A novel experimental approach to study beta-delayed neutron emissions

- Recent experimental activities
- A new method to determine P_{xn}

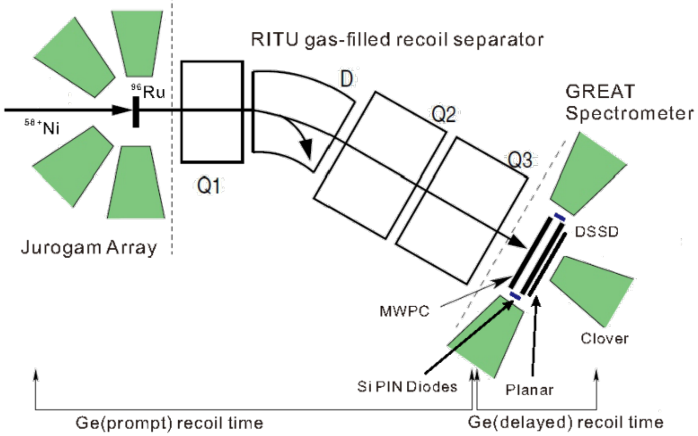
Bao-Hua Sun （孫保華）
Beihang university

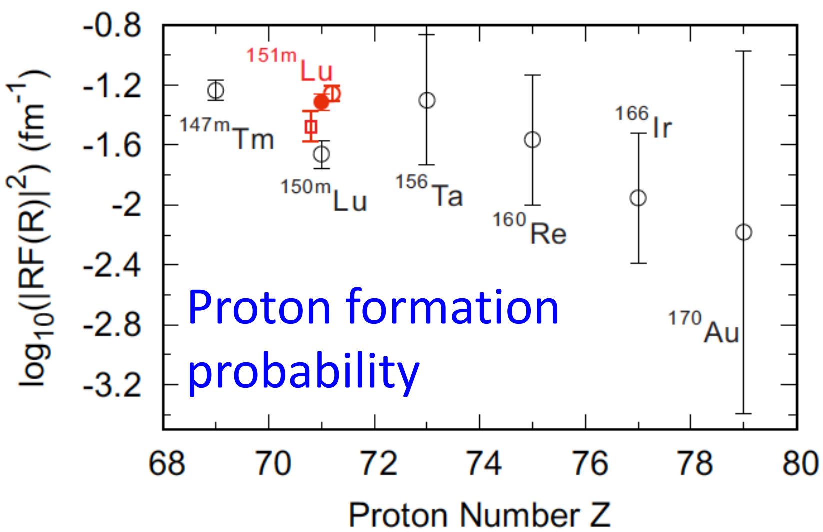
NSFC-JSPS collaboration workshop, Tsukuba

Recent experimental activities

- Decays close to the proton drip line at JYFL, Finland (2011-)

The quenching of the experimental spectroscopic factor for proton emission from the short-lived $d_{3/2}$ isomeric state in ^{151m}Lu was a long-standing problem.



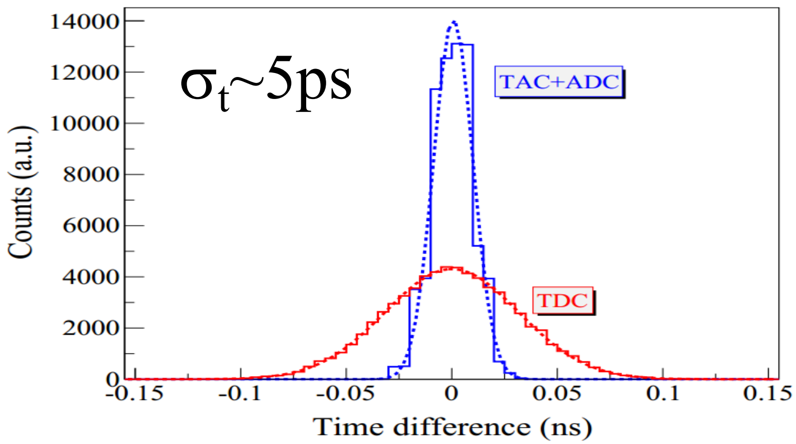


- F. Wang, BHS, Z. Liu, et al., Phys. Lett. B 770 (2017) 83–87
  Spectroscopic factor and proton formation probability for the $d_{3/2}$ proton emitter ^{151m}Lu
- Wang, BHS et al., to be sumitted to Phys. Rev C (2017)
- Tian, BHS et al., half-life measurements of ^{156m}Lu

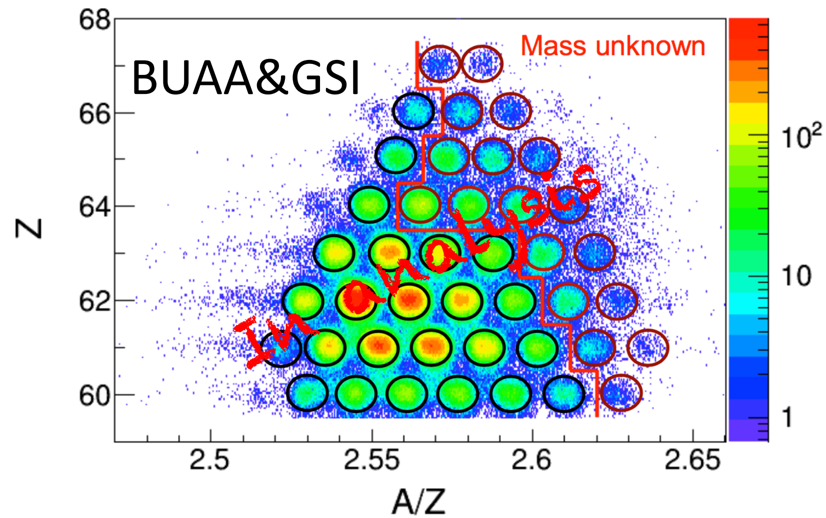
Recent experimental activities

- Decays close to the proton drip line at JYFL, Finland (2011-)
- TOF-Bρ-dE method for nuclear mass measurements (2012-)

One of the most precise timing detectors



Neutron-Rich Nd to Dy



Reaching time resolution of less than 10 ps with plastic scintillation detectors NIMA823,41(2016)

CrossMark

J.W. Zhao [a], B.H. Sun [a,b,*], I. Tanihata [a,b], S. Terashima [a,b], L.H. Zhu [a,b], A. Enomoto [c], D. Nagae [d], T. Nishimura [c], S. Omika [c], A. Ozawa [e], Y. Takeuchi [c], T. Yamaguchi [c]

