Study of unbound nuclei ^{33}Ne via 1*p* knock-out reactions

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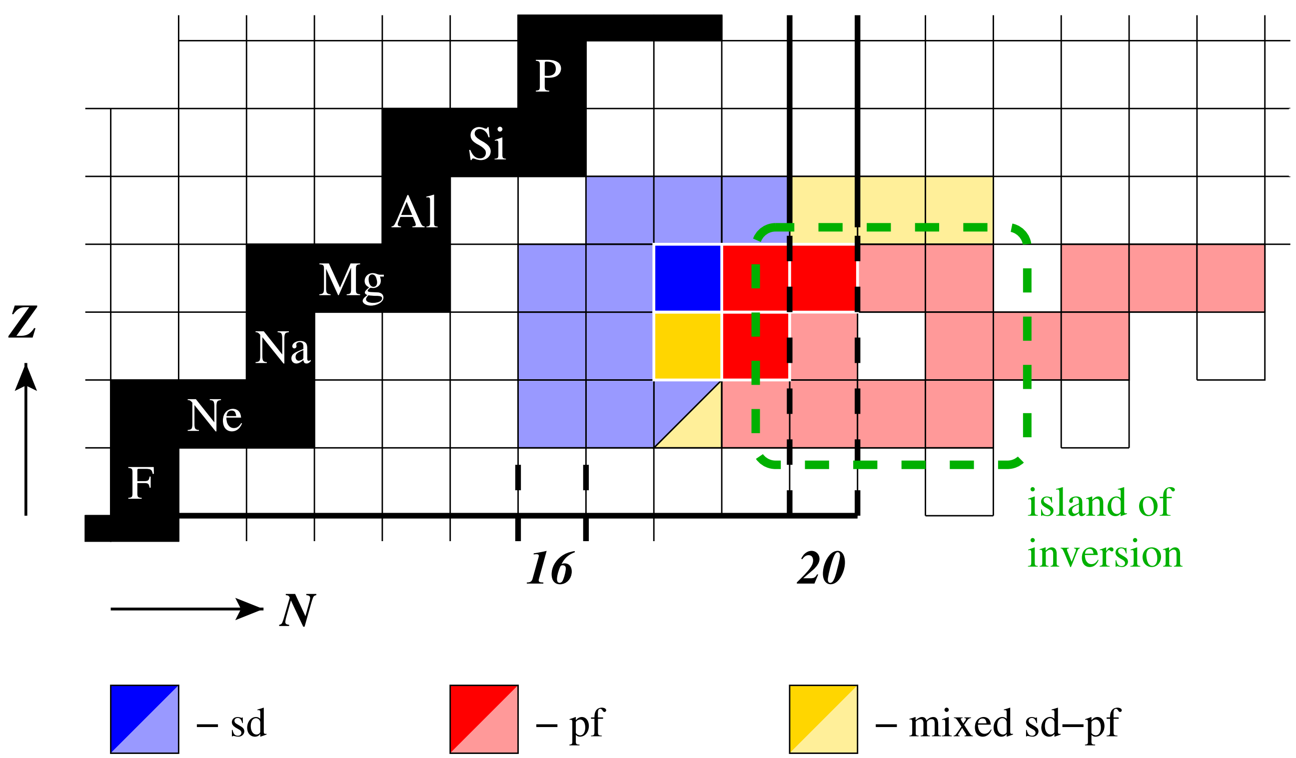
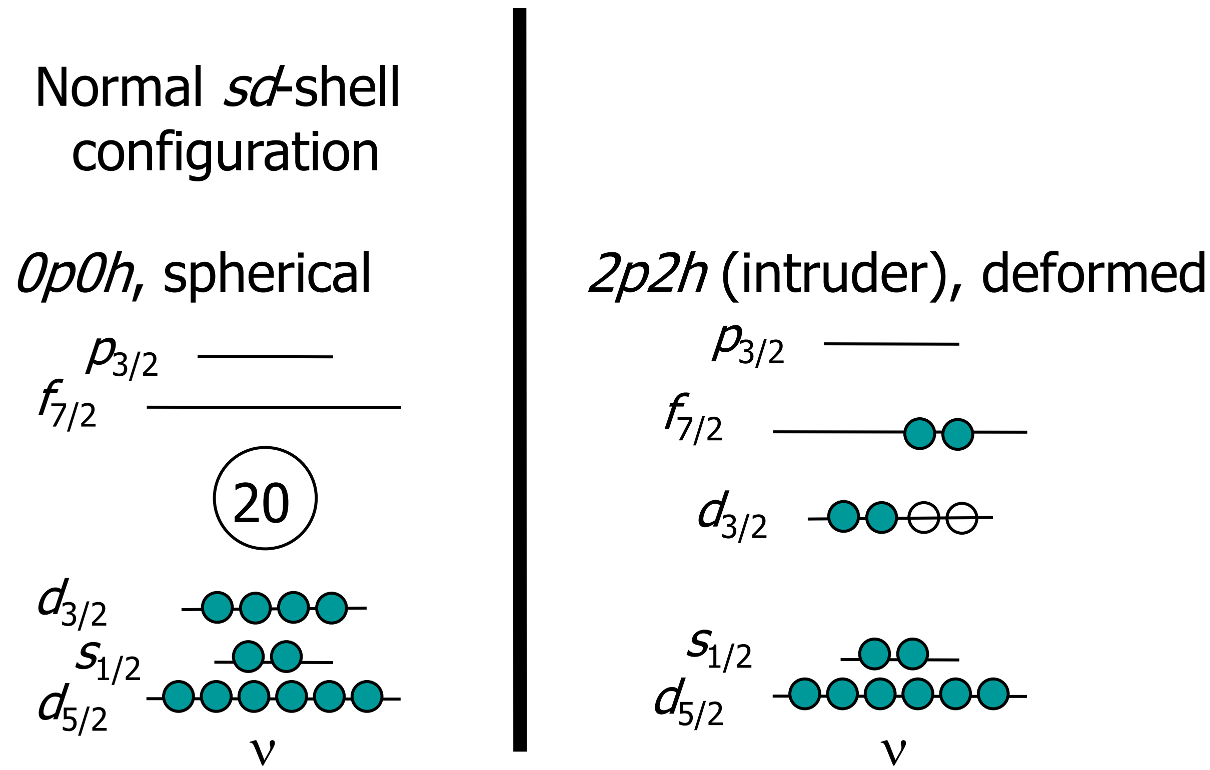
Island of inversion

