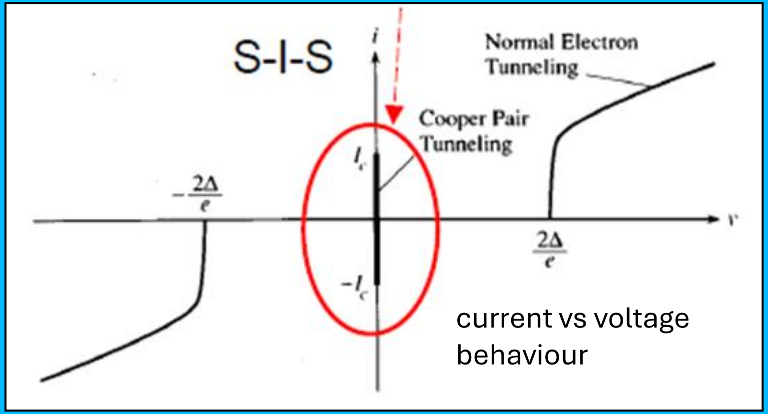
Int. Conf. EuNPC2025, Caen, France, September 22-26, 2025

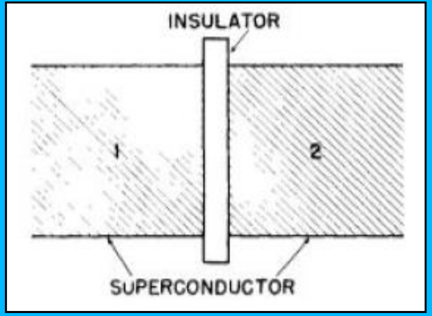
The Josephson effect: main features

DC Josephson

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

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



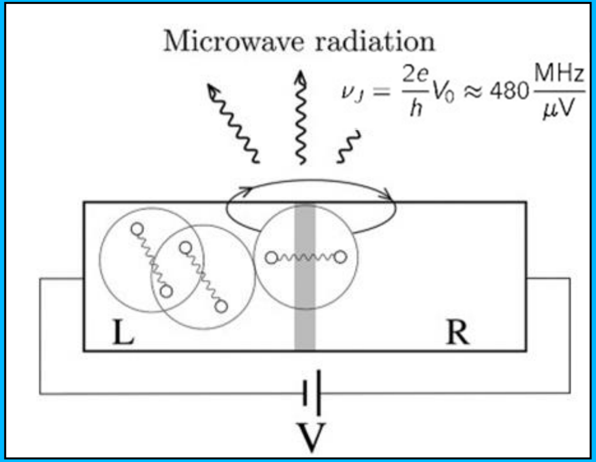


with no applied voltage a direct current flows across the link with a value defined by the relative gauge phase

AC Josephson

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

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



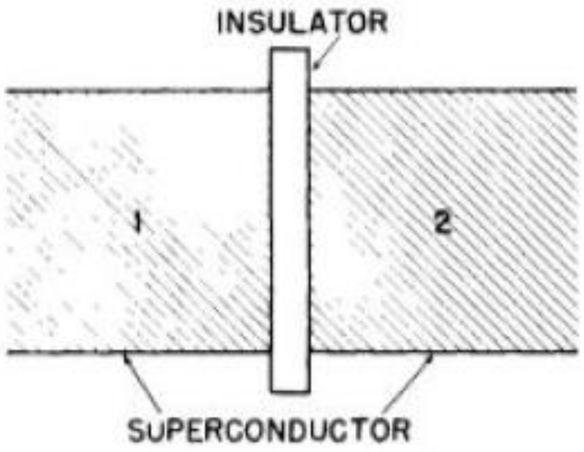
$$\phi_{rel}(t) = \phi_{rel}(0) - \frac{eV}{\hbar}t$$

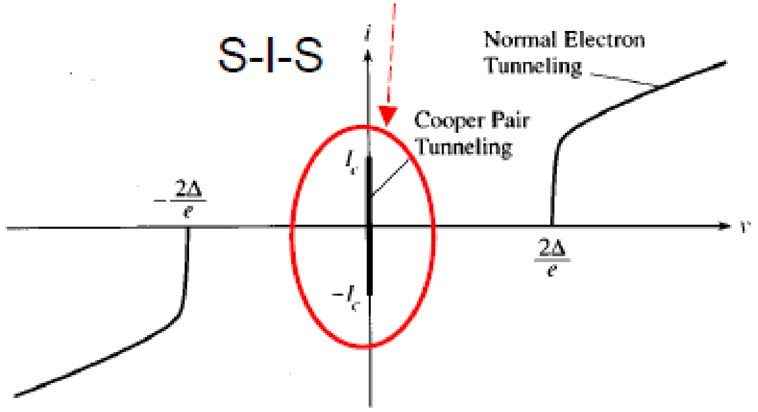
$$\omega_J = \frac{2eV}{\hbar}$$

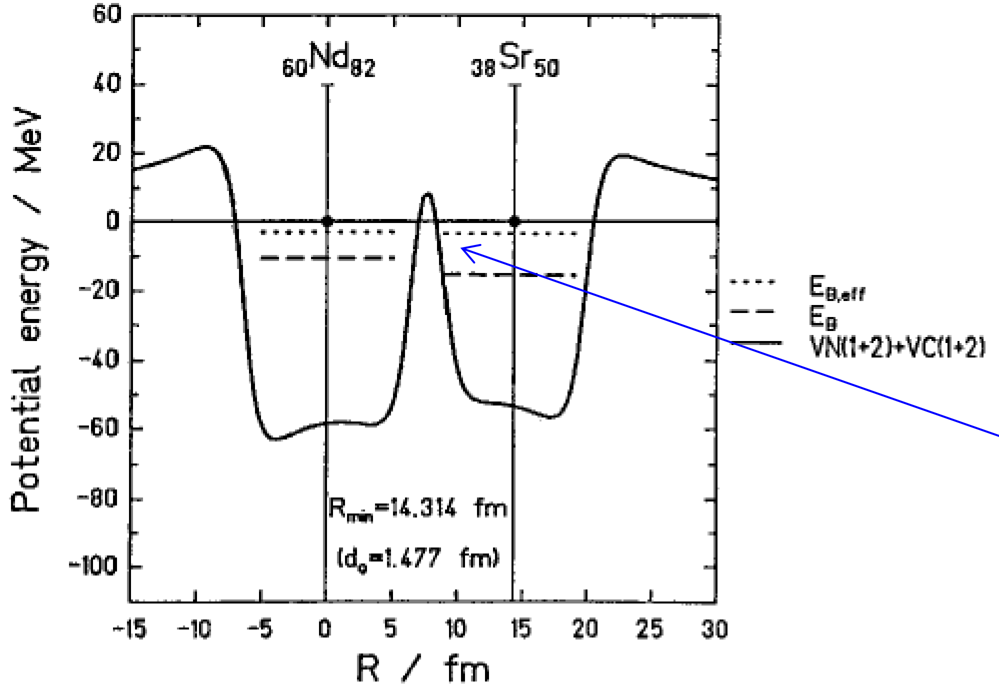
the voltage causes the phase difference across the junction to increase over time. Since phases which differ in 2π are equivalent, a linear phase growth produces an AC current and thus to emission of photons

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

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

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

PHYSICAL REVIEW C **103**, L021601 (2021)

Letter | Editors' Suggestion | Featured in Physics

Quantum entanglement in nuclear Cooper-pair tunneling with γ rays

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[2]*Departamento de Física Aplicada III, Escuela Superior de Ingenieros, Universidad de Sevilla, Camino de los Descubrimientos, Sevilla, Spain*

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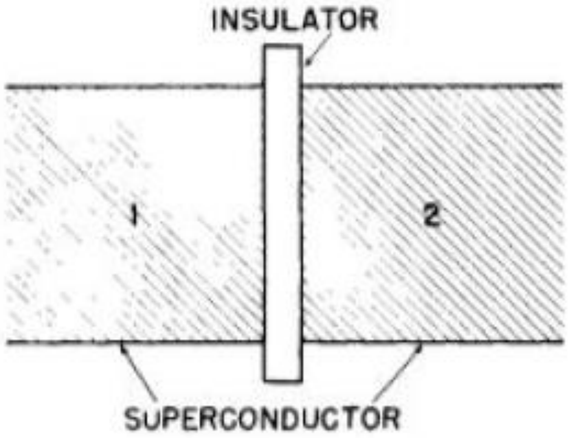
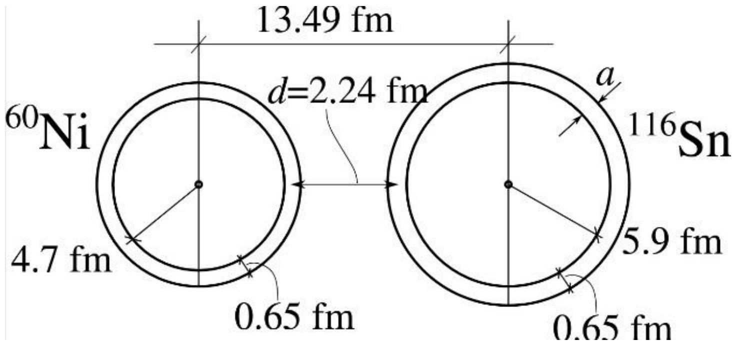
While Josephson-like junctions, transiently established in heavy-ion collisions ($\tau_{\mathrm{coll}} \approx 10^{-21}$ s) between superfluid nuclei–through which Cooper-pair tunneling (Q-value Q_{2n}) proceeds mainly in terms of successive transfer of entangled nucleons–is deprived from the macroscopic 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 $\hbar/\tau_{\mathrm{coll}}$ is predicted.

from macroscales to femtoscales

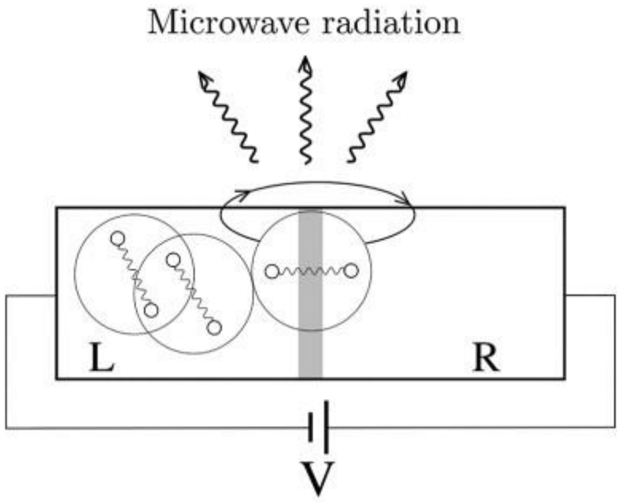


dielectric layer

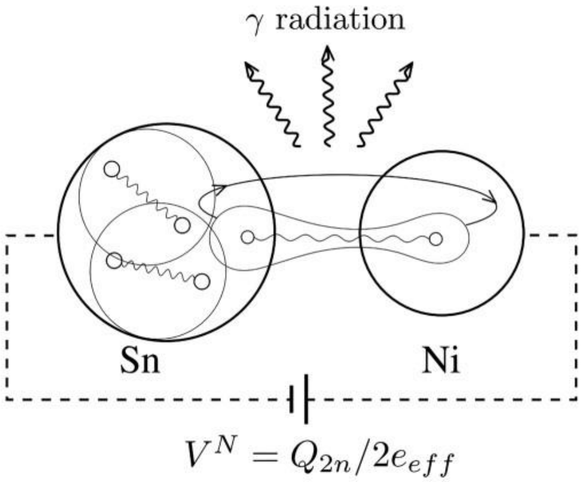


surface-surface distance of nuclei at the distance of closest approach

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



applied voltage



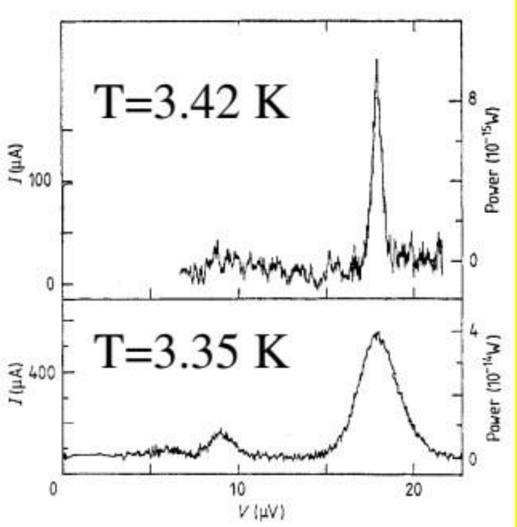
reaction Q-value divided by the effective charge of the tunneling Cooper pair