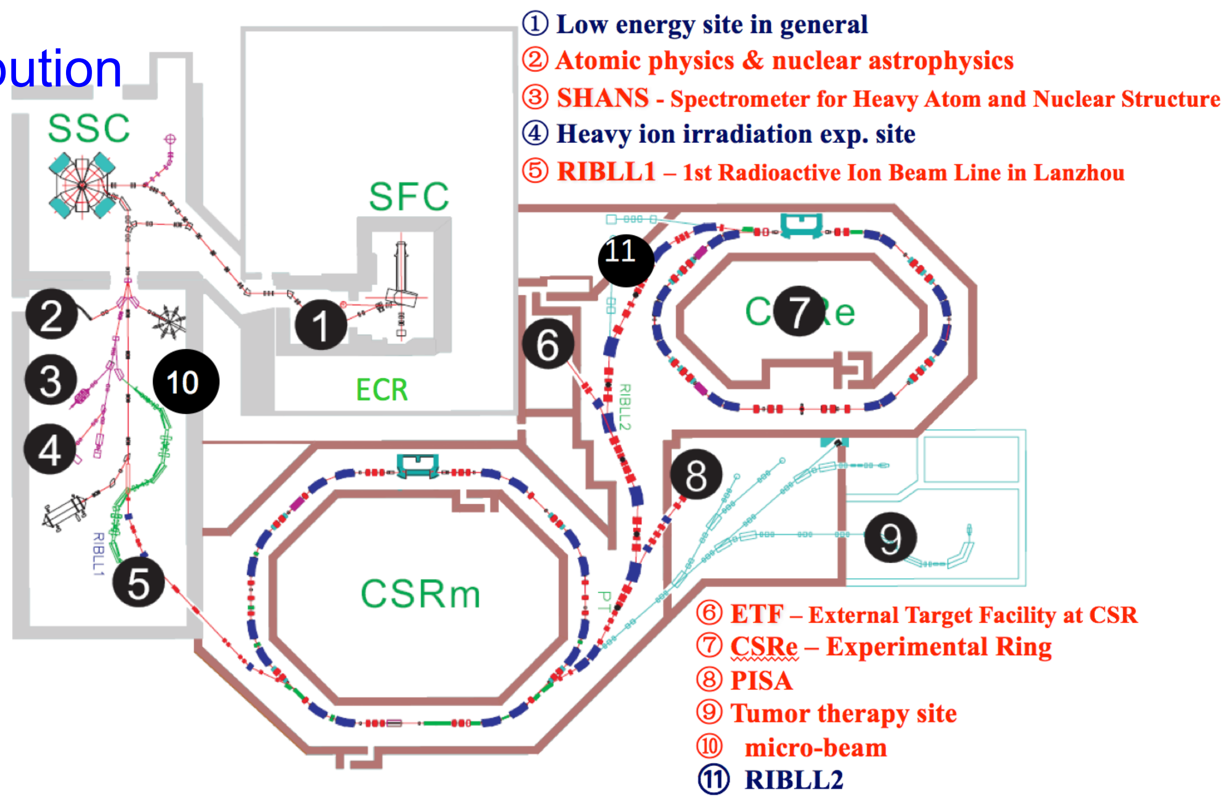
Many many thanks for sharing the beam time at HIMAC!

Recent experimental activities

- Decays close to the proton drip line at JYFL, Finland (2011-)
- TOF-Bρ-dE method for mass measurements of exotic nuclei(2012-)
- Charge-changing c.s. measurements at RIBLL2-ETF (2014.12, 2017.01)

→ Charge radii
→ Charge density distribution

Beihang-IMP collaboration



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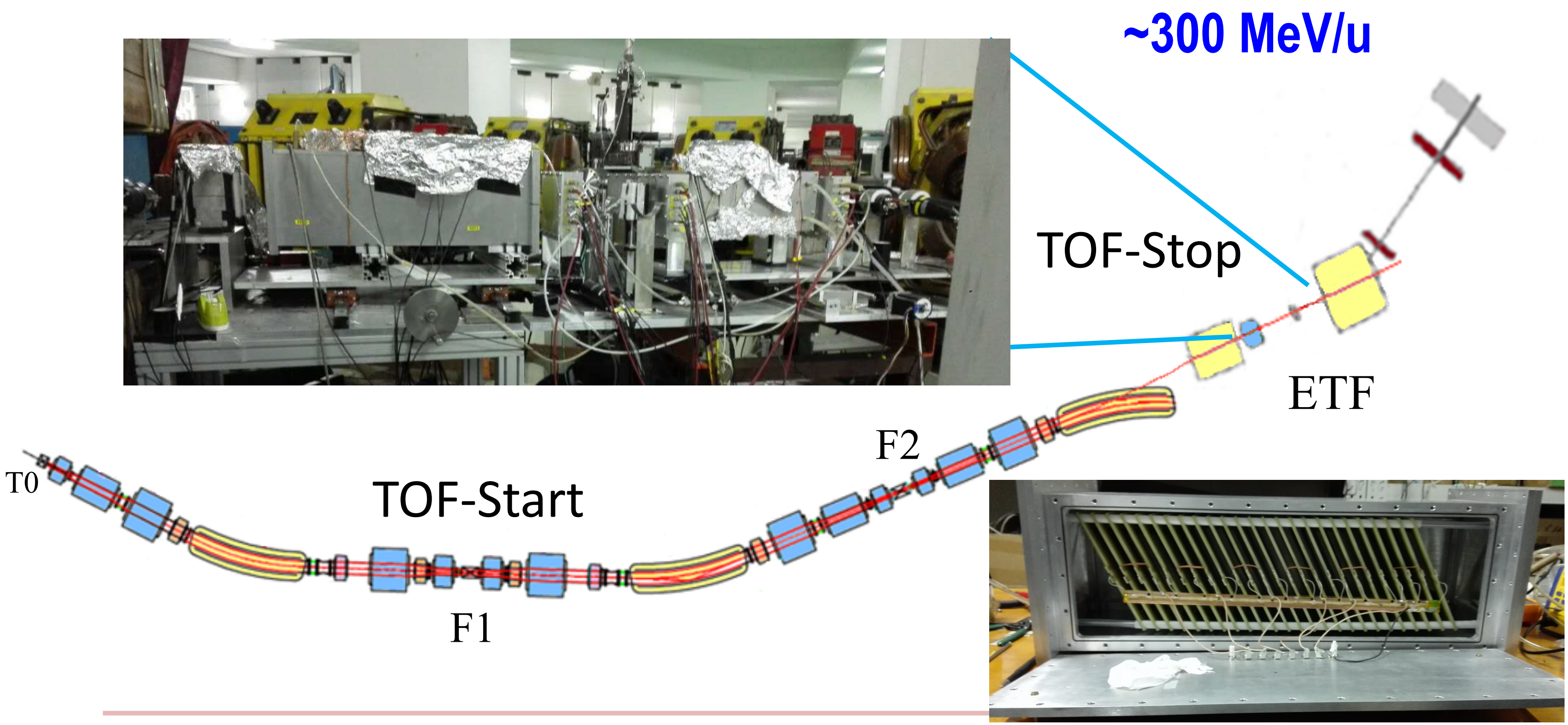