- Nuclear chart of the island of inversion



P. A. Butler et al., J. Phys. G: Nucl. Part. Phys. 44 (2017)

- Normal VS Intruder configuration

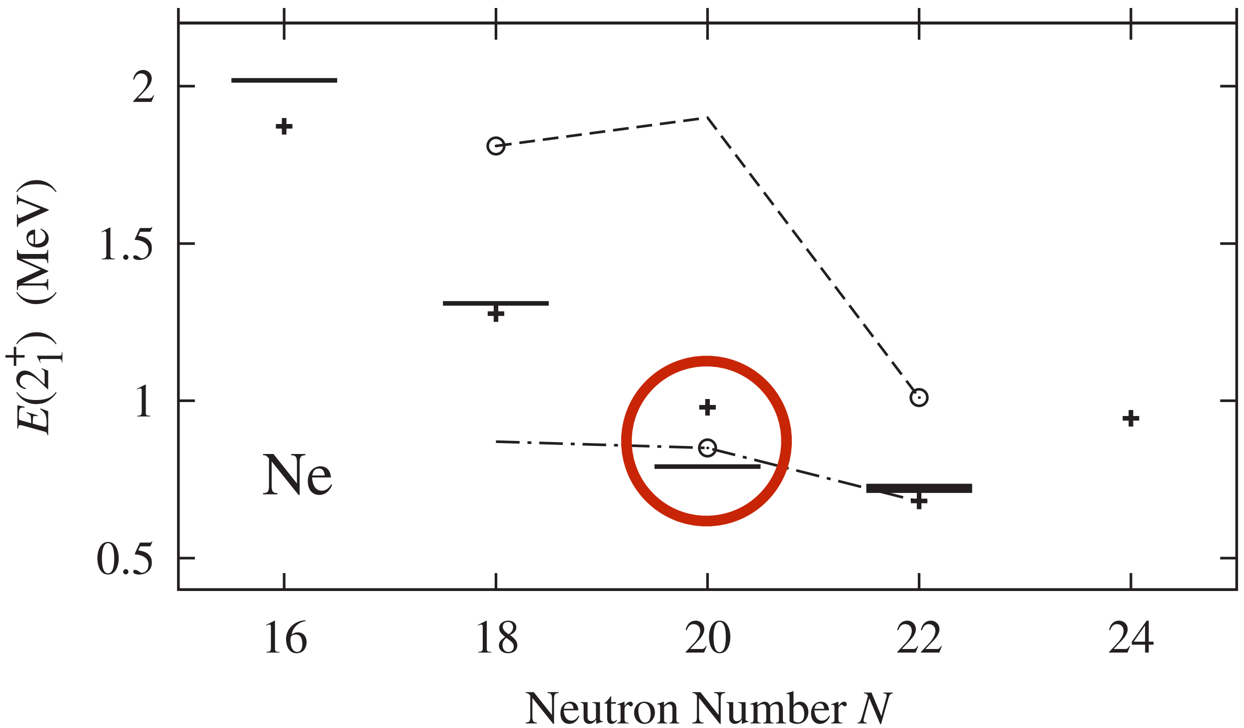


E. K. Warburton et al., Phys. Rev. C **41** (1990) 1147

- $N = 20$ shell gap is vanishing for Ne, Na, Mg isotopes.
- The *pf* shell intrude into the *sd* shell at $N = 20$, leading to vanishing of shell gap.

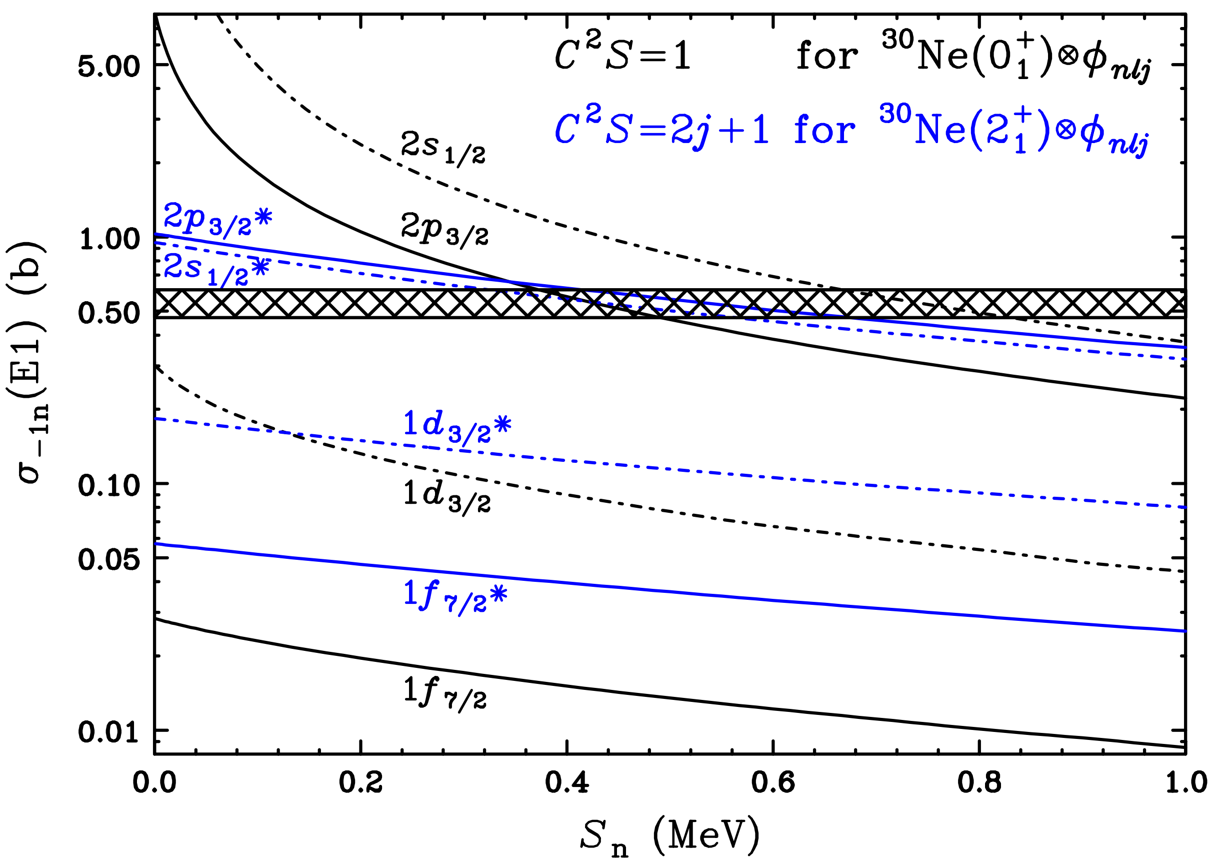
Island of inversion of Ne

- $E(2_1^+)$ in and Ne isotopes (N = even)