Possible Josephson-like effect in nuclear physics

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**

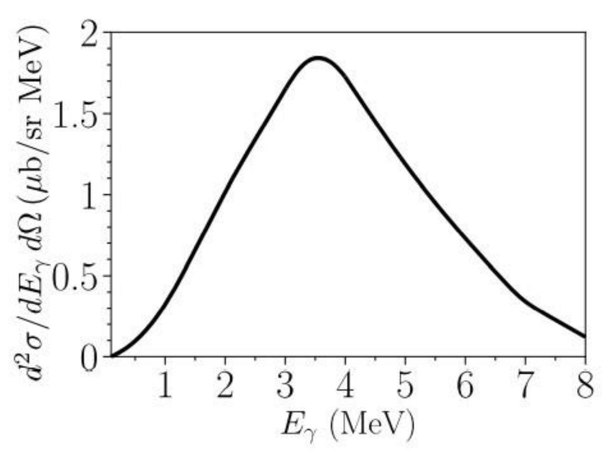
$$\nu_J = \frac{2e}{h} V_0 \approx 480 \frac{\text{MHz}}{\mu\text{V}}$$

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

double differential cross section for γ emission

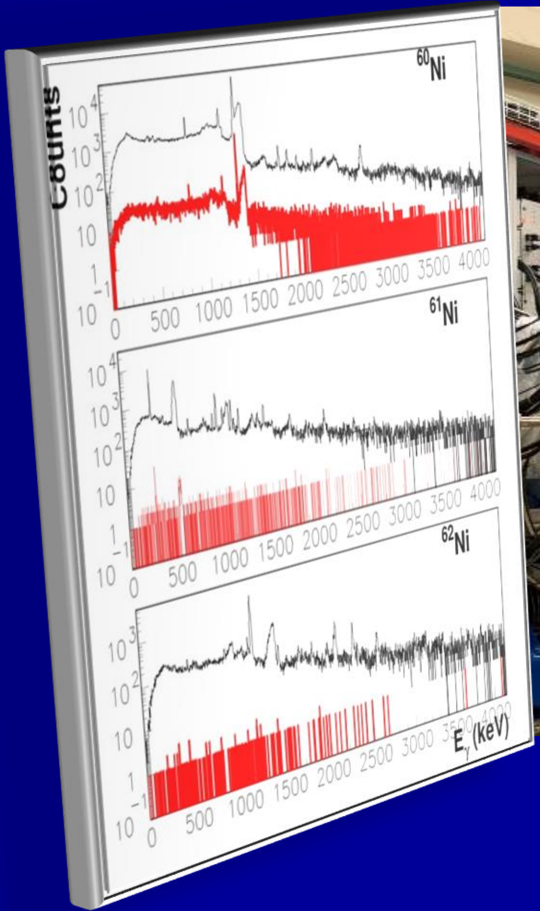


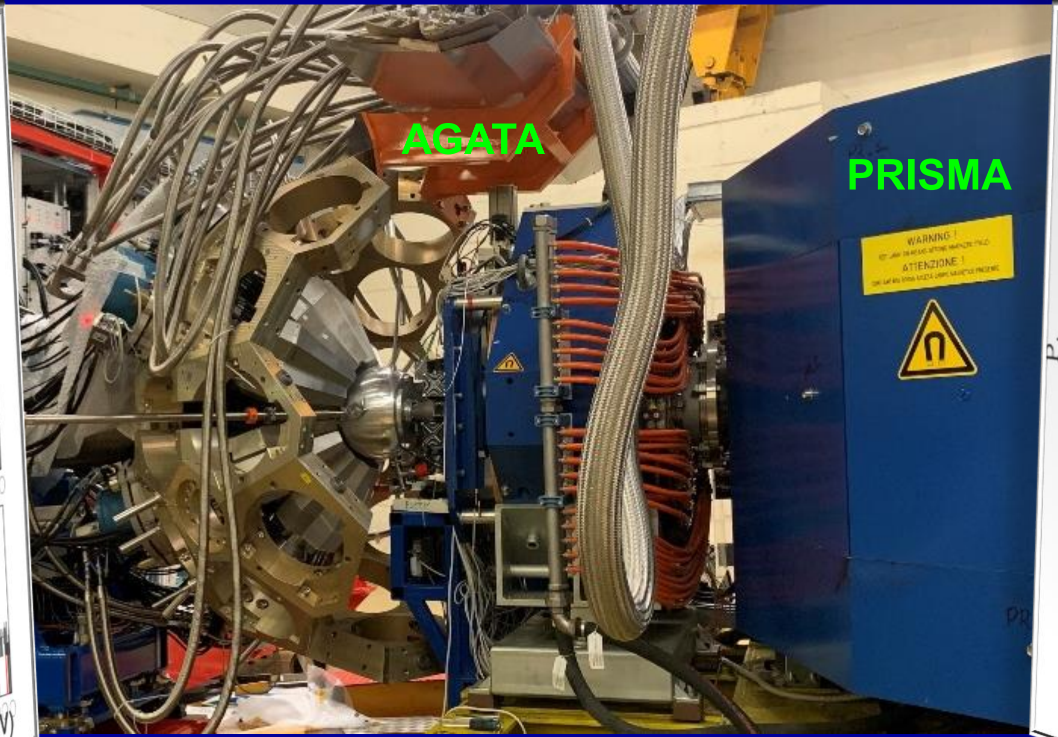
$$\frac{d^2\sigma}{d\Omega dE_\gamma} = \left(\frac{\mu_i \mu_f}{(2\pi\hbar^2)^2} \frac{k_f}{k_i}\right)\left(\frac{8\pi}{3} \frac{E_\gamma^2}{(\hbar c)^3}\right) \times \left|T_{m_\gamma}(\mathbf{k}_f, \mathbf{k}_i)\right|^2 \delta(E_\gamma + E_f - (E_i + Q))$$

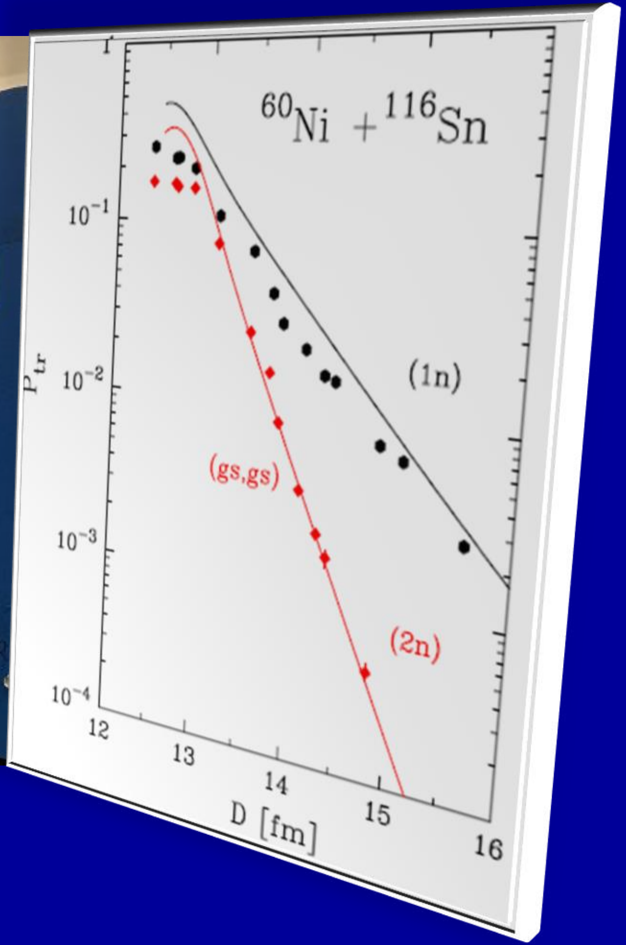
G.Potel, F. Barranco, E. Vigezzi and R. A. Broglia, Phys. Rev. C103(2021)L021601

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

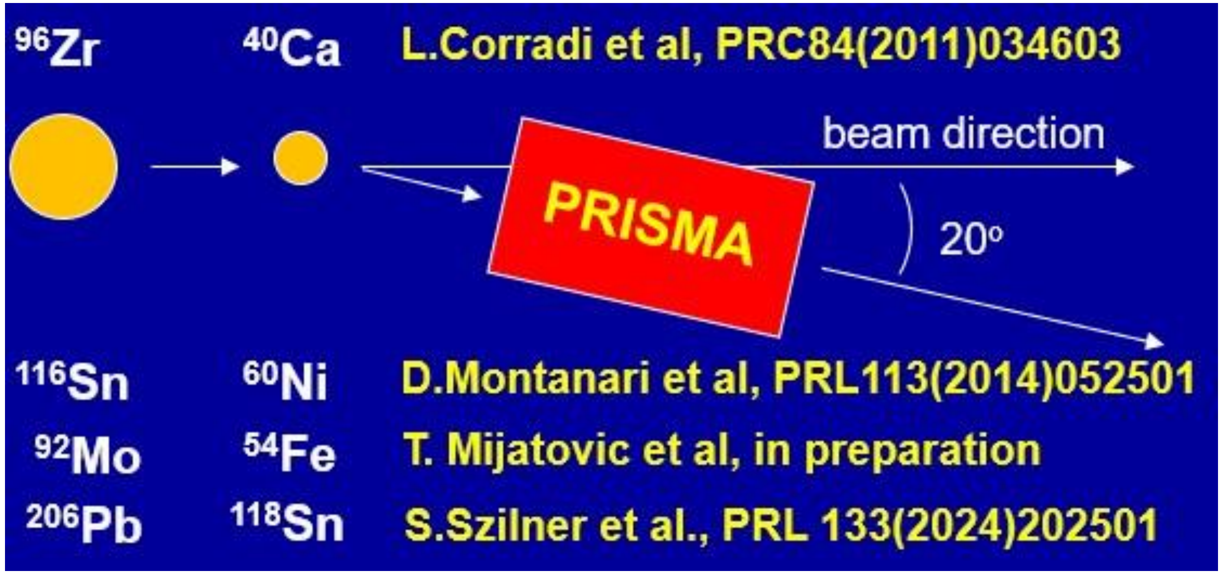
availability of data for the $^{60}Ni+^{116}Sn$ system in a wide energy range
availability of the tracking spectrometer PRISMA (high A,Z,Q resolution and efficiency)
availability of the AGATA gamma array

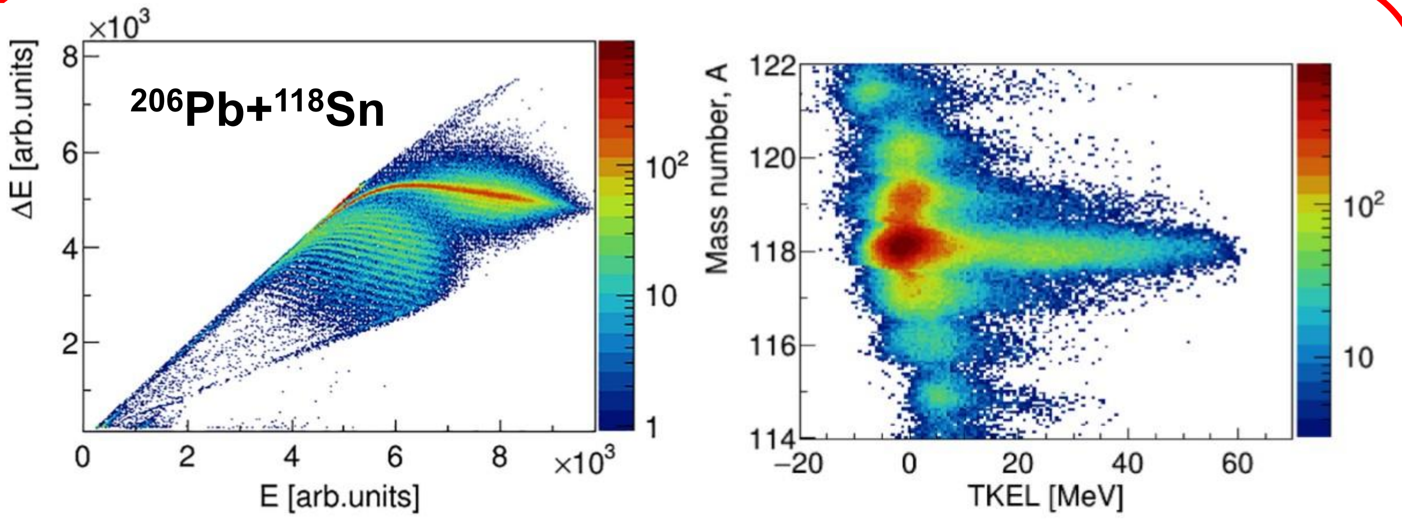






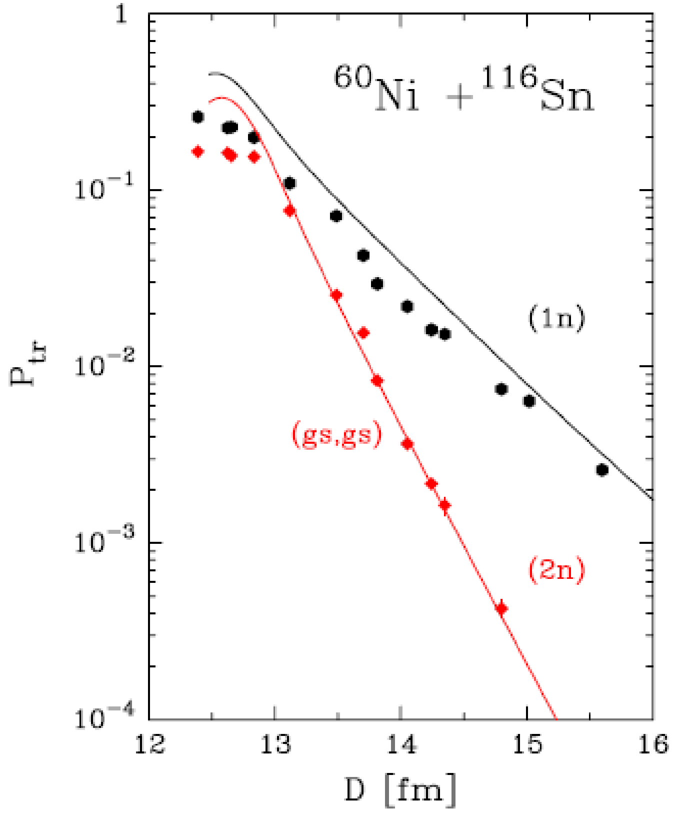
Detection of target like ions in inverse kinematics with PRISMA





see talk by S.Szilner

$Q_{g.s.}$ for +2n very close to Q_{opt} (~ 0 MeV)