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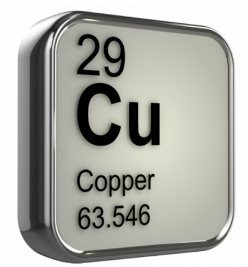
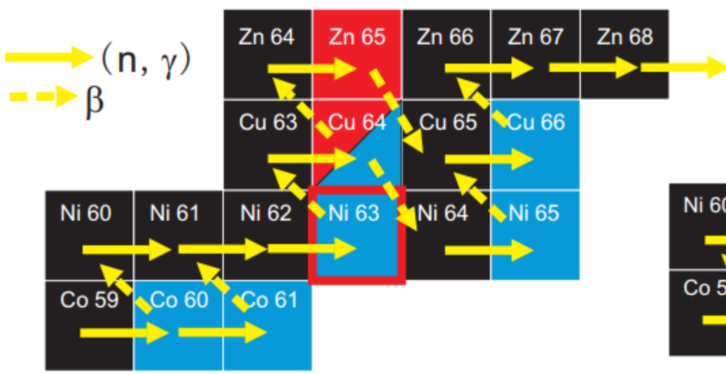
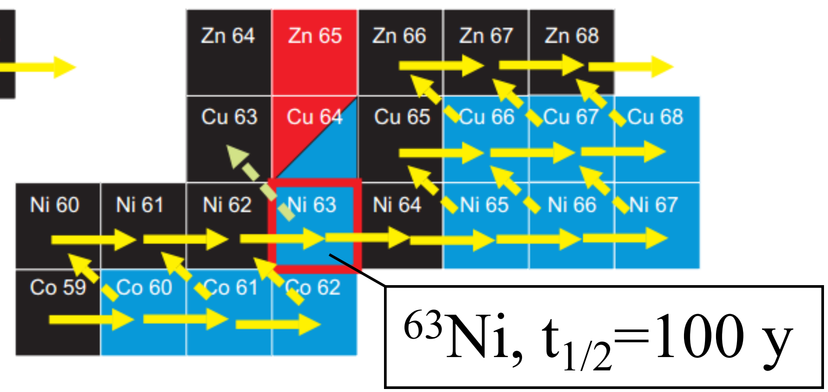
- Steller lifetime measurement of ^{63}Cu at RCNP, Osaka Univ. (2016-)







core He burning

$T \approx 300$ MK, $n_n \sim 10^6 cm^{-3}$

shell C burning

$T \approx 1$GK, $n_n > 10^{11} cm^{-3}$

RCNP proposal: E501

A novel experimental approach to study beta-delayed neutron emissions

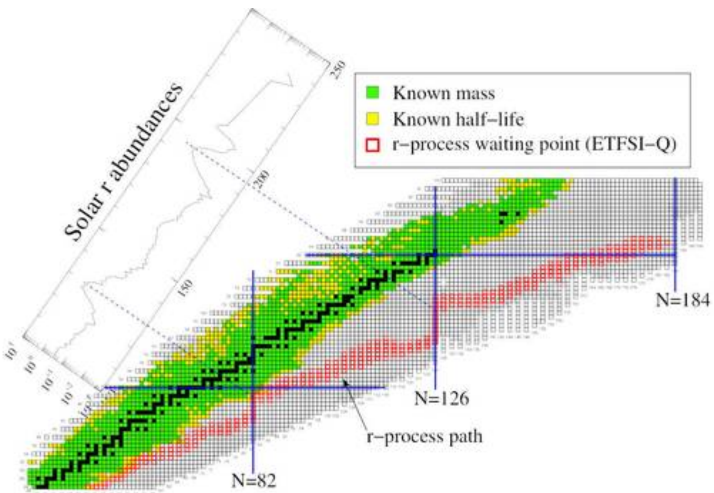
- Beta-delayed neutron-emission (P_{xn})
- A new method to determine P_{xn} (SAMRAI)
- Summary

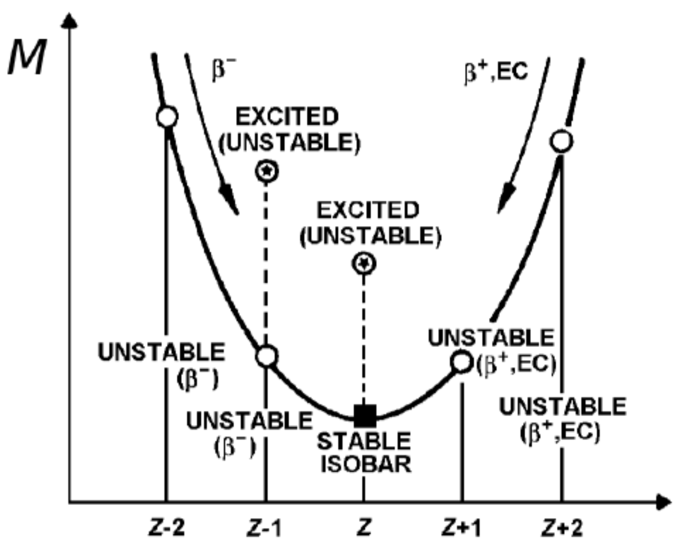
Bao-Hua Sun (孫保華)

Beihang university

Collaborators: T. Kabayashi, I. Tanihata, X.D. Xu, J.W. Zhao et al.

Beta-decays towards neutron drip-line





- The Q_β value increases far from stability.
- β–decay may populate states in the daughter above the particle separation energy (S). This happens when $S < Q_\beta$.
- β-delayed proton/neutron/alpha radioactivity
- While neutrons are emitted promptly, the proton emission is further delayed by the Coulomb barrier.