P. Doornenbal et al., PRL 103, 032501 (2009)

- σ results of ^{31}Ne compared with calculation

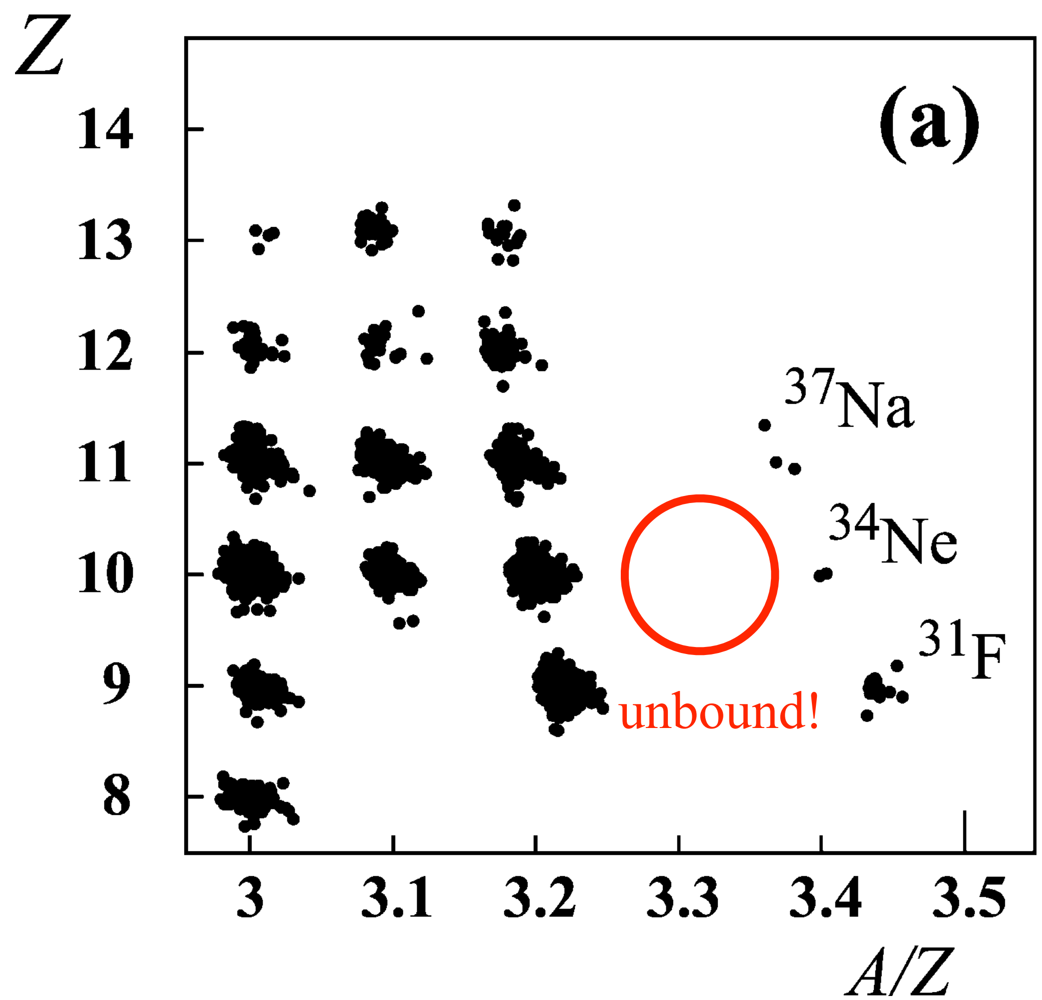


T. Nakamura et al., PRL 103, 262501 (2009)

- In case of even Ne isotopes, very low E(2+) at N = 20, 22 suggest that ^{30,32}Ne belongs to the island of inversion.
- ^{30}Ne ⊗ $2p_{3/2}$ configuration of ^{31}Ne ground state is evidence of the island of inversion.
- Spectroscopic study of ^{33}Ne is expected to broaden the understanding of island of inversion.