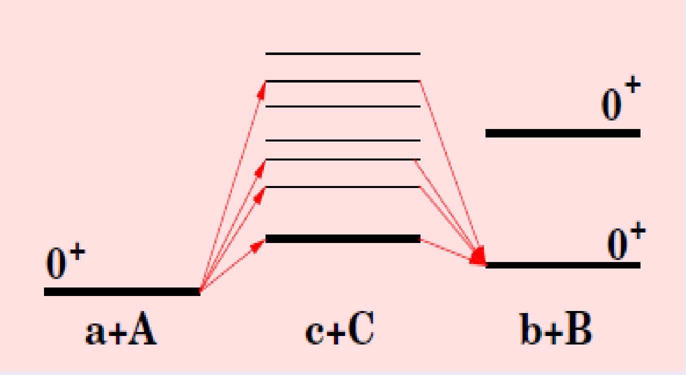


The experimental transfer probabilities are well reproduced in absolute values, for the first time with heavy ion reactions, by microscopic calculations which incorporate a successive transfer process and a microscopic optical potential

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

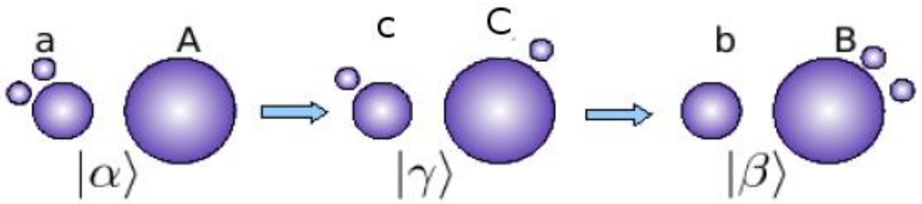
Two particle transfer (semiclassical theory, microscopic calculations)

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



3 terms : simultaneous, orthogonal and successive

only the successive term contributes to the transfer amplitude



$$(c_\beta)_{\rm succ} = \frac{1}{\hbar^2}\sum_{a_1,a_1'} B^{(A)}(a_1a_1;0)B^{(a)}(a_1'a_1';0)2\frac{(-1)^{j_1+j_1'}}{\sqrt{(2j_1+1)}\sqrt{(2j_1'+1)}}\sum_{m_1m_1'}(-1)^{m_1+m_1'}$$
$$\times\int_{-\infty}^{+\infty} dt\, f_{m_1m_1'}(\mathcal{R})e^{i[(E_\beta-E_\gamma)t+\delta_{\beta\gamma}(t)+\hbar(m_1'-m_1)\Phi(t)]/\hbar}$$
$$\times\int_{-\infty}^{t} dt\, f_{-m_1-m_1'}(\mathcal{R})e^{i[(E_\gamma-E_\alpha)t+\delta_{\gamma\alpha}(t)-\hbar(m_1'-m_1)\Phi(t)]/\hbar}.$$

Original proposal approved by the LNL PAC → experiment performed in 2023

PIAVE-ALPI ACCELERATOR

Search for a Josephson-like effect in the $^{116}Sn+^{60}Ni$ system

PRISMA + AGATA experiment

Spokesperson(s): L. Corradi, S. Szilner
(GLIMOS: L. Corradi)

L. Corradi[1], E. Fioretto[1], F. Galtarossa[1], A. Goasduff[1], A. Gottardo[1], A. M. Stefanini[1], J. J. Valiente-Dobón[1], M. Balogh[1], D. Brugnara[1], G. de Angelis[1], A. Ertoprak[1], B. Gongora[1], T. Marchi[1], D.R. Napoli[1], J. Pellumaj[1], R.M. Pérez-Vidal[1], M. Sedlak[1], L. Zago[1], I. Zanon[1], G. Montagnoli[2], D. Mengoni[2], M. del Fabbro[2], F. Scarlassara[2], P. Aguilera[2], D. Bazzacco[2], R. Escudeiro[2], S.M. Lenzi[2], R. Menegazzo[2], S. Pigliapoco[2], F. Recchia[2], K. Rezynkina[2], G. Zhang[2], S. Szilner[3], J. Diklić[3], D. Jelavić Malenica[3], T. Mijatović[3], M. Milin[4], G. Benzoni[5], S. Bottoni[6,5], A. Bracco[6,5], F. Camera[6,5], F. Crespi[6,5], R. Depalo[6,5], E. Gamba[6,5], S. Leoni[6,5], B. Million[5], O. Wieland[5], M. Caamano[7], Y. Ayyad[7], F. Barranco[8], G. Pollarolo[9], G. Potel[10], E. Vigezzi[5], R. A. Broglia[11,6]

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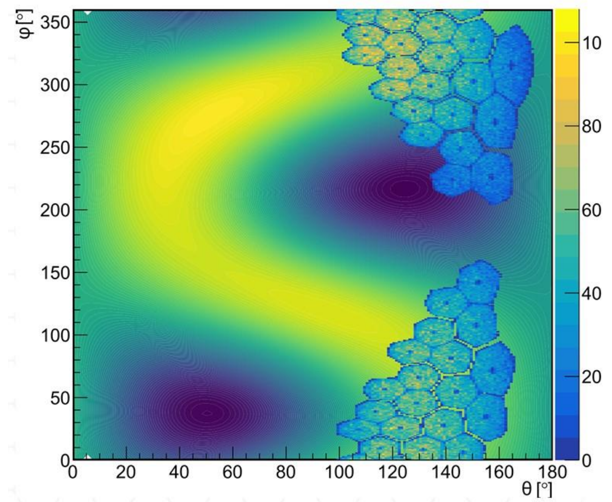
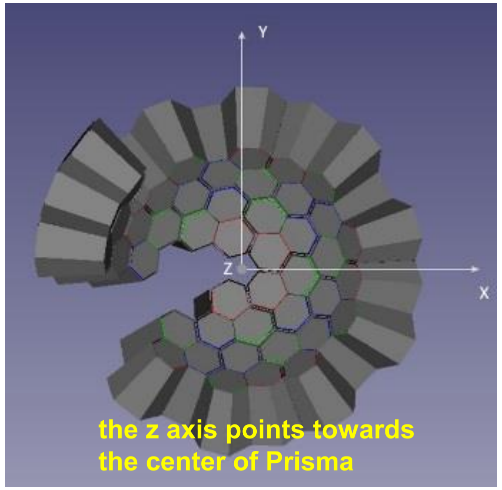
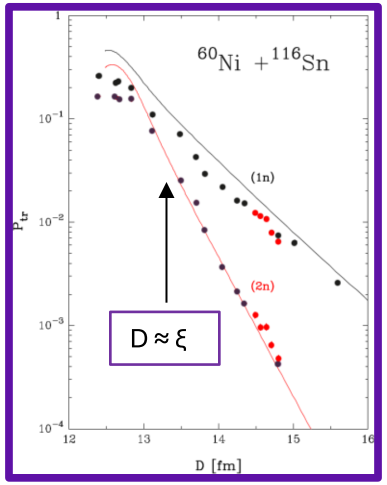
[9] *Dip. di Fisica Teorica, Universitá di Torino, and Istituto Nazionale di Fisica Nucleare, Torino, Italy*
[10] *Lawrence Livermore National Laboratory, Livermore, California, USA*
[11] *The Niels Bohr Institute, University of Copenhagen, Denmark*

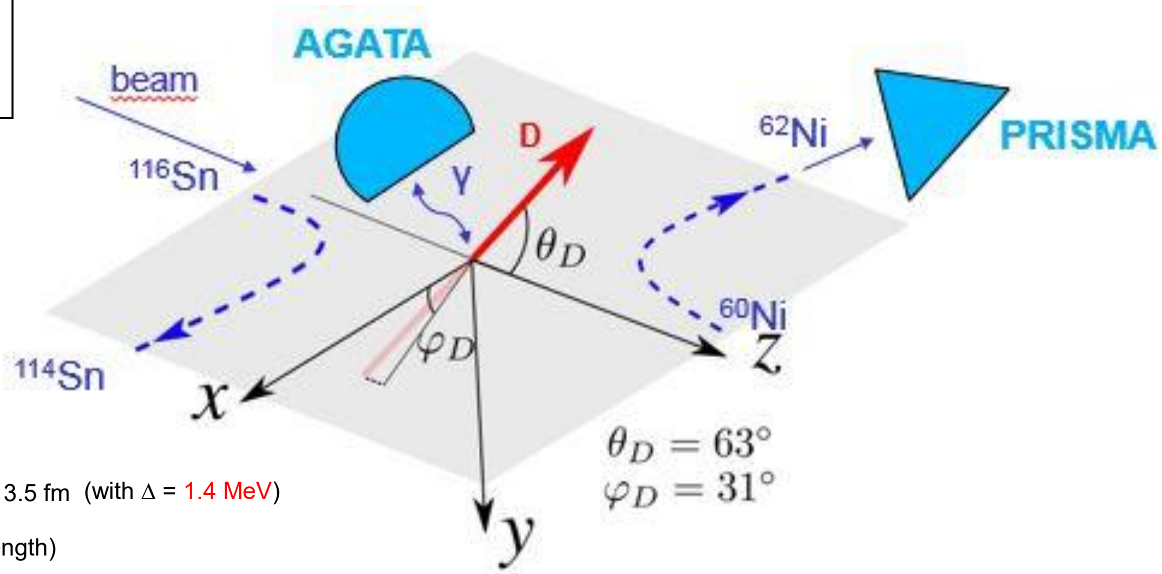
Search for a nuclear Josephson effect - PRISMA-AGATA experiment Feb. 2023





the theoretically predicted (**G.Potel et al.**) gamma ray angular pattern matches the detector's configuration for polar angles larger than ≈ 110°





$\xi = \frac{\hbar v_F}{\pi \Delta} \approx 13.5$ fm (with Δ = 1.4 MeV)

(correlation length)

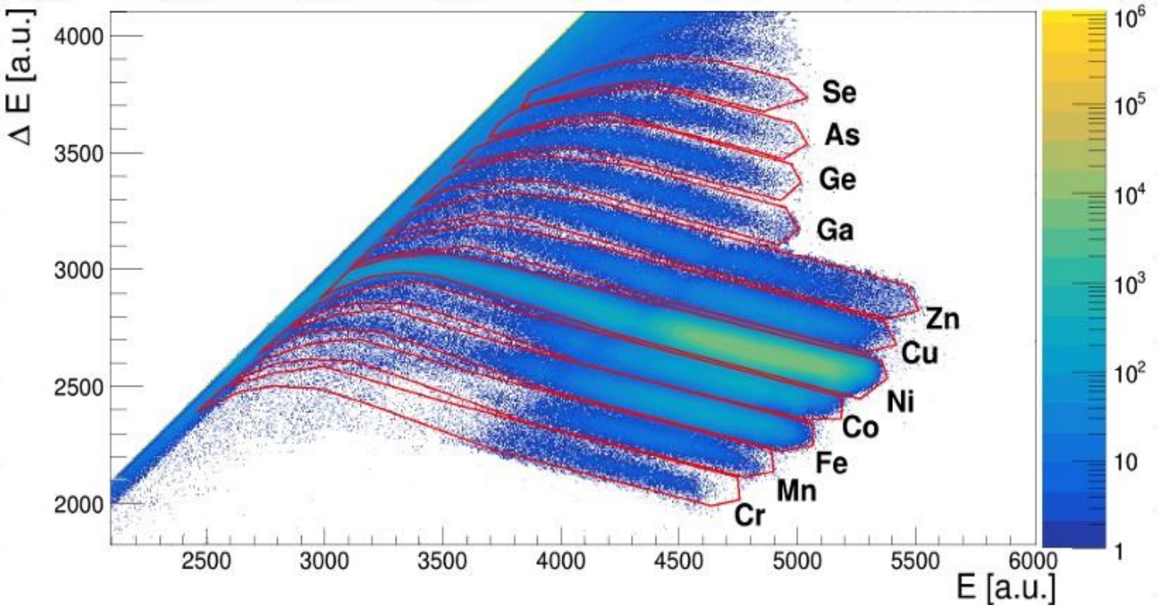
^{116}Sn beam PIAVE+ALPI
E_{lab} = 452.5 MeV, I = 2 pnA
Target thickness 200 μg/cm^2
Prisma $\Delta\Omega$ = 30 msr
Prisma θ_{lab} = 20°
Agata ε_γ = 2.8% (at 4 MeV)
Theoretical dσ/dΩ = 30.36 μb/sr