Beta-delayed neutron emission: an example

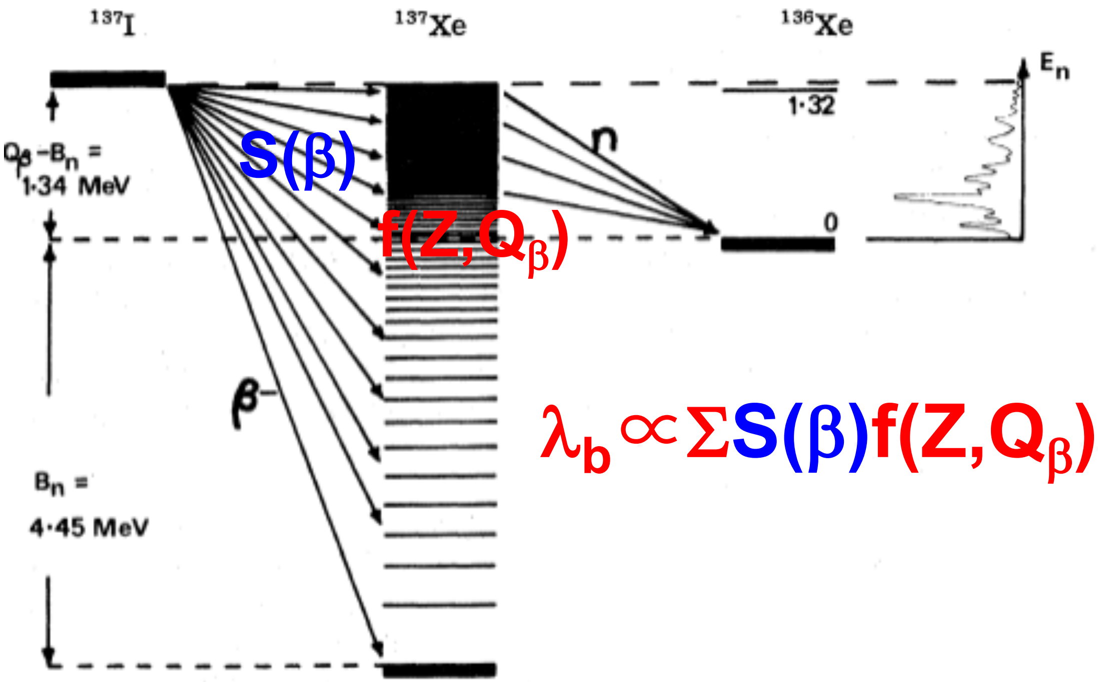


FIG. 2. Energy-level diagram for β-delayed neutron emission from ^{137}Xe.

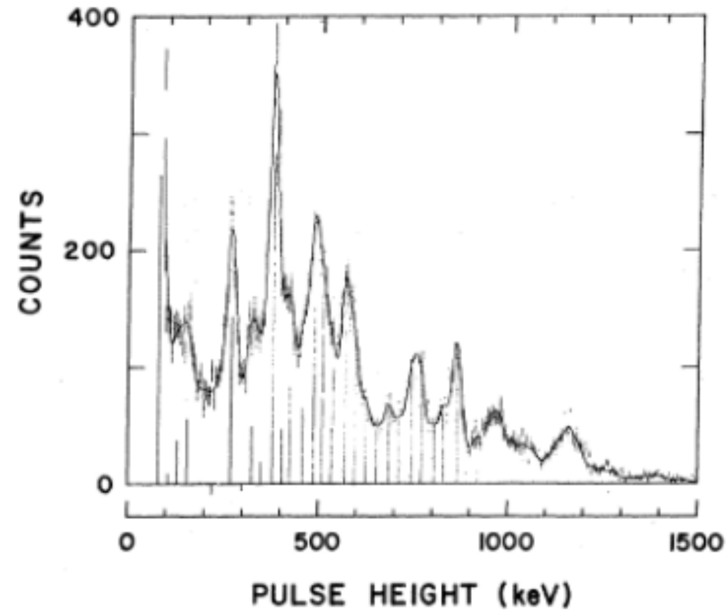


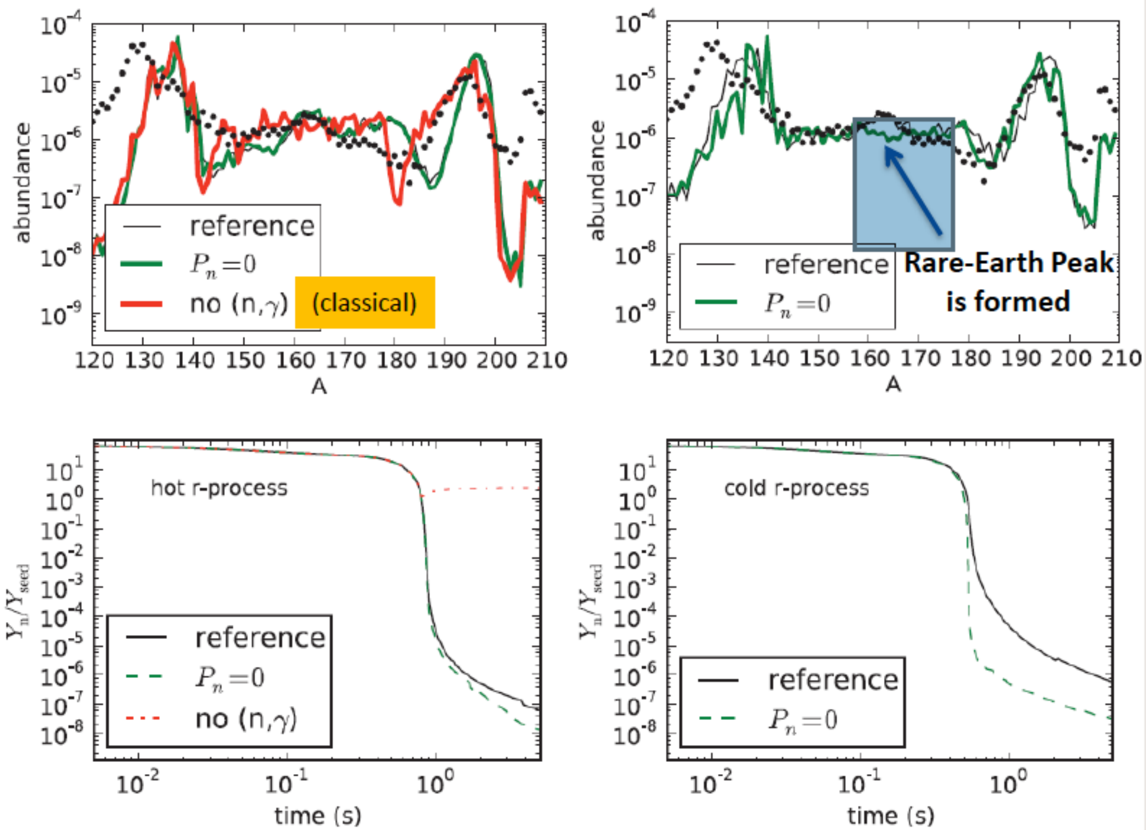
FIG. 1. Experimental pulse-height distribution of delayed neutrons from ^{137}Xe. Error bars on data indicate statistical uncertainty. Solid curve is sum of energy-dependent response functions, whose energy and relative amplitudes are shown as vertical lines.