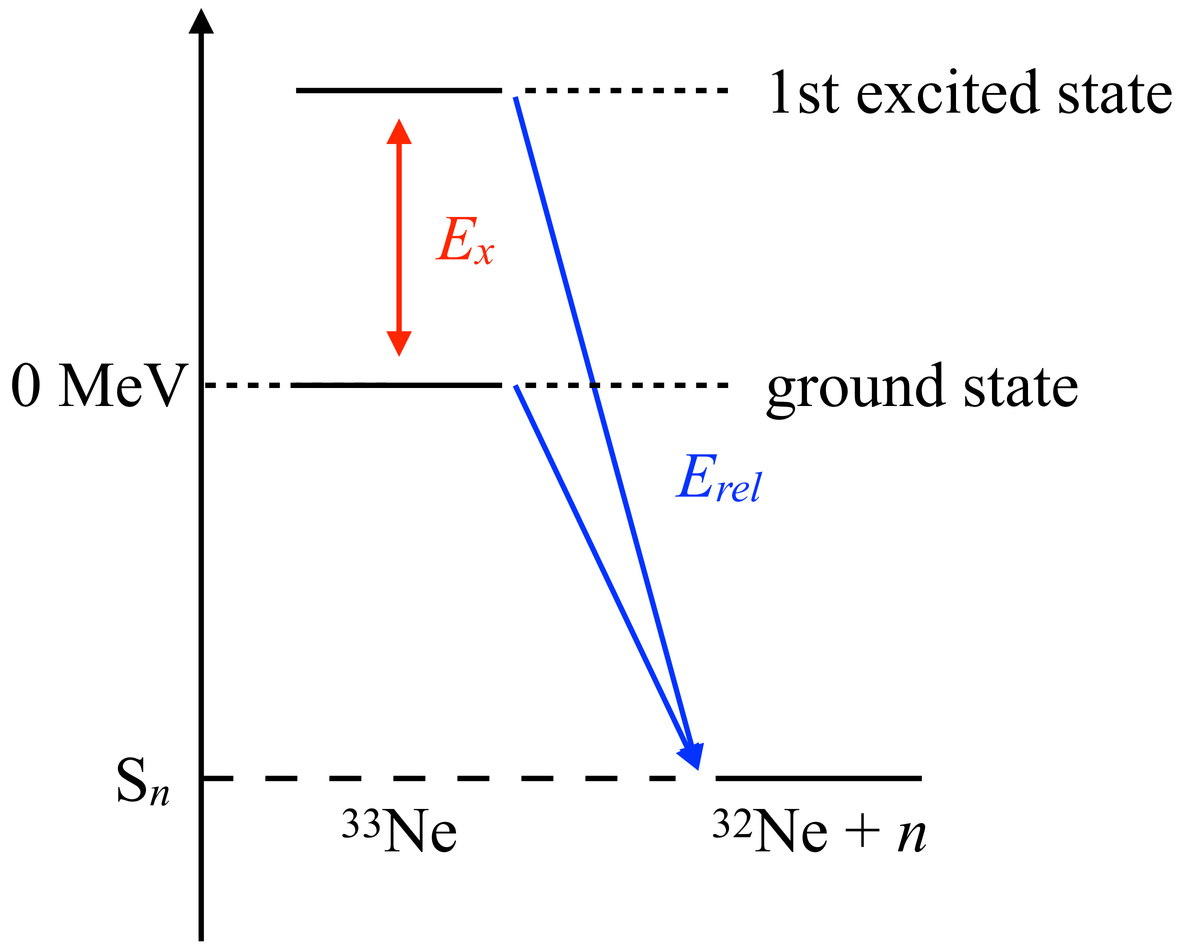
Mass of ^{33}Ne

- PID plot near ^{33}Ne isotopes



M. Notani et al., PLB 542, 49 (2002)

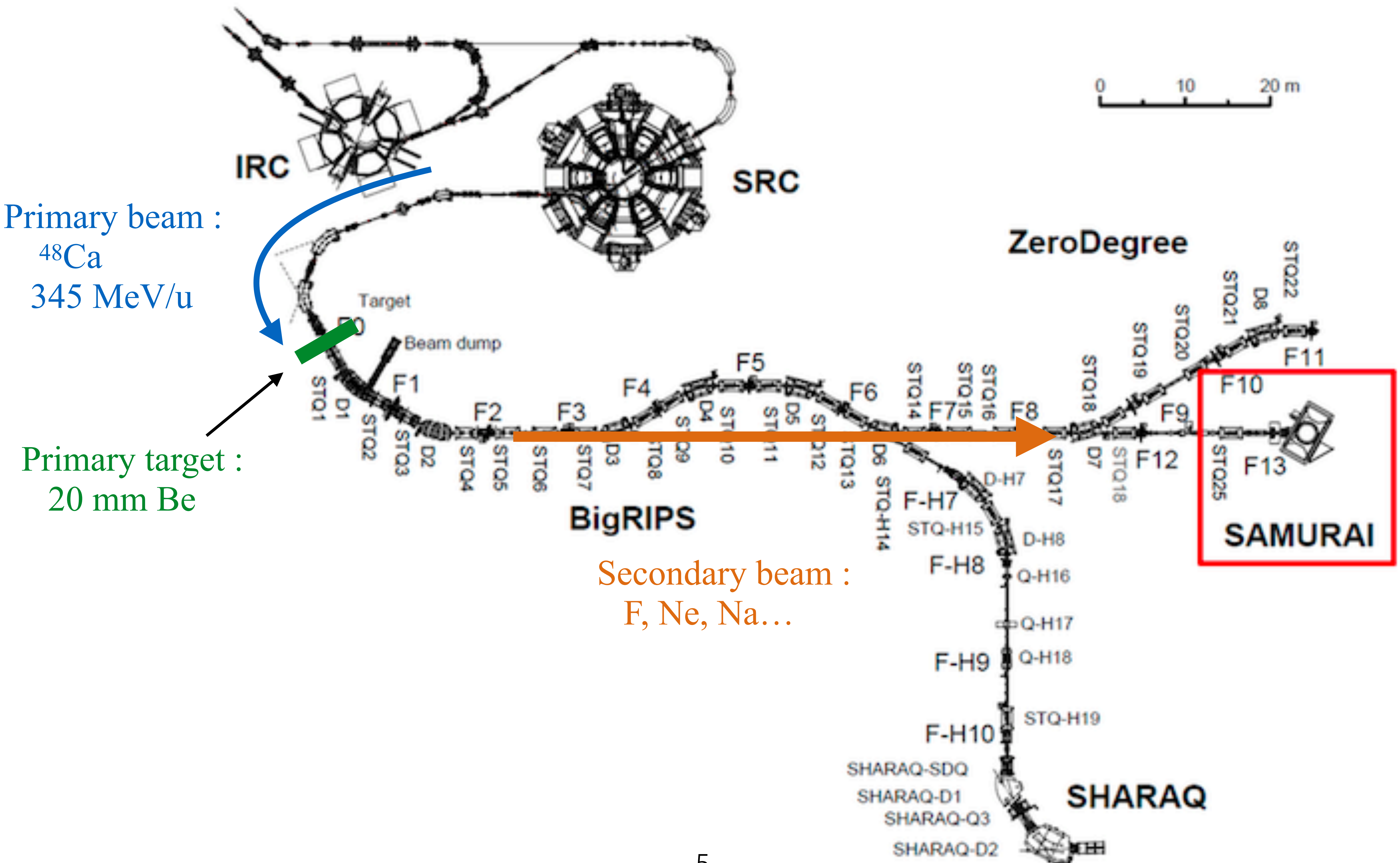
- Unbound nuclei case



- It is known that ^{33}Ne is an unbound nucleus.
- The mass of ^{33}Ne can be obtained by measurement of S_n.
- AME2012 predicts S_n to be -0.9 MeV.

Experimental setup (BigRIPS)