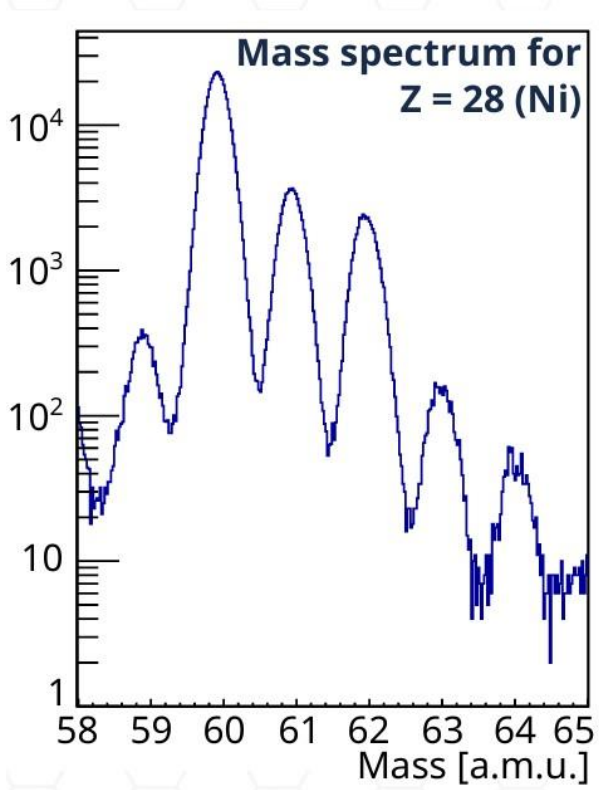
expected few tens/day
γ coincidences with ^{62}Ni ions

Data taken at INFN – Laboratori Nazionali di Legnaro

Spokespersons L.Corradi, S.Szilner

Preliminary results: nuclear charge and mass determination





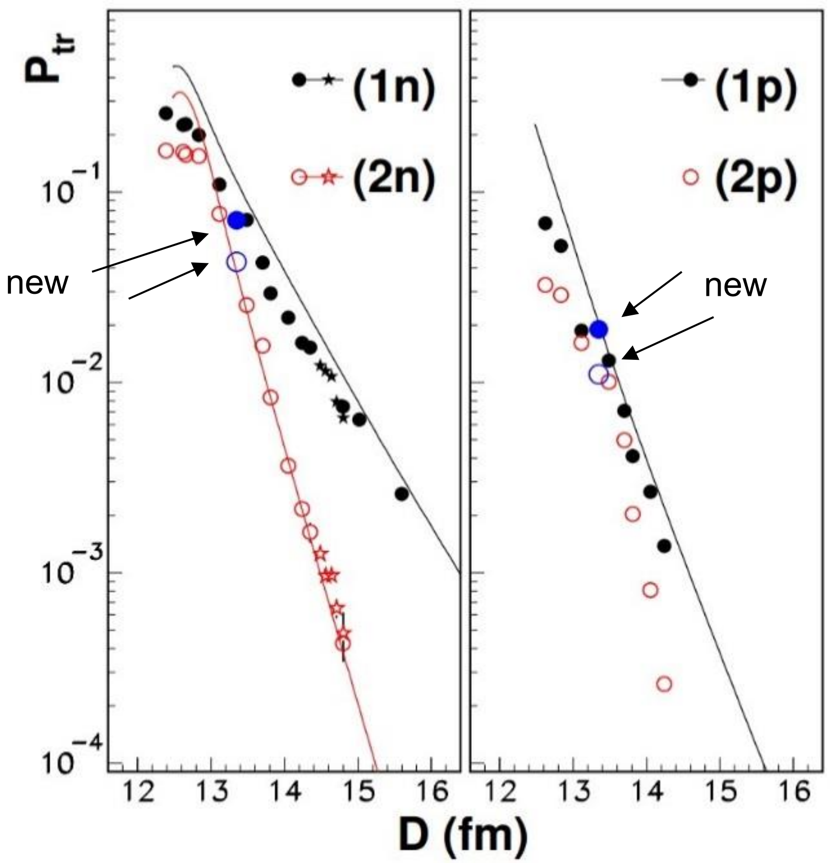
The high Z and A resolutions allowed to well distinguish the multitude of neutron and proton transfer channels at energies below the Coulomb barrier

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

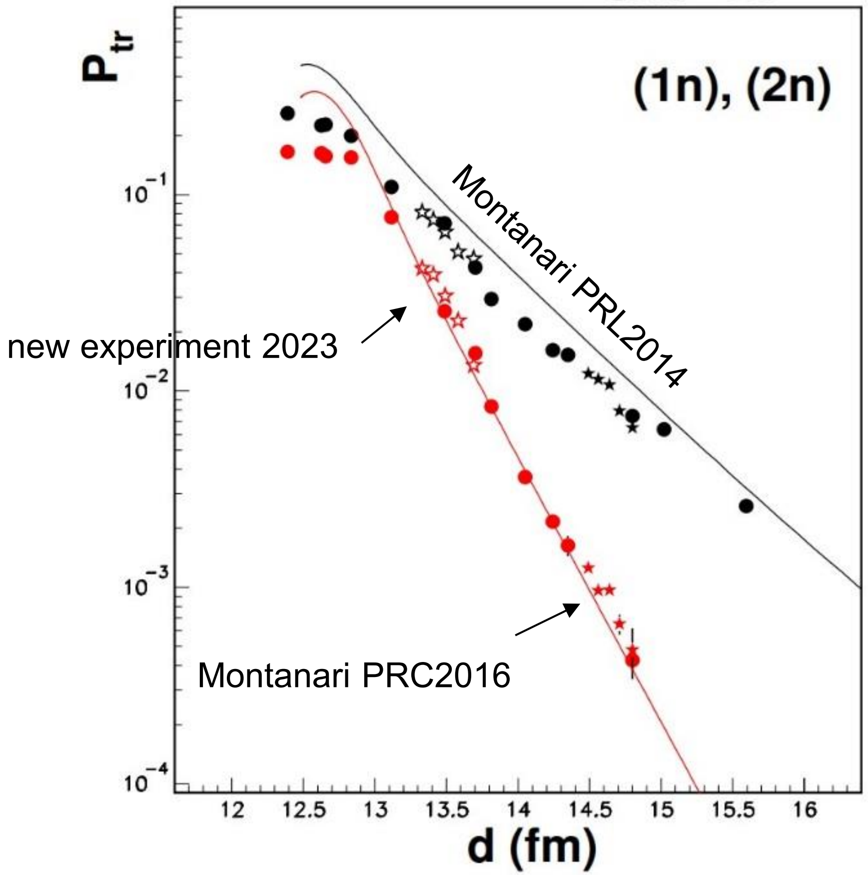
Data analysis by G.Andreetta (PhD)

Extraction of transfer probabilities

from total integral



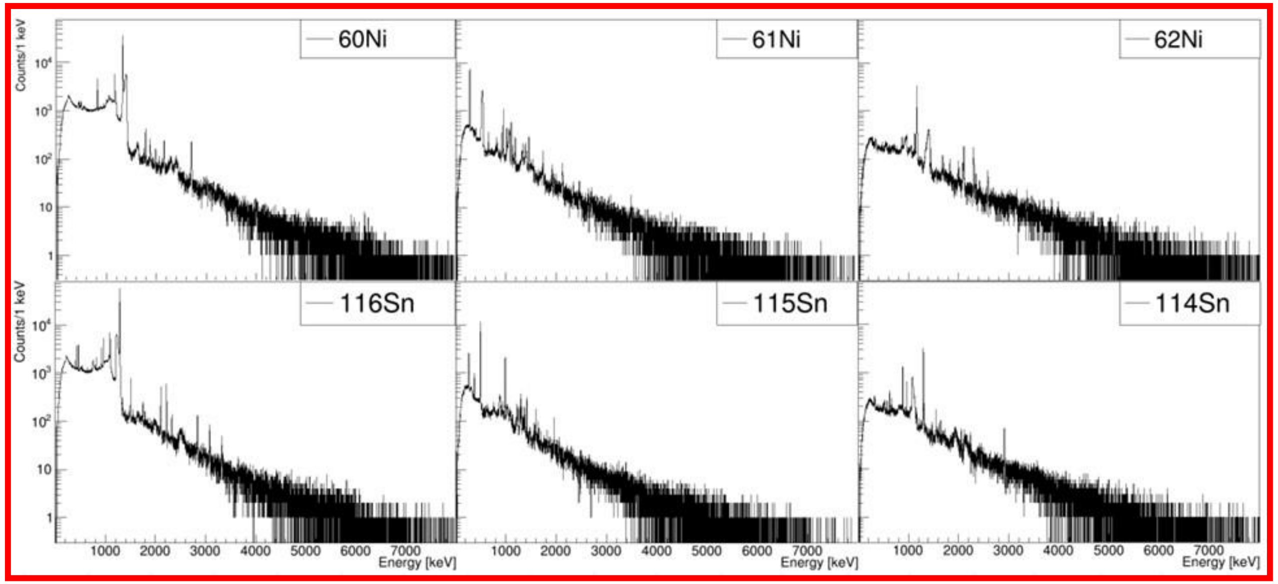
from binning in angular distribution



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

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

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



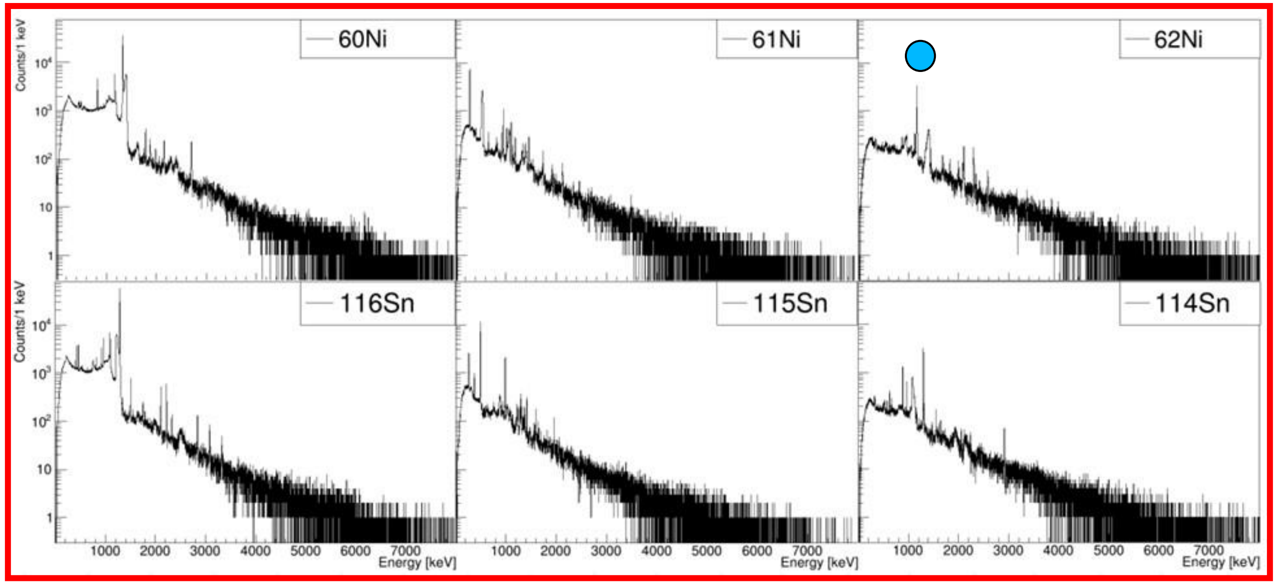
AGATA 2023 - 37 crystals

In this experiment (carried out at sub-barrier energies !) we could detect discrete gamma transitions at energies around 3 MeV with strengths about 3 orders of magnitudes lower than the main peaks