Shalev, Rudstam, PRL28,687(1972)

β-delayed neutron spectrum can reveal a great deal about the underlying wave functions involved and hence is interesting for nuclear structure investigations.

P_{xn} required for r-process

Beta delayed neutrons are of great relevance in reshaping the abundance during/after the neutron freeze-out, providing later time neutrons in r-process nucleosynthesis and in the determination of r-process lifetimes: change elemental abundance, provide neutrons



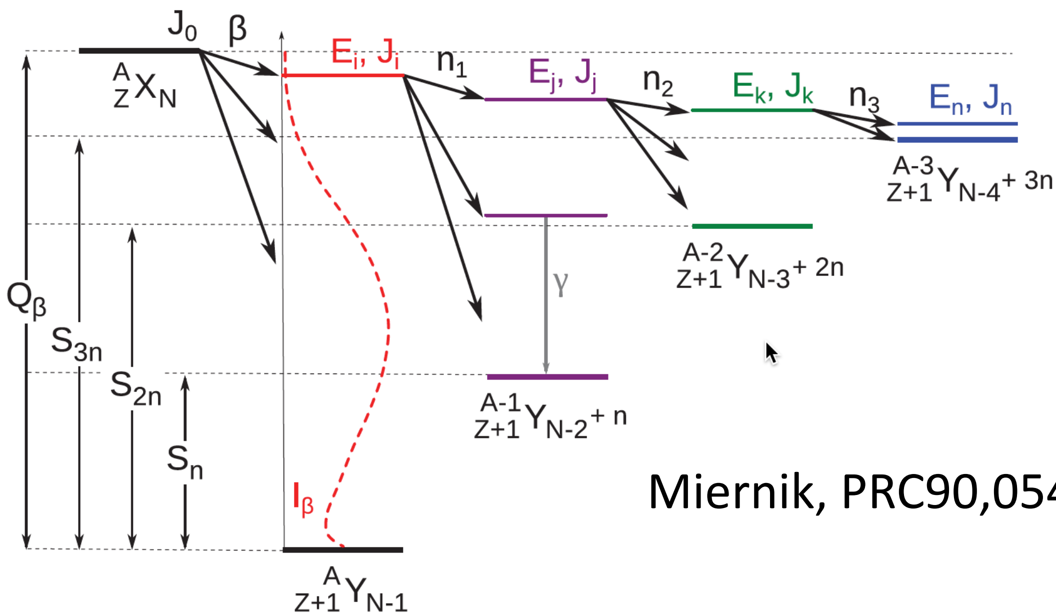
FRDM
+ Möller 2003
+ exp. $t_{1/2}$

Production of additional neutrons: influence on n/seed ratio at later times

A. Arcones and G. Martinez Pinedo, Phys. Rev. C83, 045804 (2011)

Beta-delayed neutron emission

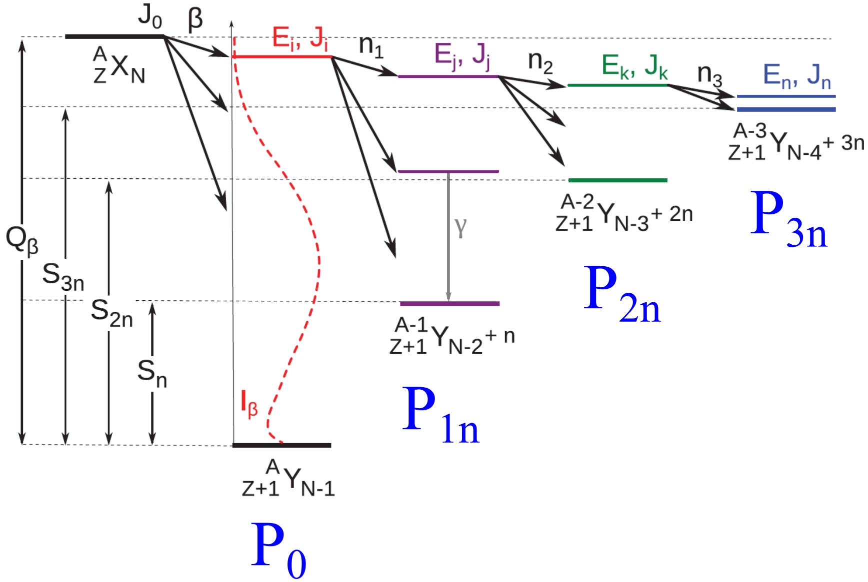
Sequential model of the multineutron emission process



Miernik, PRC90,054306(2014)

- After beta transition, the daughter nucleus can be a in state of excitation energy E_i
- The (E_i,J_i) state may de-excite by gamma emissions or (when energetically allowed) by neutron emissions. neutron-gamma emission competition, generally gamma-emission is much smaller (<10%)
- the subsequent de-excitation of the daughter nuclides

Beta-delayed neutron emission



$$P_n = \sum_{i=1}^{\infty} P_{in}$$

$$P_0 + P_n = 1$$

$$Q_{\beta n} = Q_\beta - S_n$$

P_{xn}: the probability of a beta-delayed *x*-neutron decay event occurring, i.e., the probability of populating the (A-*x*,Z+1) nucleus.