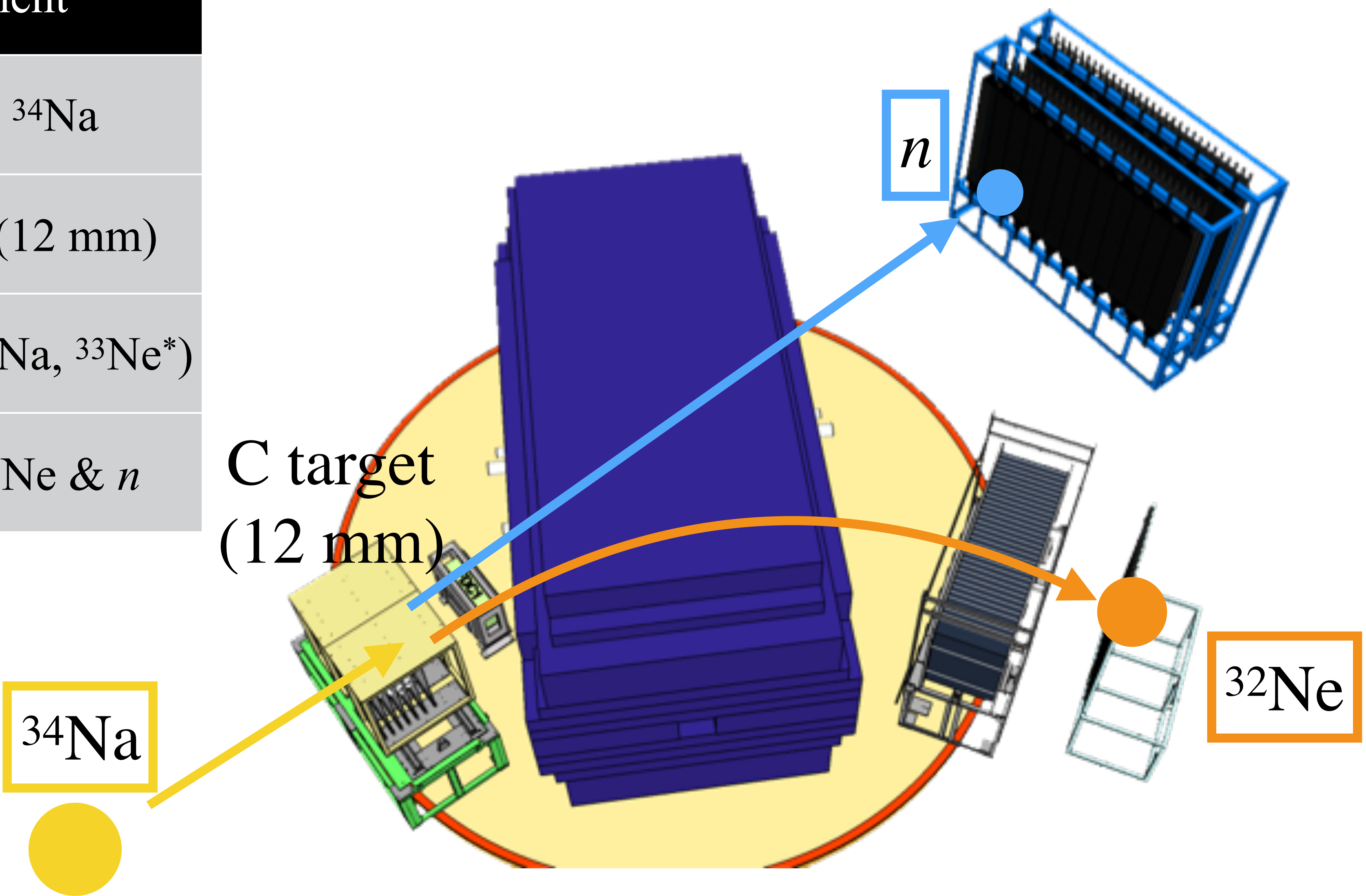
- Schematic view of BigRIPS



Experimental setup (SAMURAI)

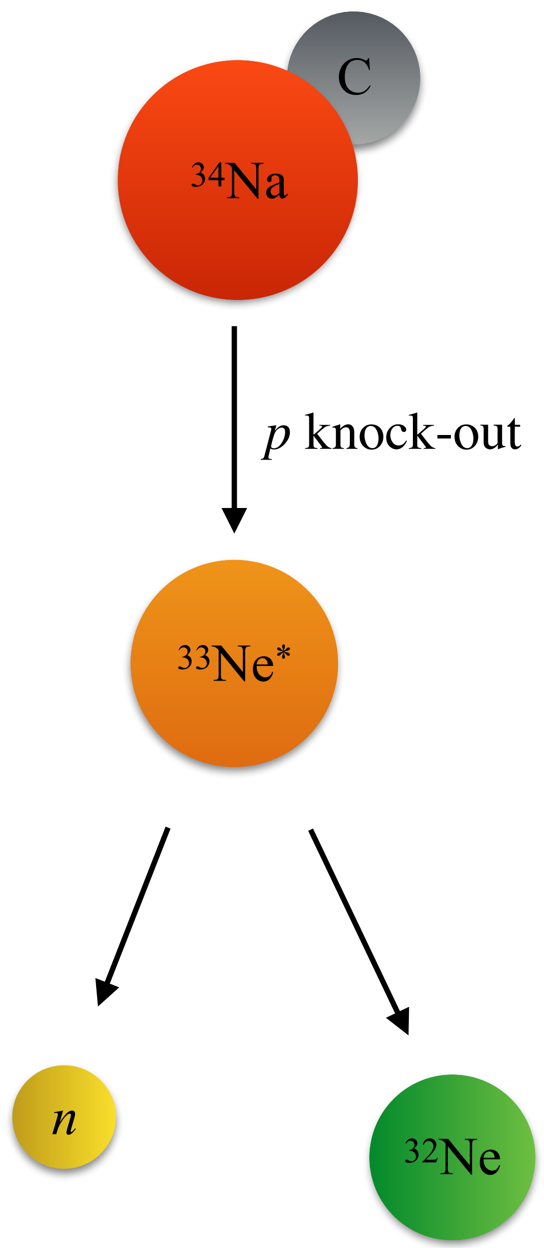
- **S**uperconducting **A**nalyzer for **MU**lti-particles from **RA**dio**I**sotope beams

S027 experiment	
Secondary beam	^{34}Na
Reaction target	C (12 mm)
reaction	C(^{34}Na, ^{33}Ne*)
Fragments	^{32}Ne & *n*



Procedure of analysis

1. Select the ^{34}Na beam.
   - Beam PID using ***Bρ*-*Δ*E-TOF** method
2. Select the ^{32}Ne & *n* fragments.
   - Charged fragment PID using ***Bρ*-*Δ*E-TOF** method
   - Neutron selection with **1*n* coincidence**
3. Reconstruct relative energy (E_{rel}) spectrum.
   - **Invariant mass method** from 4-momenta of fragments
   - Neutron detector **efficiency** & geometrical **acceptance**



Beam analysis

- Beam PID
  - F5 position for rigidity ($B\rho$) of beam
  - Energy loss (ΔE) at ICB
  - Time of flight (TOF) from F7 to F13