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

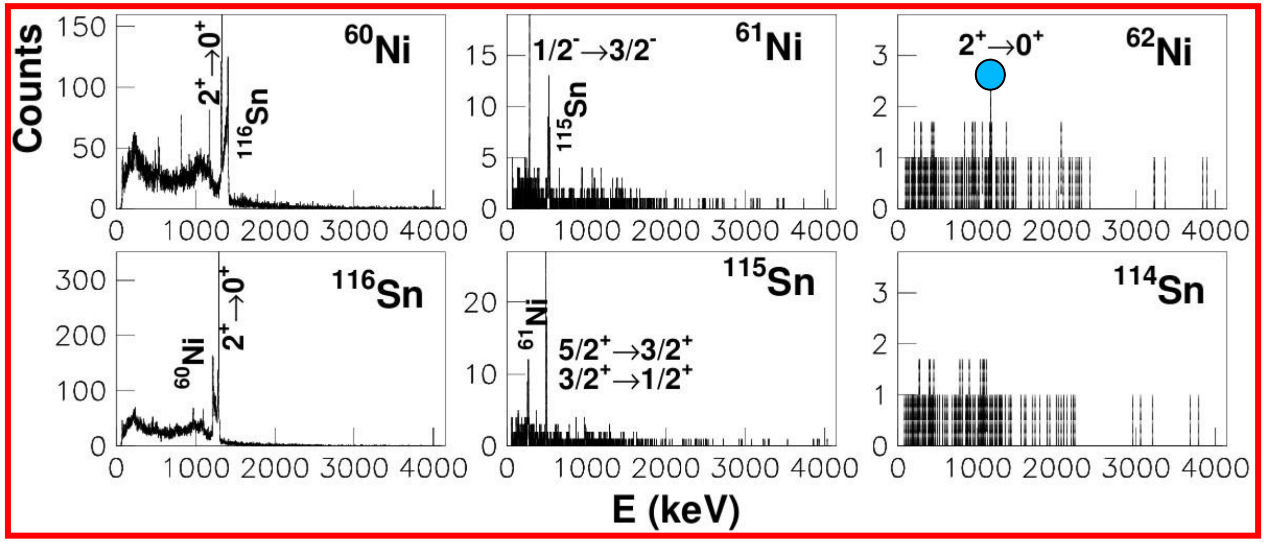
L.Corradi, S.Szilner et al., PRISMA+AGATA exp 2023

D = 13.5 fm ≈ ξ



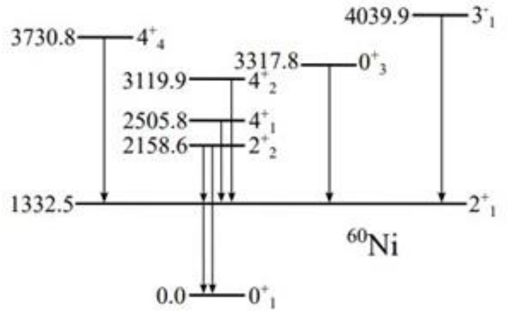
D.Montanari et al, PRC93(2016)054623

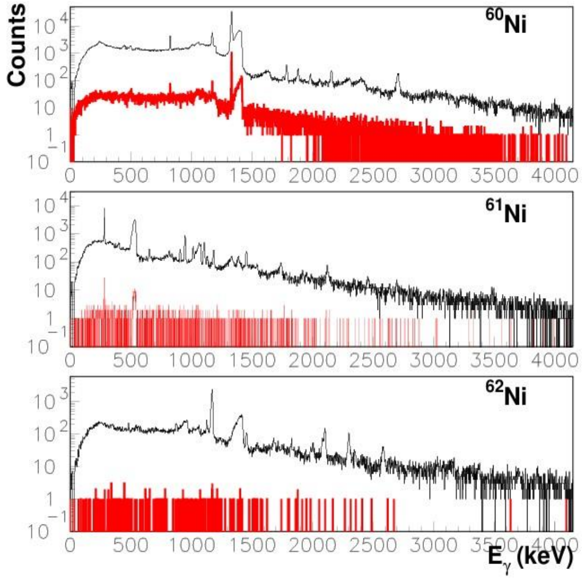
D = 14.5 fm > ξ

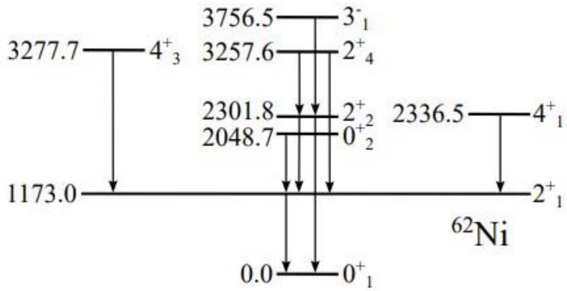


AGATA 2023 - 37 crystals

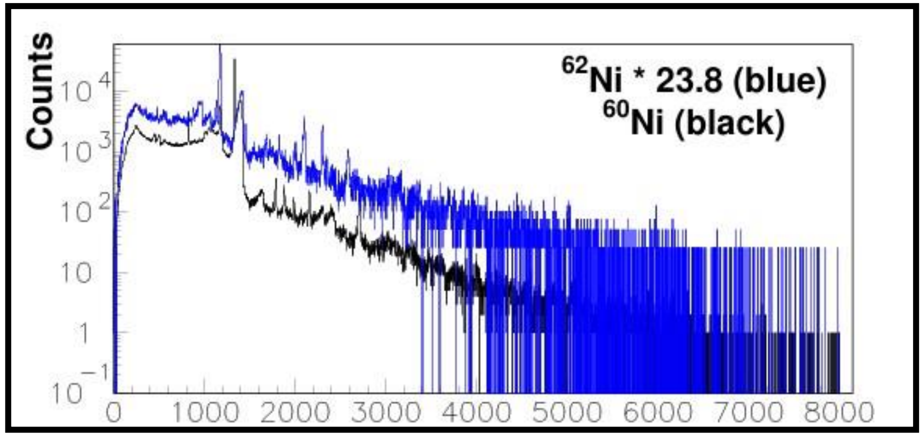
AGATA 2012 - 12 crystals







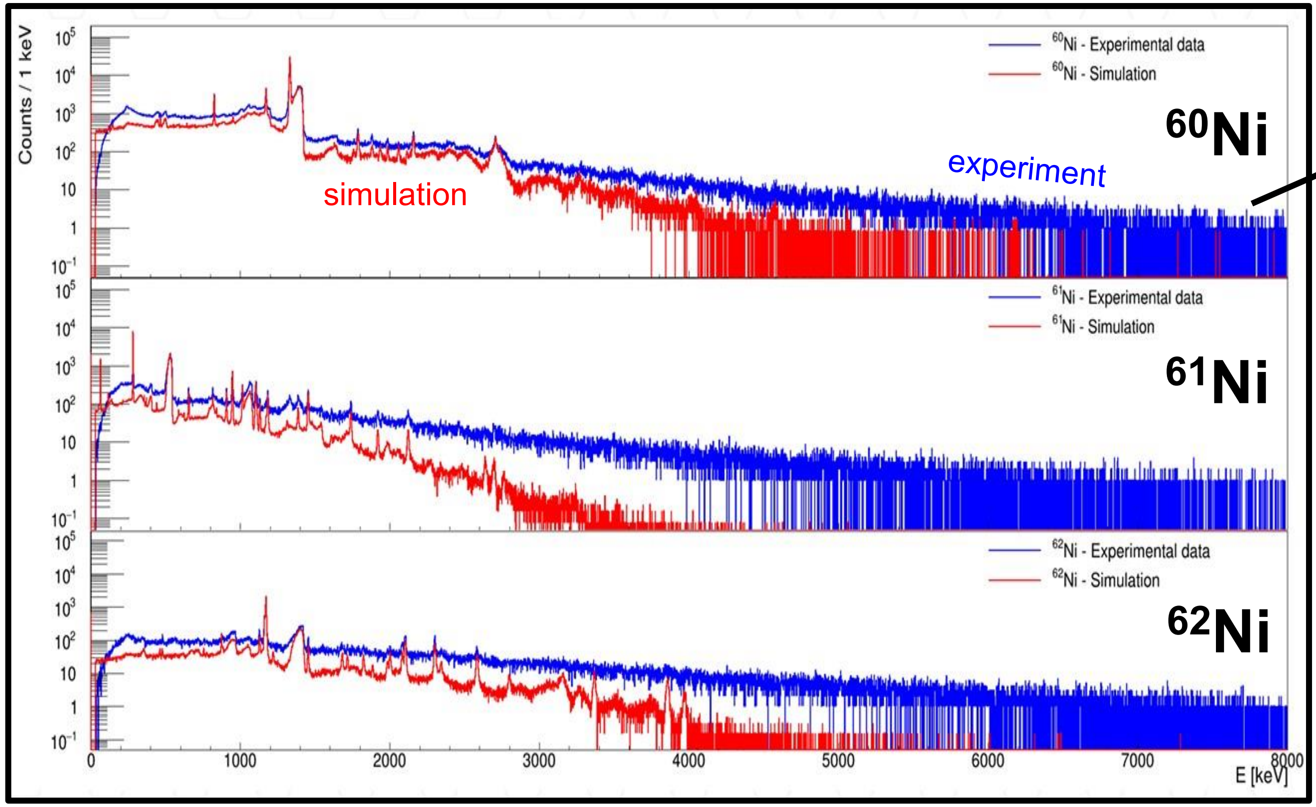
Experimental Doppler corrected gamma spectra compared with simulations

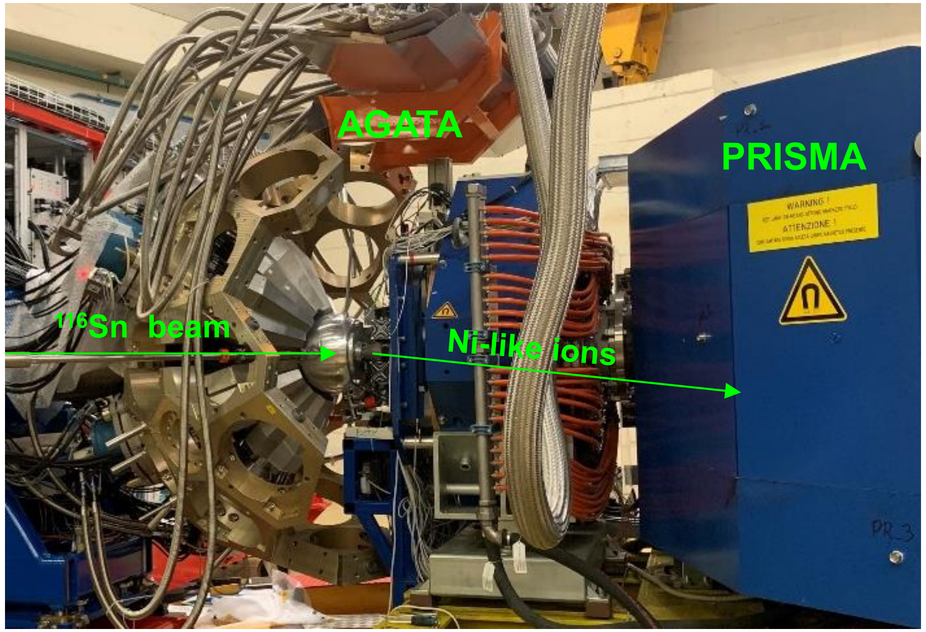


Average gamma background in ^{62}Ni : experiment >> simulations

Yield (^{62}Ni) x σ(^{60}Ni)/σ(^{62}Ni) >> Yield (^{60}Ni)

the simulations incorporate the geometry and efficiency of AGATA and take into account the energies and strengths of all known gamma transitions