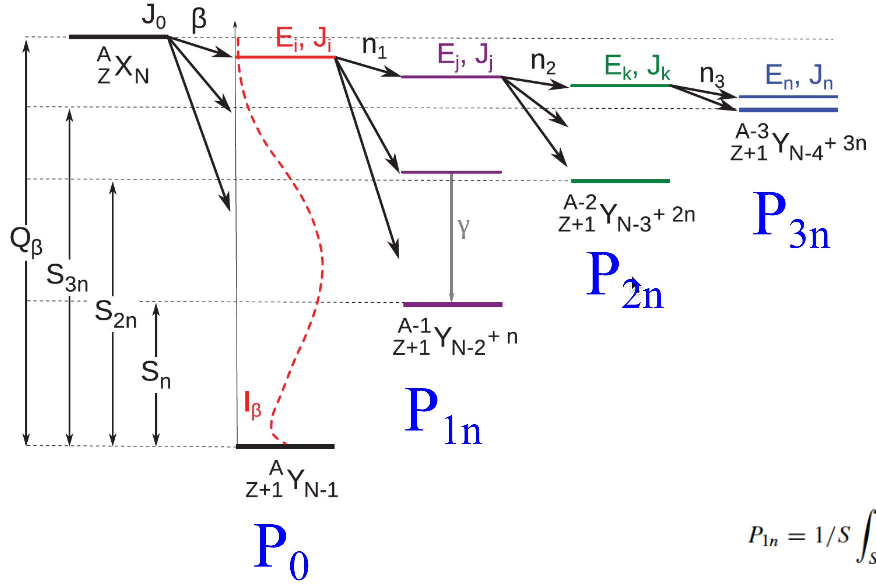
P_0: the probability that beta decay occurs without neutron emission.

P_n: total neutron emission probability, i.e., the probability that any neutron activity occurs

$Q_{\beta n}$: energy window or phase space available for β-decayed neutron decay. Going from stability, S_n decreasing, Q_β/P_{xn} increasing

Birch et al., Nuclear Data sheets 128(2015)131

P_{xn} required for r-process



$$P_n = \sum_{i=1}^{\infty} P_{in} \qquad P_0 + P_n = 1$$

$$Q_{\beta n} = Q_\beta - S_n$$

K. Miernik, PRC88, 041301(R) (2013); PRC90,054306(2014)

$$P_{1n} = 1/S \int_{S_n}^{Q_\beta} S_\beta(E_i) f(Q_\beta - E_i) dE_i \left(\int_{S_n}^{S_{2n}} \sum_{J_i=J_0-1}^{J_0+1} \omega(J_i) \sum_{J_j} T_l(E_i - E_j)\rho(E_j - S_n, J_j) dE_j \right.$$
$$\left. + \int_{S_{2n}}^{Q_\beta} \sum_{J_i=J_0-1}^{J_0+1} \omega(J_i) \sum_{J_j} T_l(E_i - E_j)\rho(E_j - S_n, J_j) \frac{\Gamma_\gamma(E_j)}{\Gamma_{\text{tot}}} dE_j \right),$$
$$P_{2n} = 1/S \int_{S_{2n}}^{Q_\beta} S_\beta(E_i) f(Q_\beta - E_i) dE_i \int_{S_{2n}}^{Q_\beta} \sum_{J_i=J_0-1}^{J_0+1} \omega(J_i) \sum_{J_j} T_l(E_i - E_j)\rho(E_j - S_{2n}, J_j) \frac{\Gamma_n(E_j)}{\Gamma_{\text{tot}}} dE_j$$
$$\left(\int_{S_{2n}}^{S_{3n}} \sum_{J_k} T_l(E_j - E_k)\rho(E_k - S_{2n}, J_k) \frac{\Gamma_n(E_k)}{\Gamma_{\text{tot}}} dE_k + \int_{S_{3n}}^{Q_\beta} \sum_{J_k} T_l(E_j - E_k)\rho(E_k - S_{2n}, J_k) \frac{\Gamma_\gamma(E_k)}{\Gamma_{\text{tot}}} dE_k \right),$$
$$P_{>3n} = 1/S \int_{S_{3n}}^{Q_\beta} S_\beta(E_i) f(Q_\beta - E_i) dE_i \int_{S_{3n}}^{Q_\beta} \sum_{J_i=J_0-1}^{J_0+1} \omega(J_i) \sum_{J_j} T_l(E_i - E_j)\rho(E_j - S_{2n}, J_j) \frac{\Gamma_n(E_j)}{\Gamma_{\text{tot}}} dE_j$$
$$\int_{S_{3n}}^{Q_\beta} \sum_{J_k} T_l(E_j - E_k)\rho(E_k - S_{3n}, J_k) \frac{\Gamma_n(E_k)}{\Gamma_{tot}} dE_k \int_{S_{3n}}^{Q_\beta} \sum_{J_n} T_l(E_k - E_n)\rho(E_n - S_{3n}, J_n) \frac{\Gamma_n(E_n)}{\Gamma_{\text{tot}}} dE_n,$$
$$S = \int_0^{Q_\beta} S_\beta(E_i) f(Q_\beta - E_i) dE_i,$$

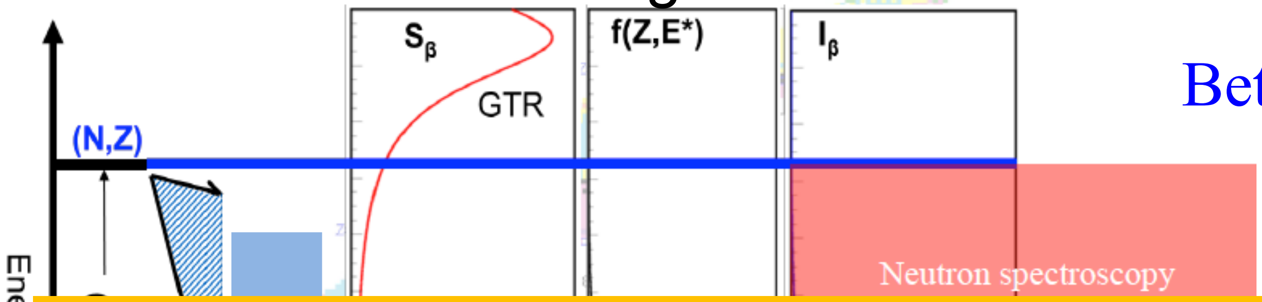
The β-delayed neutron-emission probability (P_n) depends on the β-strength function (S_β), Fermi integral (f), and neutron width (Γ_n). This can be represented by the following equation:

$$P_n = \frac{\int_{S_n}^{Q_\beta} \frac{\Gamma_n(E)}{\Gamma_{\text{tot}}(E)} S_\beta(E) f(Z+1, Q_\beta - E) dE}{\int_0^{Q_\beta} S_\beta(E) f(Z+1, Q_\beta - E) dE}, \qquad (1)$$

where E is the excitation energy of the daughter nuclide and Γ_{tot} is the total state width. In principle, many-neutron emission is also possible whenever $Q_\beta > S_{xn}$. However, P_n, as defined by Eq. (1), describes the probability for one or more neutron emission.