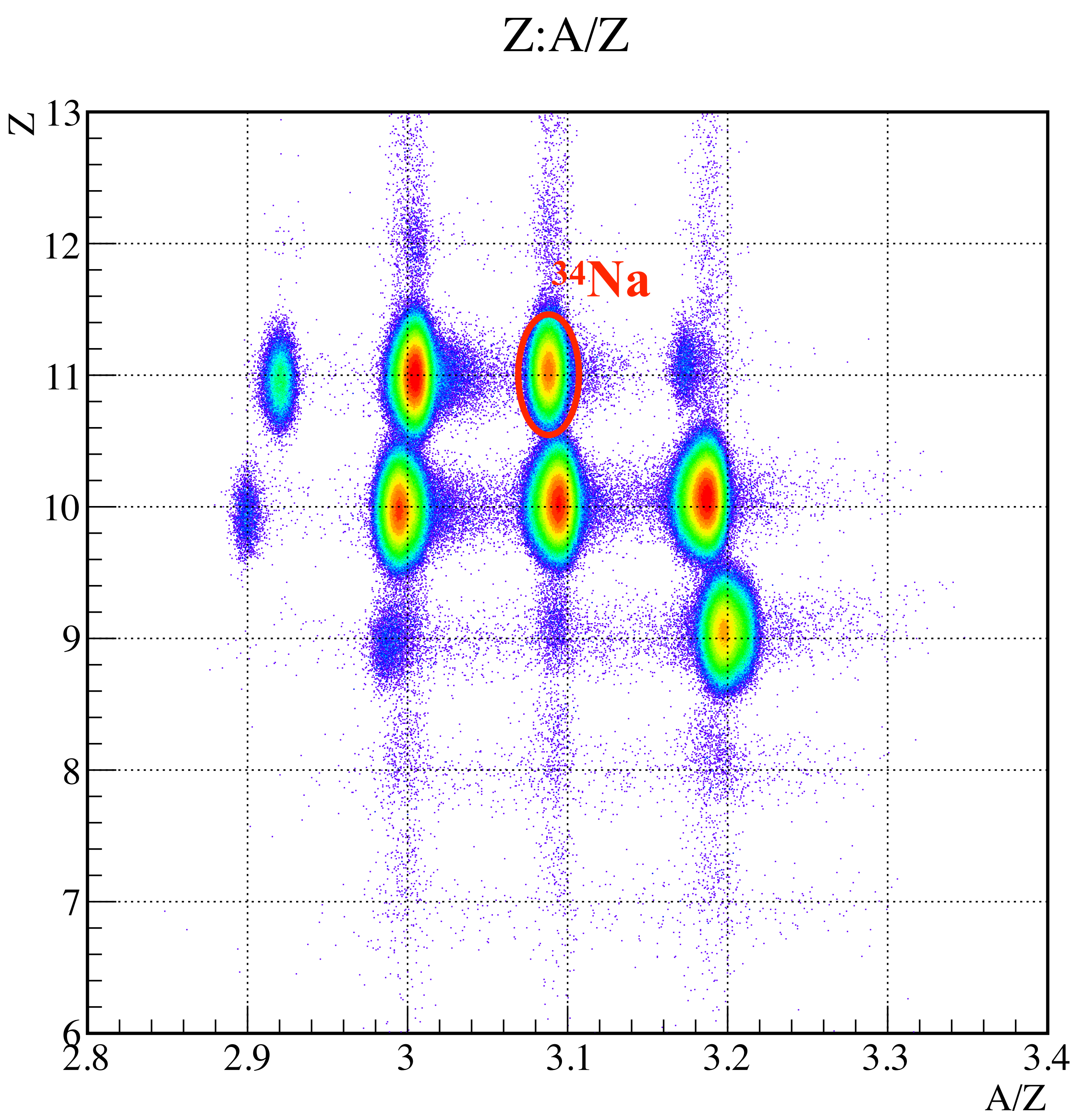
→

$$\frac{A}{Z} = \frac{B\rho}{\gamma m_u c\beta}$$

$$Z = p_0\sqrt{\frac{\Delta E}{f(\beta_5)}} + p_1$$

- Beam Profile
  - BDC analysis

Beam PID results (^{34}Na)



Secondary beam (^{34}Na)	
Total number	3.42598×10^5
Beam intensity	~7 pps
Energy	~260 MeV/u
$\Delta Z/Z$	1.32% (in σ)
$\Delta A/A$	0.14% (in σ)

Fragments analysis

- Charged fragments PID
  - $B\rho$ reconstruction using FDC data with transfer matrix
  - ΔE at Hodoscope
  - TOF from target to Hodoscope

$$\frac{A}{Z} = \frac{B\rho}{\gamma m_u c\beta}$$

$$Z = p_0\sqrt{\frac{\Delta E}{f(\beta_5)}} + p_1$$

- Neutron
  - TOF from target to neutron detectors
  - Position at neutron detectors

Fragment momentum

Direction of charged fragments

$$\hat{p} = \frac{\vec{r}_{FDC1} - \vec{r}_r}{|\vec{r}_{FDC1} - \vec{r}_r|}$$

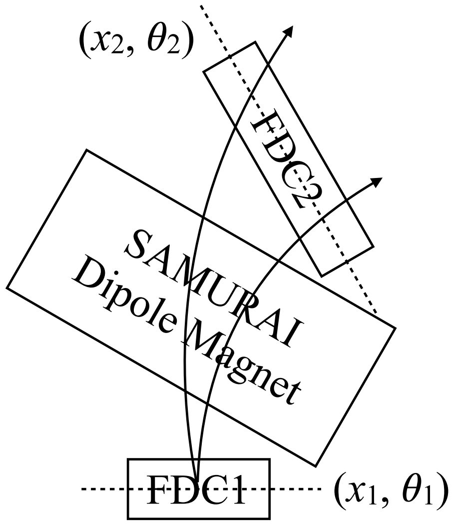
$\hat{p}$: (unit vector of $\vec{p}$)

$\vec{r}_{FDC1}$: (position at FDC1)

$\vec{r}_r$: (reaction point)