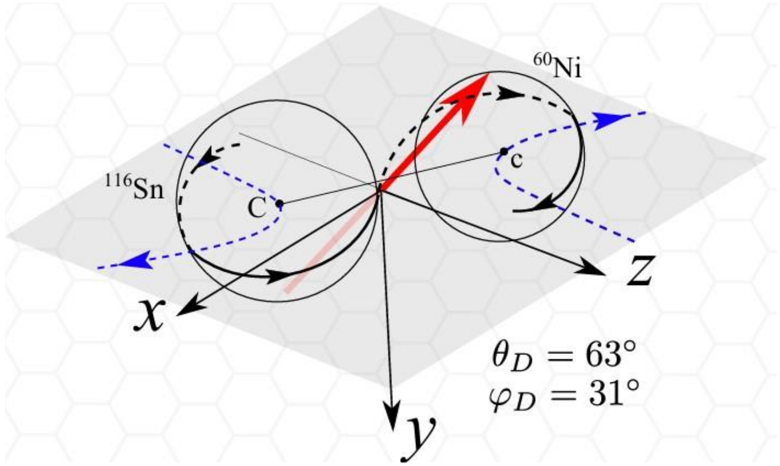




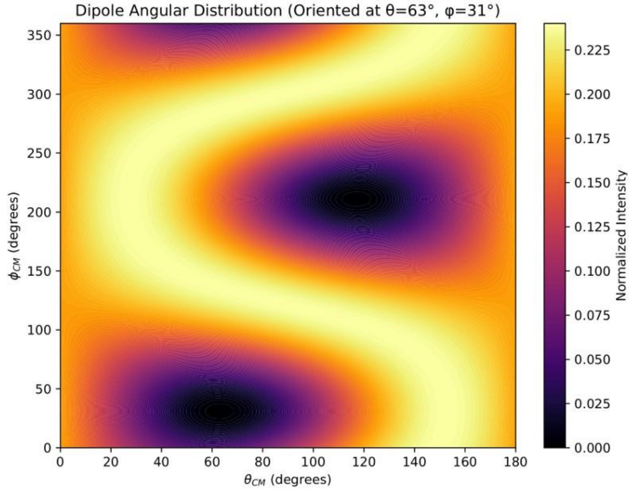
Data analysis by G.Andreetta (PhD)

Josephson dipole gamma ray angular distributions

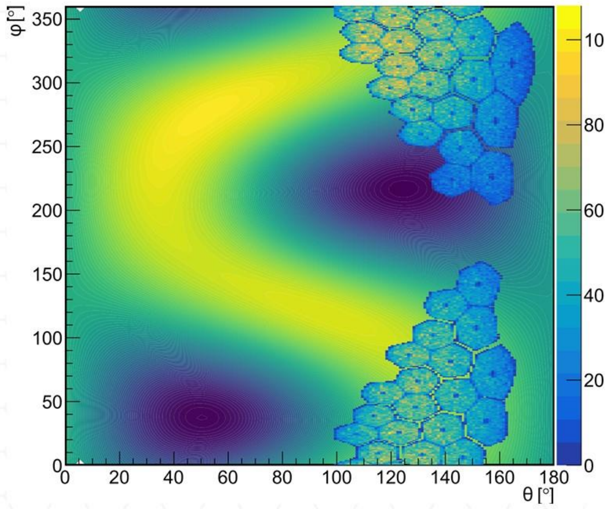
scheme of the reaction



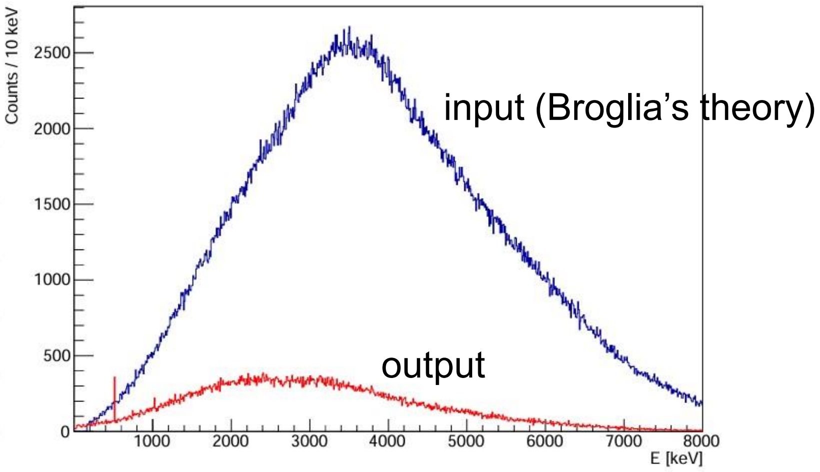
theoretical predictions



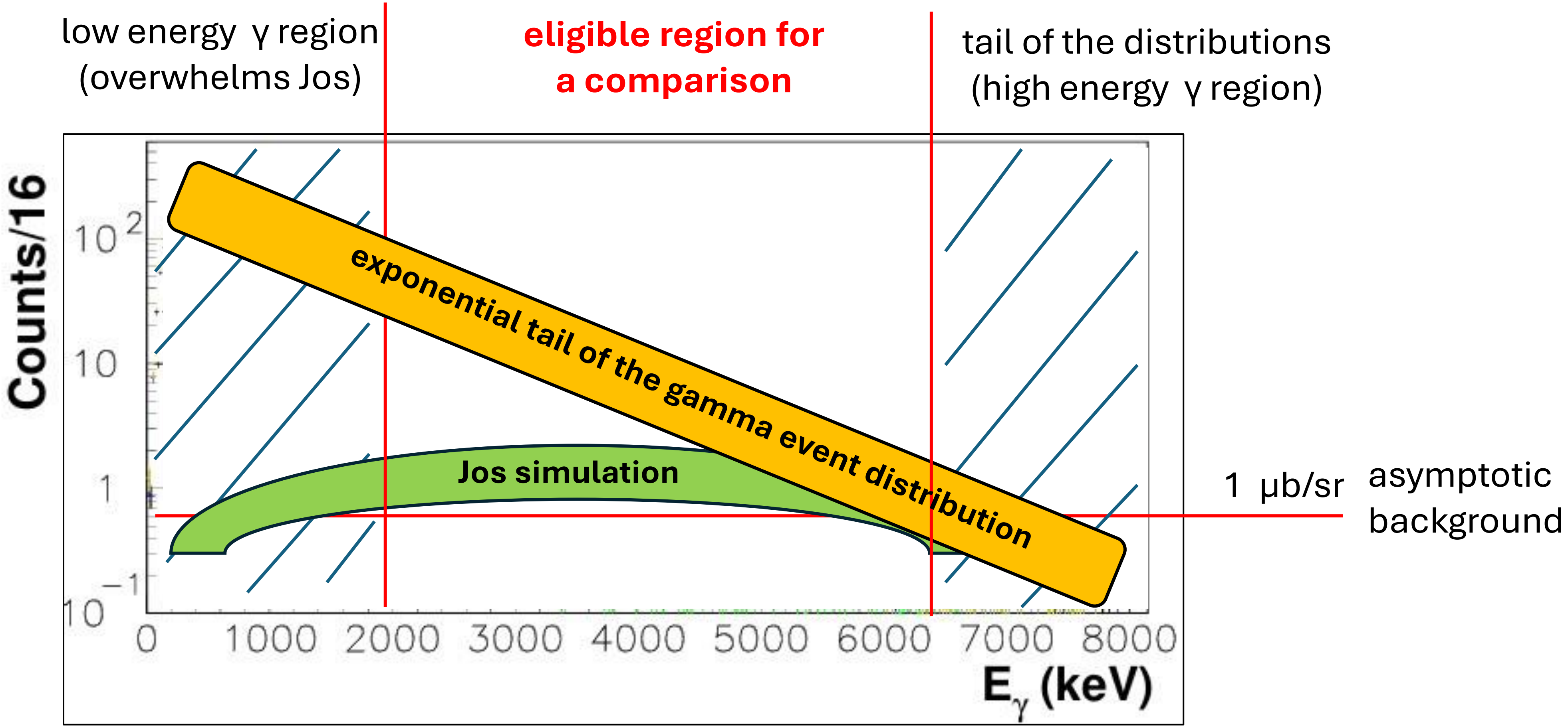
overlap with AGATA geometry



simulations



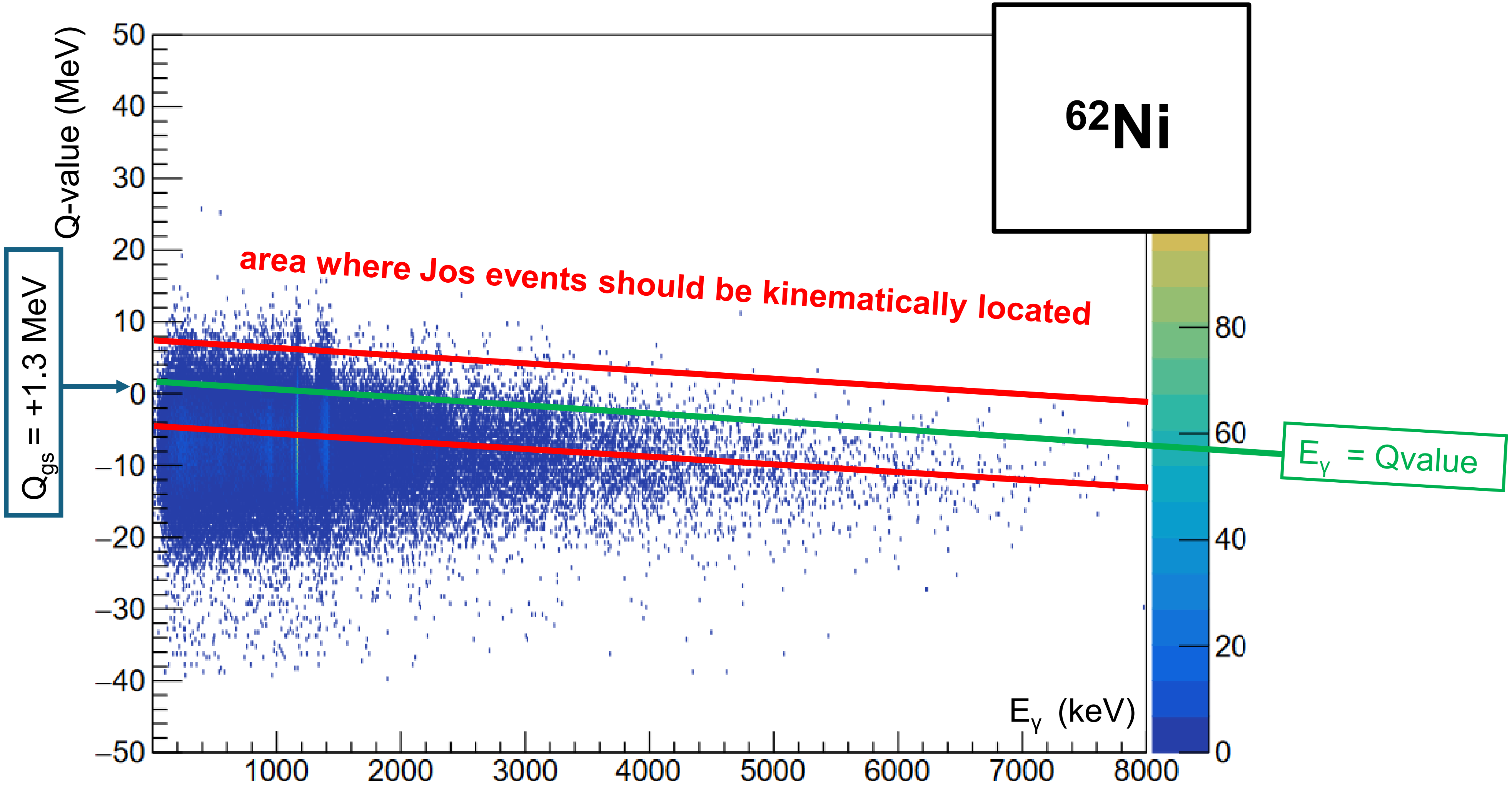
Summary : schematic overview of present situation