Beta strength and nuclear lifetime/branching ratio

N. J. Stone (2014) Strength function



Beta-ray (DSSD)

^{3}He, liquid/plastic scintillator

Many experimental difficulties

- Complex detector array
- Coincidence measurements for β, γ and neutron
- Hard (impossible) for weak transition due to the energy phase space
- Low efficiency for beta-delayed multi-neutron emission decay (P_{2n}/P_{3n})

PRL 117, 142701 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

Strong Neutron-γ Competition above the Neutron Threshold in the Decay of ^{70}Co

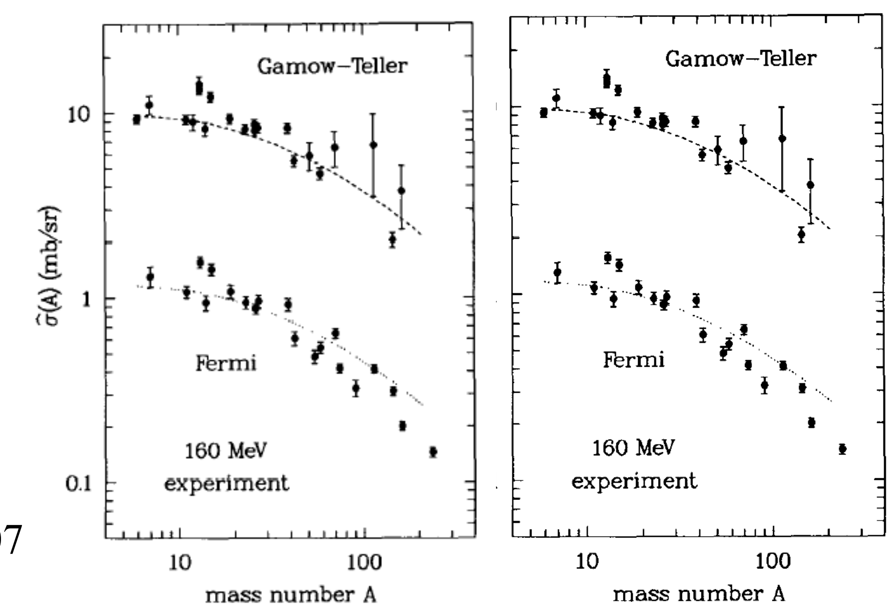
Charge-exchange reaction at ≥ 100 MeV/u

Cex at intermediate beam energies has long been a powerful technique to study β-transition strength, especially can probe excitation regions, which are inaccessible to β-decay.

Proportionality relationship between Cex and β-transition strength for allowed GT/F transition for E~100 AMeV and above: (~10%)

$$\left(\frac{d\sigma}{d\Omega}\right)_{q=0} = \hat{\sigma}(A,E)\,B(GT)$$

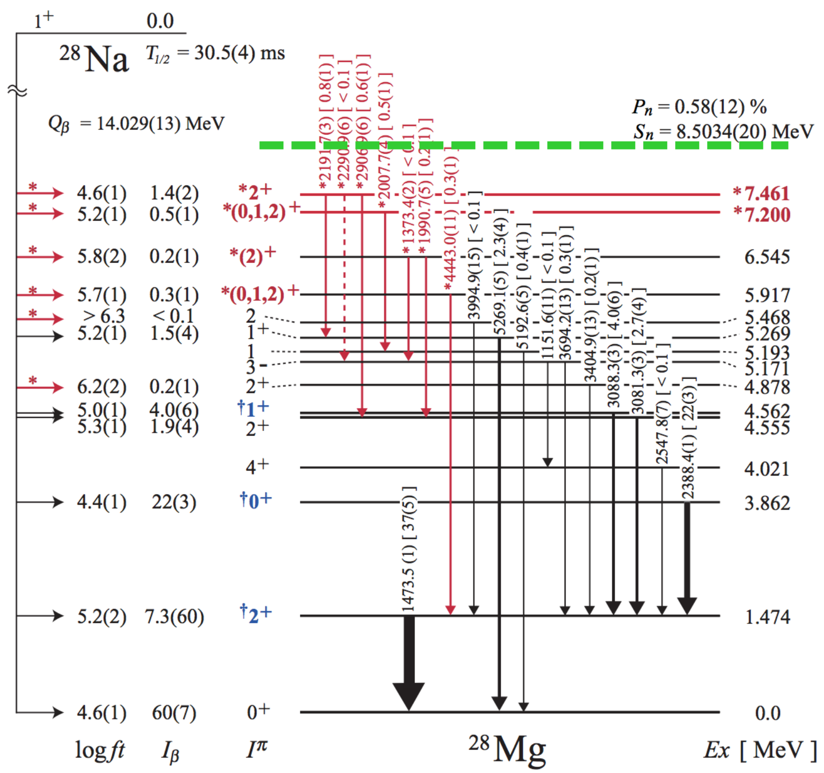
Unit cross section — Transition strength