Rigidity ($B\rho$) of charged fragments

$$p/Z = B\rho = (B\rho)_0(1+\delta)$$

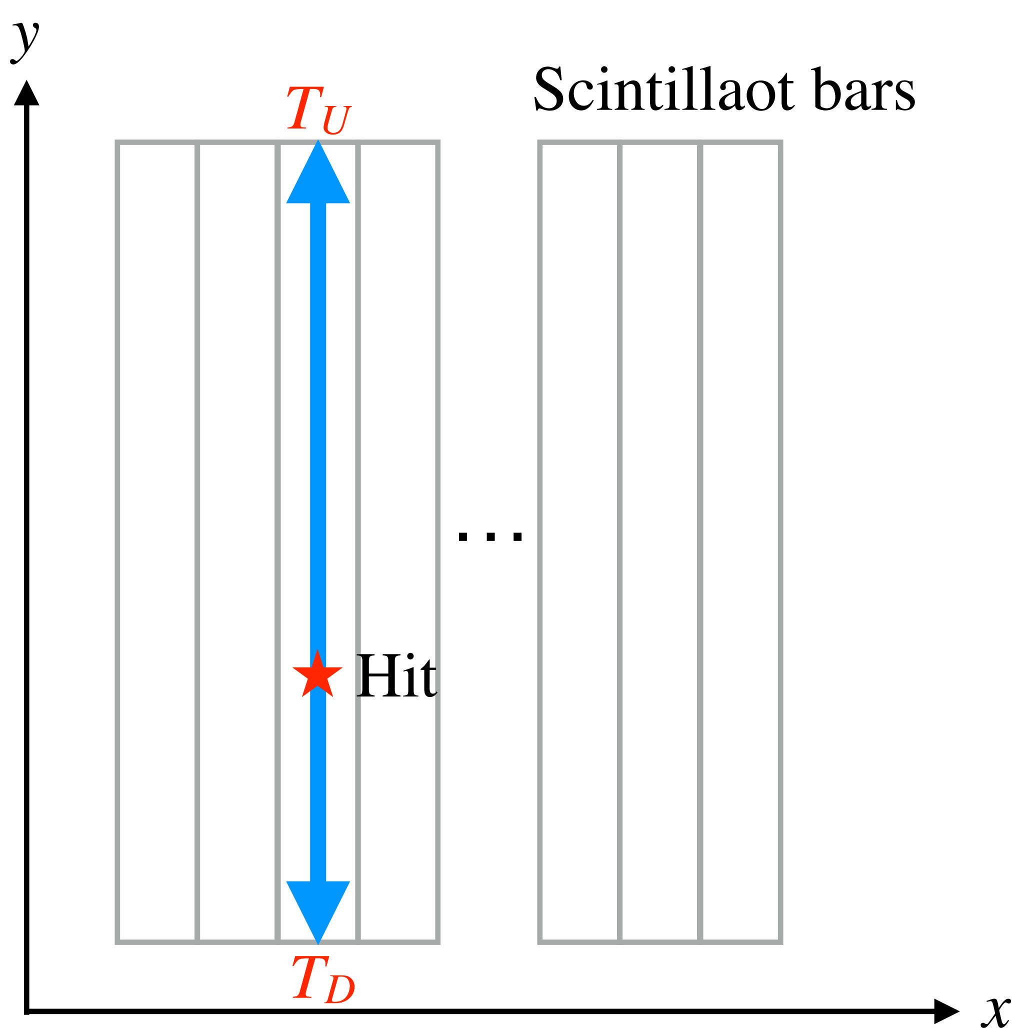


$$\begin{bmatrix} x \\ \theta \\ \delta \end{bmatrix}_{\mathrm{FDC2}} = \begin{bmatrix} (x|x) & (x|\theta) & (x|\delta) \\ (\theta|x) & (\theta|\theta) & (\theta|\delta) \\ (\delta|x) & (\delta|\theta) & (\delta|\delta) \end{bmatrix} \begin{bmatrix} x \\ \theta \\ \delta \end{bmatrix}_{\mathrm{FDC1}}$$

◇ Transfer matrices were obtained from OPTRACE calculation

Neutron analysis

Schematic picture of neutron detector



x position : scintillator bar position

y position : $y = c_0 + c_1 \cdot (T_U - T_D)$

Neutron 4 - momentum calculation

$$\mathrm{TOF_n} = (\mathrm{T_U} + \mathrm{T_D})/2 - \mathrm{T_{target}}$$

$$\vec{v}_n = (\vec{r}_n - \vec{r}_r)/\mathrm{TOF_n}$$

$\vec{r}_n$: (neutron hit point)

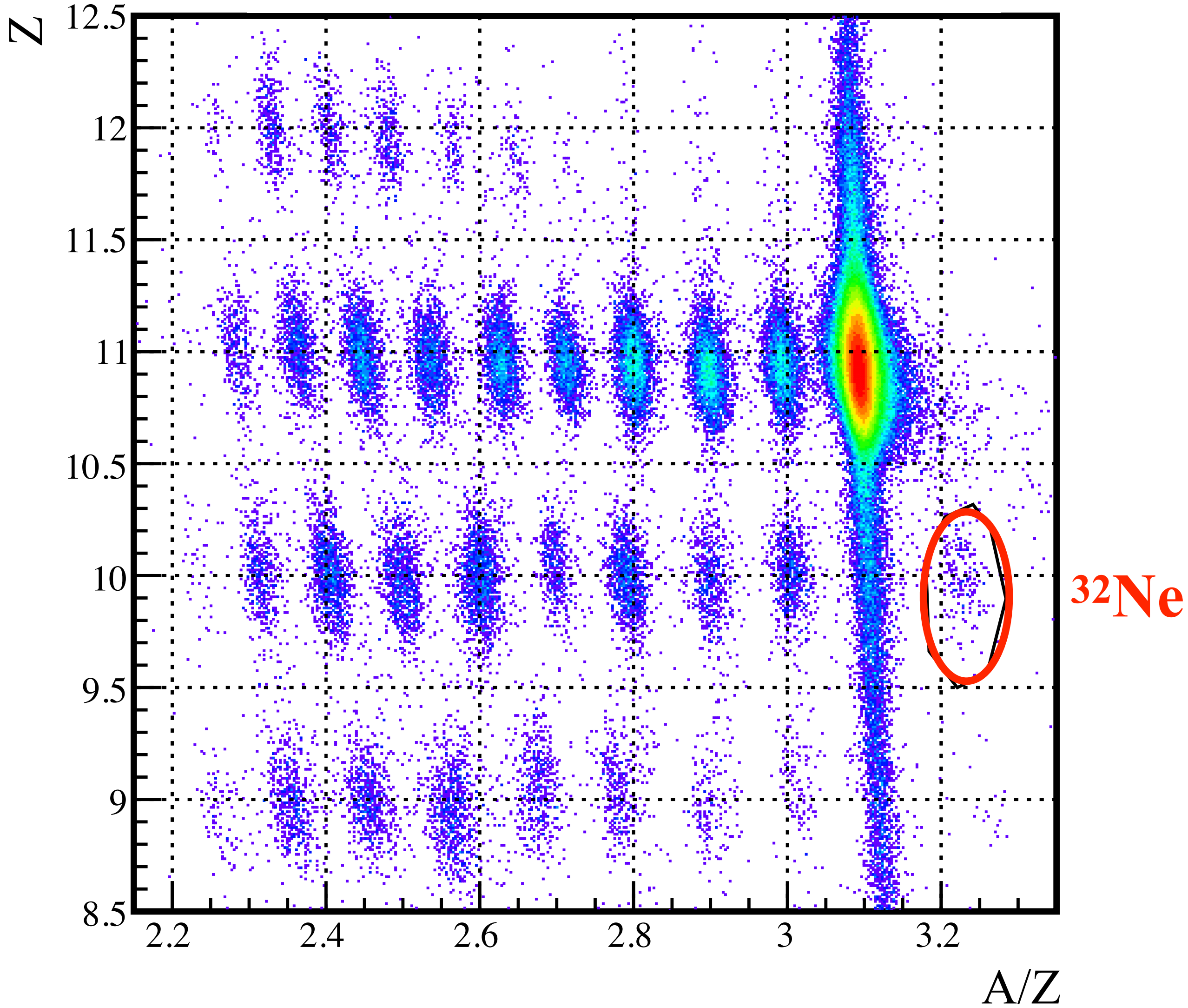
$\vec{r}_r$: (reaction point)