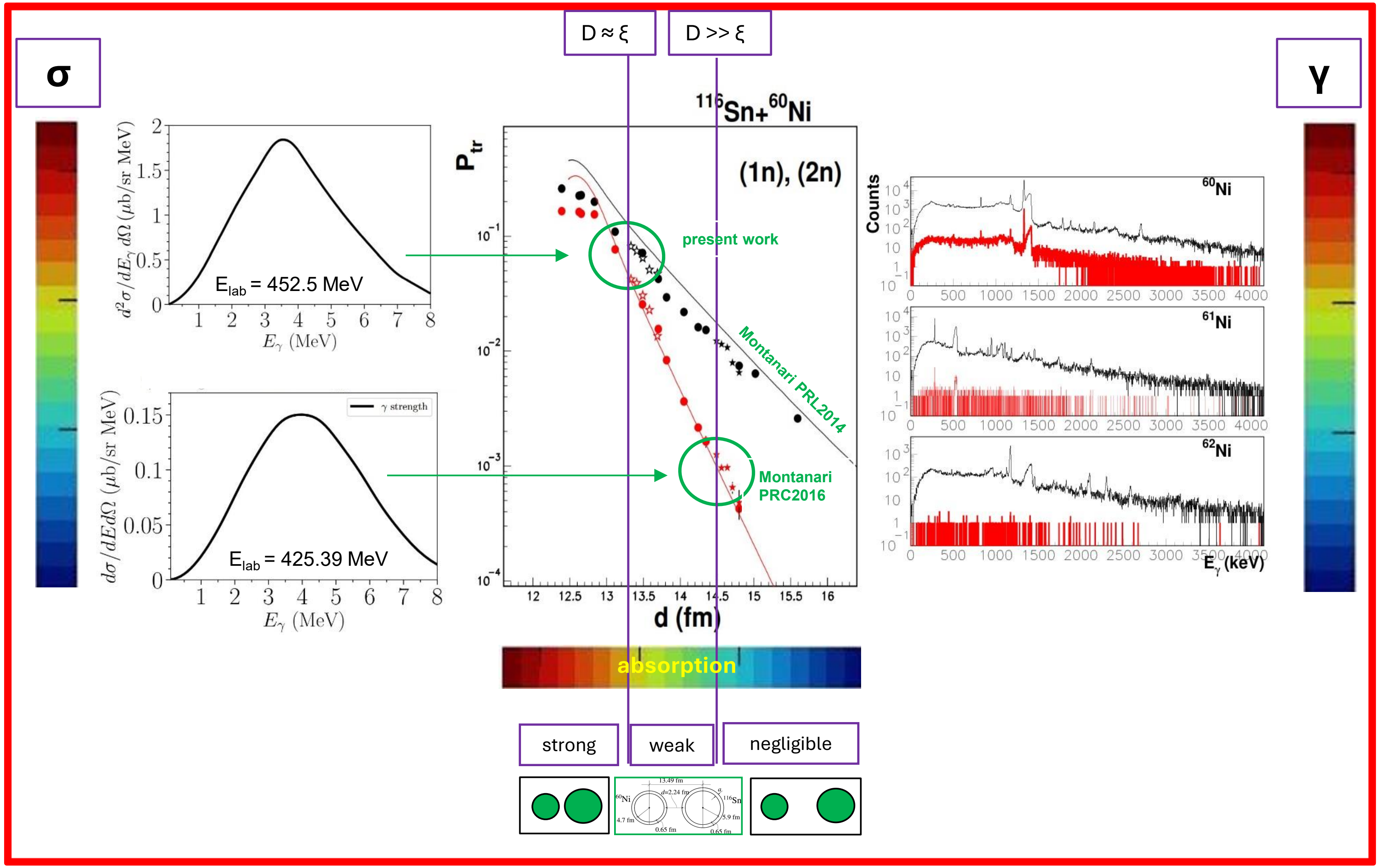
analysis is in progress to characterize the possible sources of background, to compare the ^{60}Ni and ^{62}Ni spectra scaled by the cross sections, to get absolute number of counts for the Jos distributions in simulations

Spare slides

Preliminary results: Q-value vs E_γ matrix



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

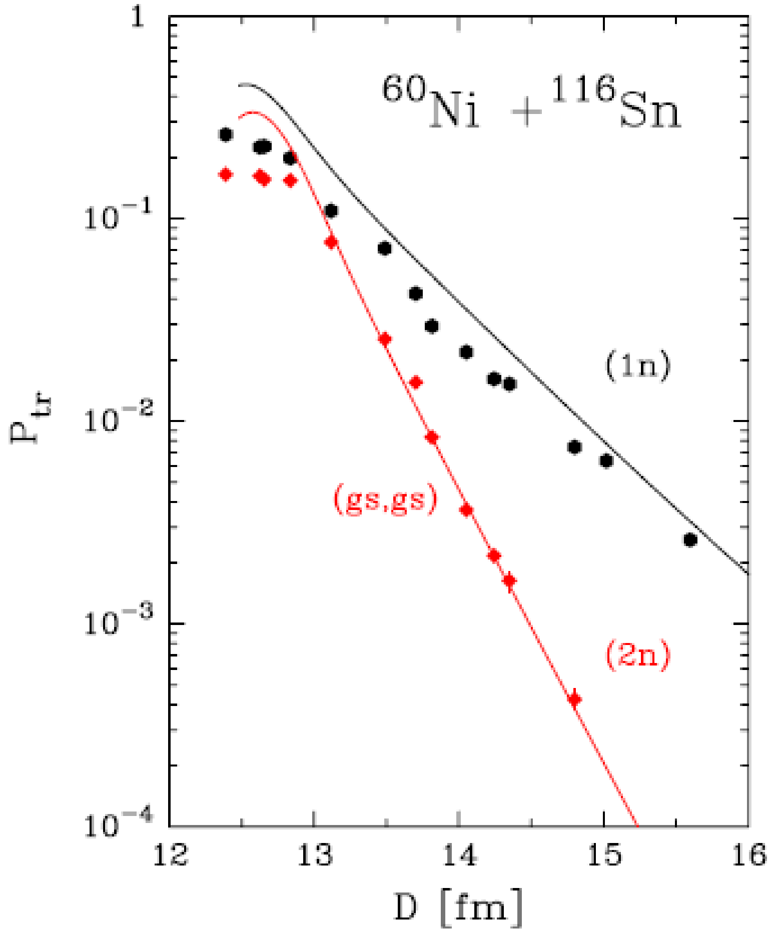


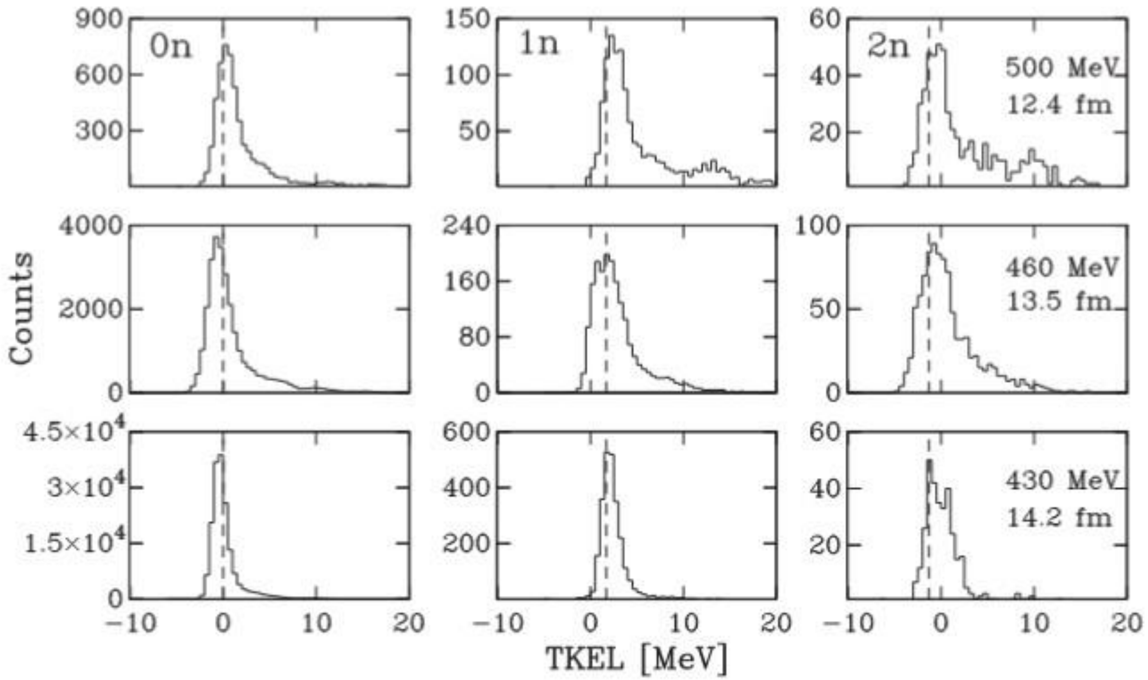
Transfer probabilities : comparison between exp and microscopic theory

$Q_{g.s.}$ for +2n very close to Q_{opt} (~ 0 MeV)

→

Transfer strength very close to the g.s. to g.s. transitions

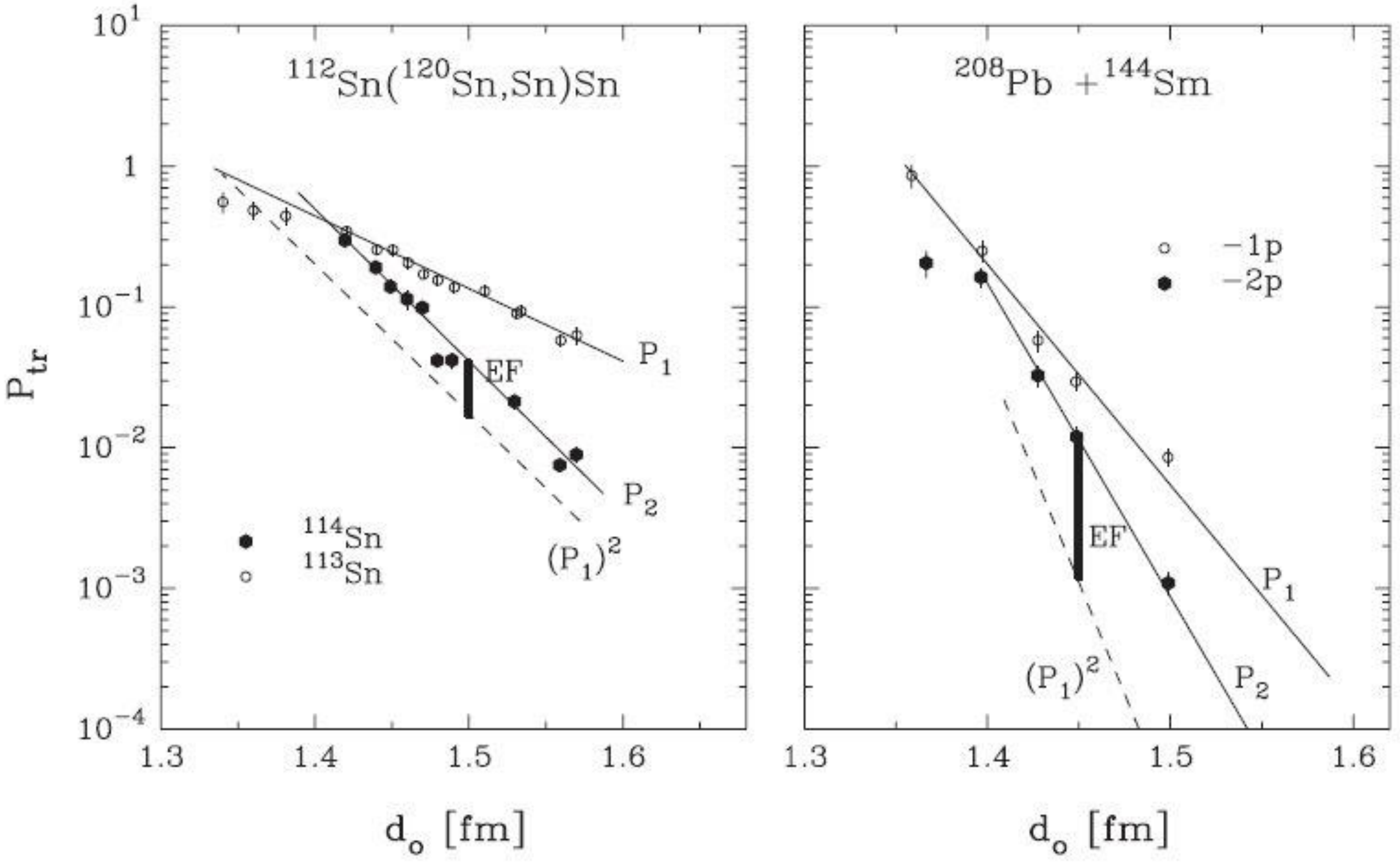




D.Montanari, L.Corradi, S.Szilner, G.Pollarolo et al, PRL113(2014)052501

The experimental transfer probabilities for both (1n) and (2n) channels 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

Enhancement coefficients



Enhancement coefficients:

ratio of the actual cross section to the prediction of models using uncorrelated states. It should indicate the overall effect of nucleon-nucleon correlation

one compares the one- and two-particle transfer probabilities as a function of the distance of closest approach

In past experiments one hoped to identify a direct link between enhancement factors and supercurrents originating from Cooper pair tunnelling, but the interpretation in terms of a nuclear Josephson turned out to be much more complex

Nuclear Josephson effect

Theory – developed mainly in the '70

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
[…]

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

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
[…]

Theory – recent revival due to advances in calculations

G.Potel, F. Barranco, E. Vigezzi and R. A. Broglia, Phys. Rev. C103(2021)L021601
P. Magierski, Physics 14(2021)27
[…]