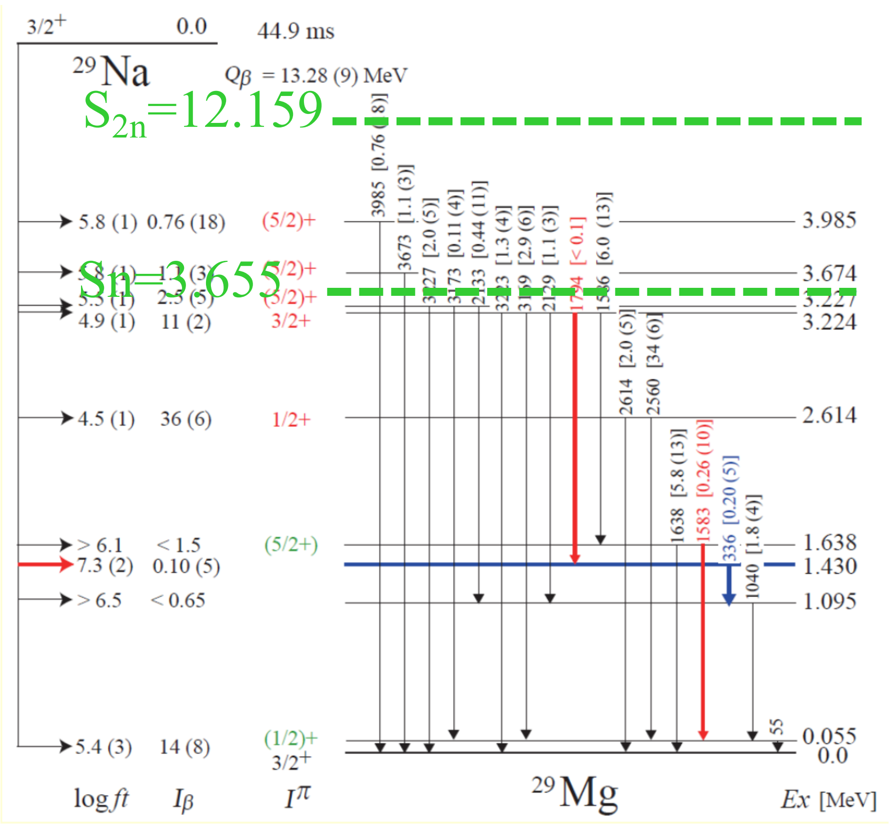
Bertsch, Esbensen, Rep. Prog. Phys. 50(1987)607
Osterfeld, Rev. Mod. Phys. 64(1992)491

Proposal at BIGRIPS-SUMRAI, RIBF

^{28}Na: P_n=0.58(12)%



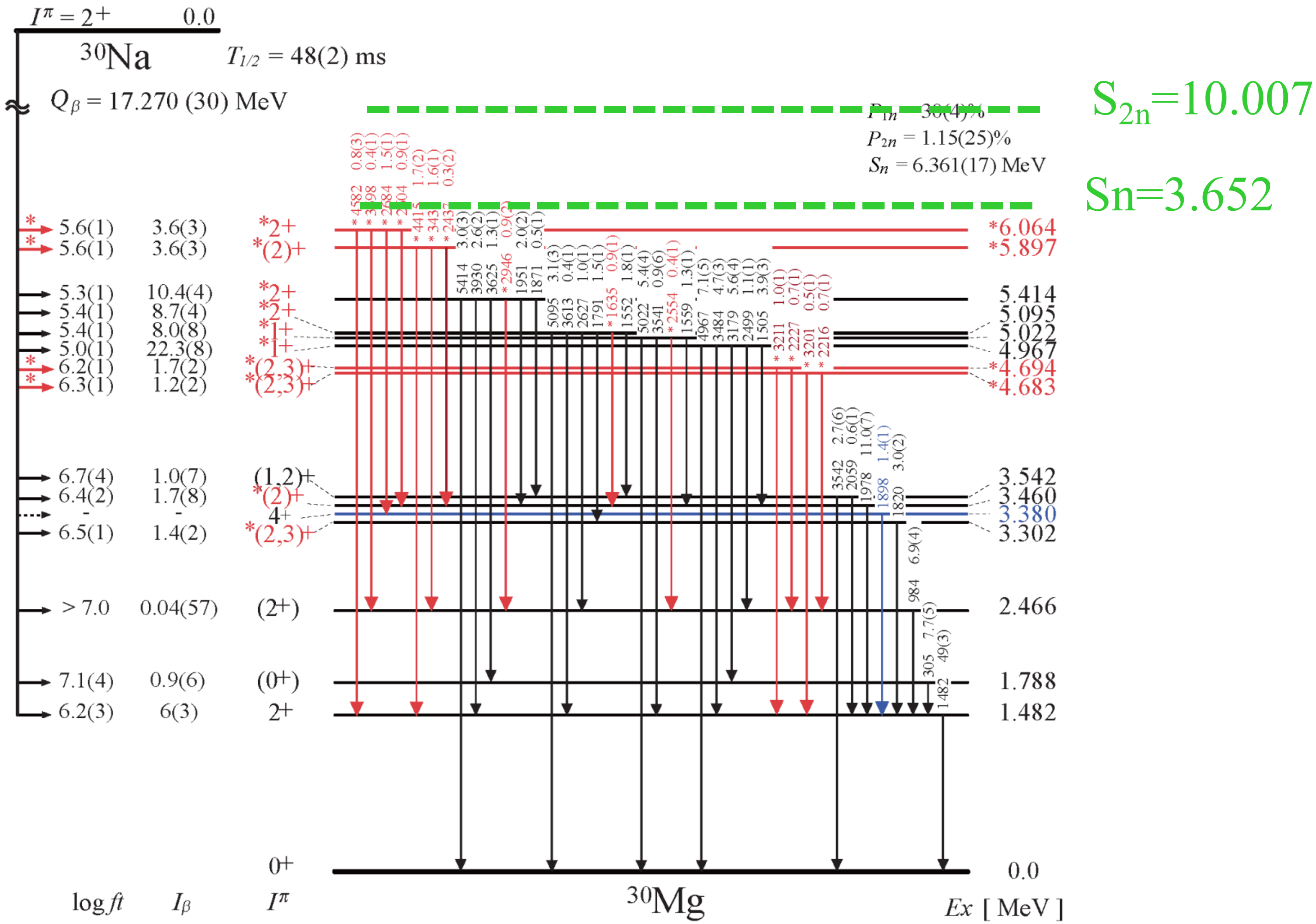
^{29}Na: P_n=25%,unknown P_{2n}



PHYSICAL REVIEW C **85**, 034310 (2012)

Proposal at BIGRIPS-SUMRAI, RIBF

^{30}Na: Pn=30(4)%, P_{2n}=1.15(25)%



Summary

- We propose to have the first experiment to demonstrate the possibility of studying beta-decay of neutron-rich nuclide relevant to r-process via nuclear charge-exchange reactions of Na isotopes in inverse kinematics at > 100 MeV/u.
- This method can be very robust to determine precisely the branching ratios of beta-delayed neutron emissions and also the individual transitions, and can be applied to study very neutron-rich nuclei relevant for r-process study.
- More details will be presented in the coming SUMRAI workshop

Looking forward to collaborating with you!

Beihang-RIBF-Tohuku-Tsukuba-Saitama…