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

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

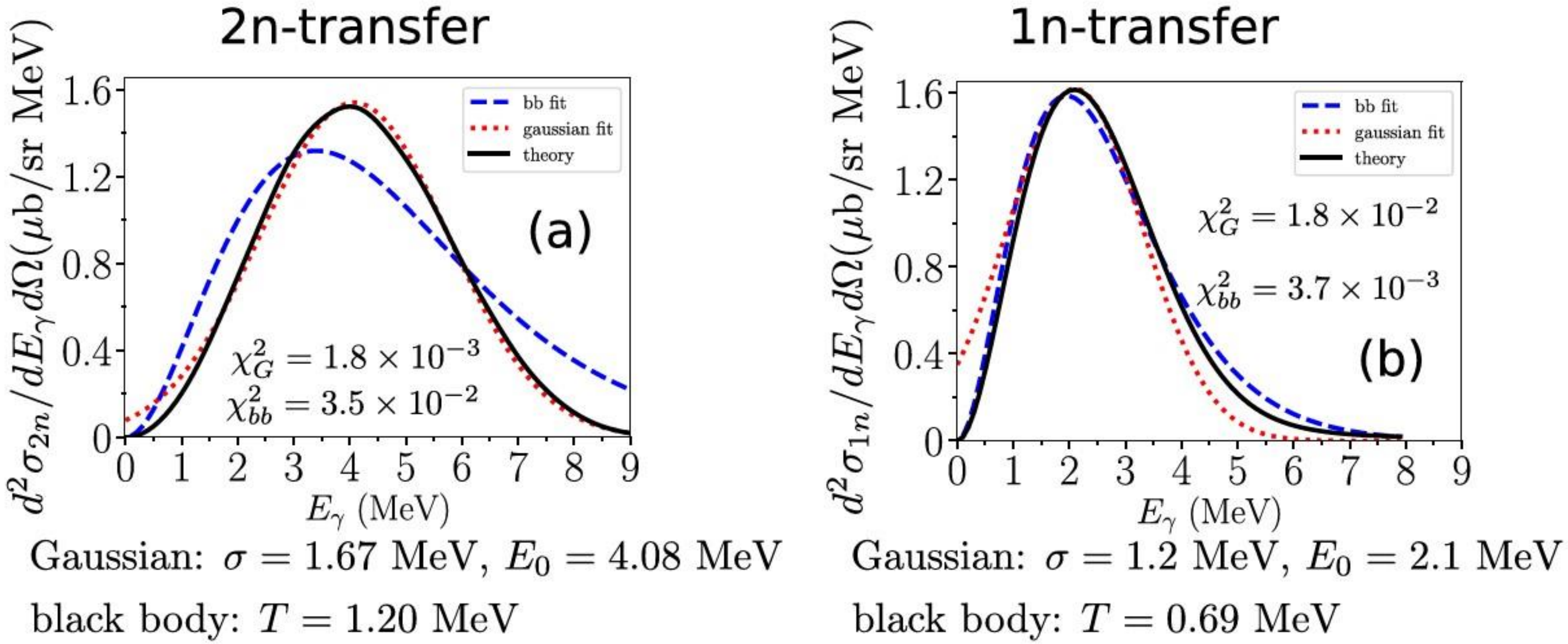
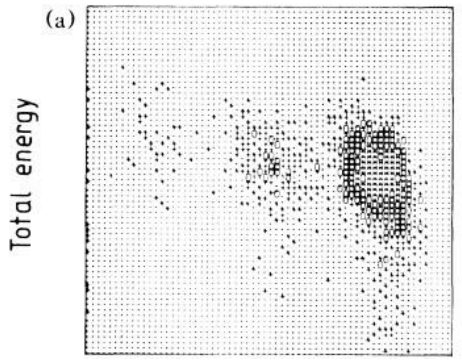
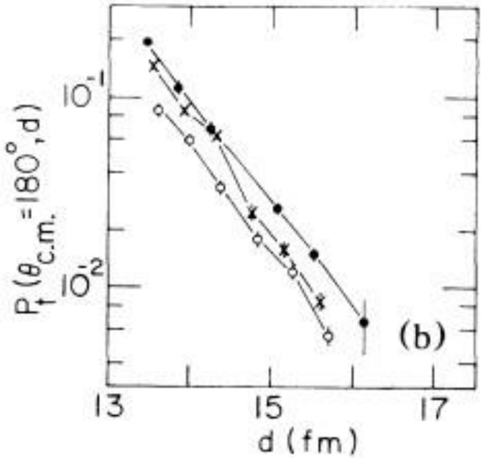


FIG. 1. The γ-strength function for $2n$- and $1n$-tunneling and associated blackbody ($\chi^2_{\rm bb}$) and Gaussian (χ^2_G) fits. (a) (Continuous black line) γ emission (gs)→(gs) two-neutron tunneling [Eq. (1b)] absolute double differential cross section for $E_{\rm c.m.} = 154.26$ MeV and $\theta_{\rm c.m.} = 140^\circ$ as a function of the emitted γ-ray energy E_γ, calculated with Eq. (8); (b) (continuous black line) γ emission in one-neutron tunneling [Eq. (1a)] absolute double differential cross section at the same kinematical conditions as (a), calculated with an expression similar to (8) for each of the incoherent quasiparticle contributions (11, 4 being the most important ones), taking properly into account the angular momentum coupling coefficients associated with the quasiparticle contributions of total angular momentum j. Also displayed are the Gaussian (red dotted curve) and blackbody (blue dashed curve) fits and associated chi-squared values and parameters.

Measurements of transfer reactions at sub-barrier energies

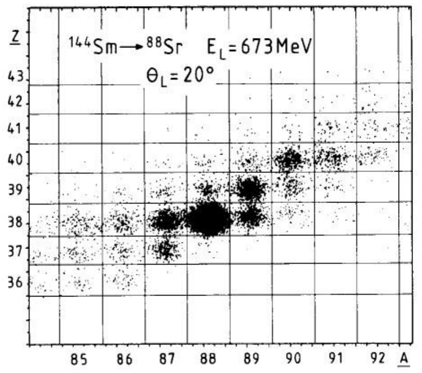
Daresbury RMS	GSI magnetic spectrometer	Argonne split pole	LNL tracking spectrometer

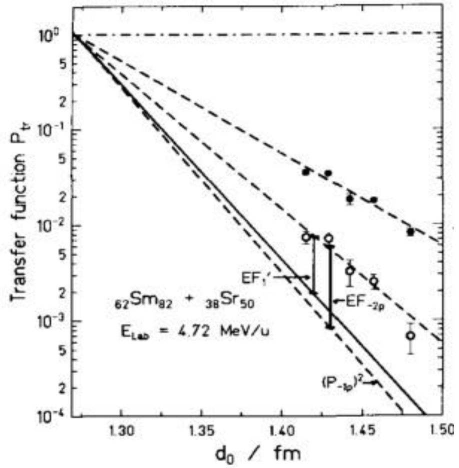




direct kinematics

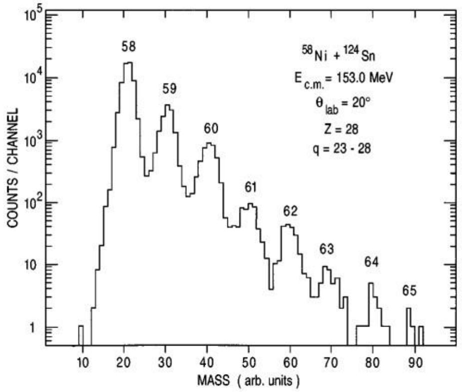
R.Betts et al., PRL59(1987)978

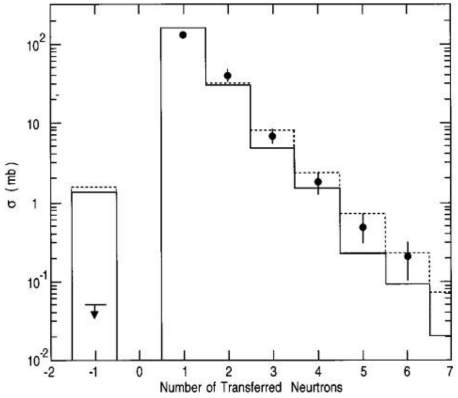




direct/inverse kinematics

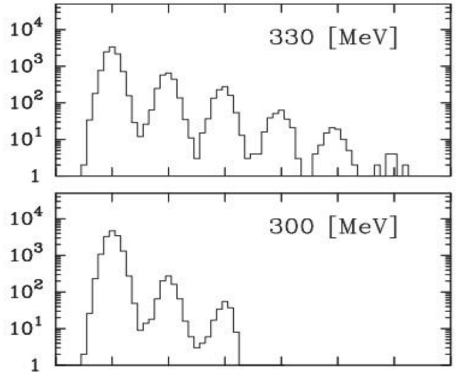
R.Kunkel et al., PLB208(1988)355

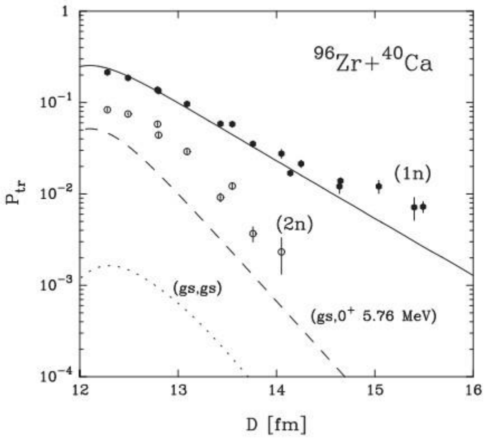




inverse kinematics

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

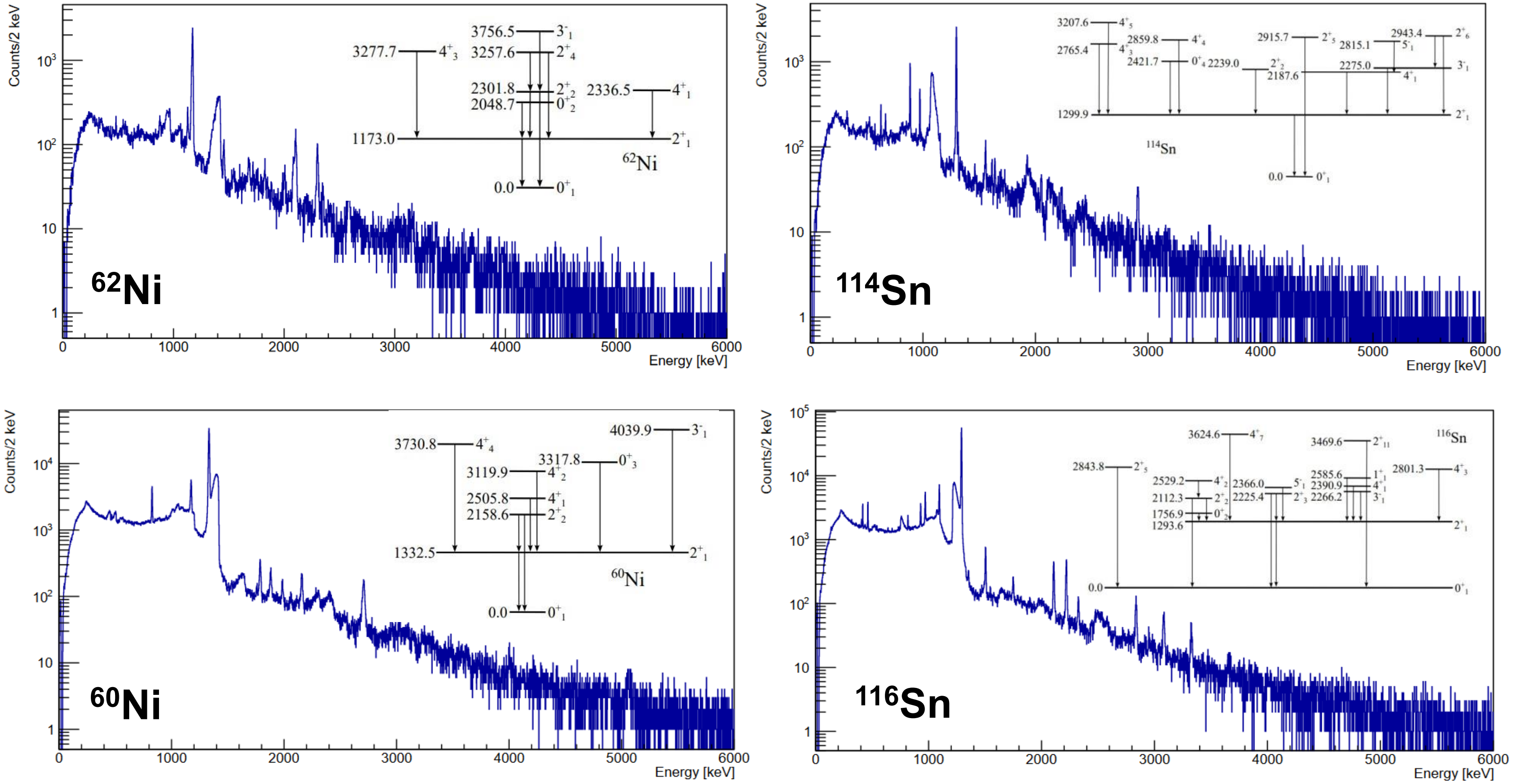




inverse kinematics

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

Gamma ray spectra Doppler corrected for the light and heavy partners



The very large statistics allows to observe, even at sub-barrier energies, a wealth of discrete gamma lines