$$\vec{p}_n = \gamma_n m_n \vec{v}_n$$

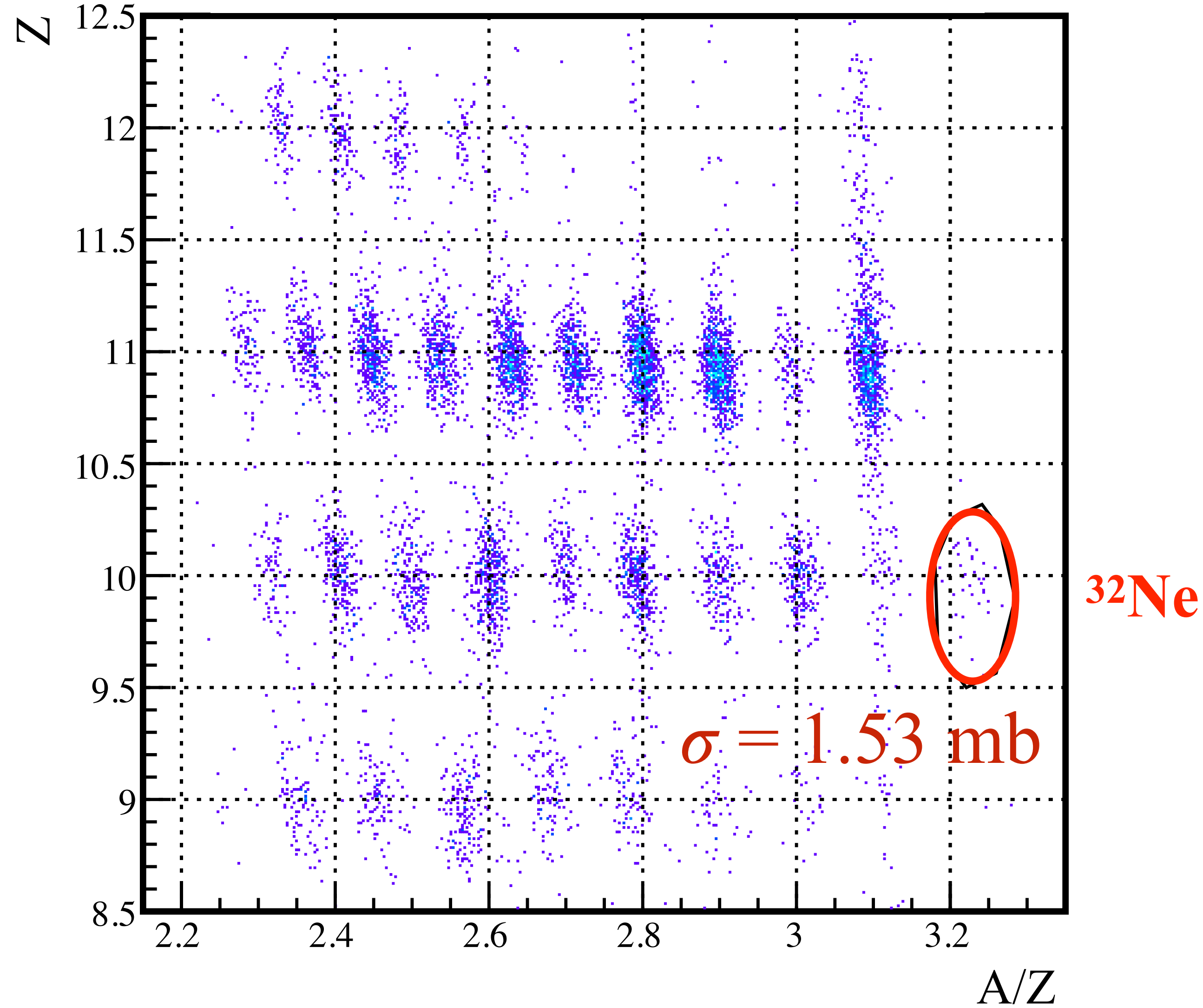
$$E_n = \gamma m_n c^2$$

Fragment PID

w/o neutron coincidence



with neutron coincidence



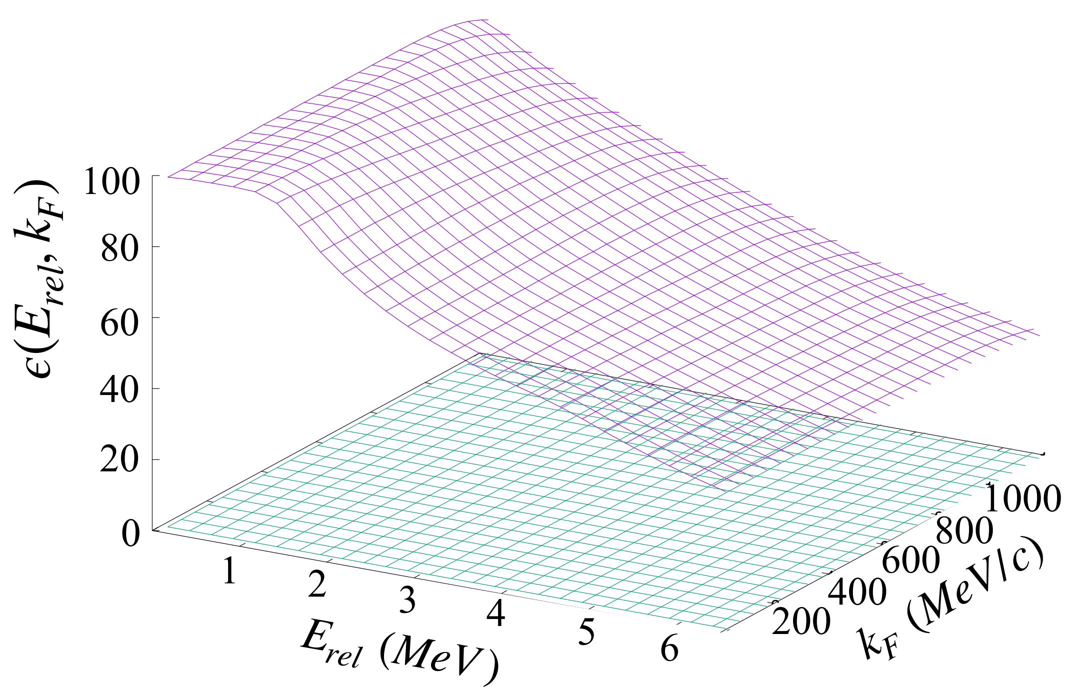
^{32}Ne	Number of events
w/o *n* coincidence	193
with *n* coincidence	27

Acceptance correction

- Energy differential cross section

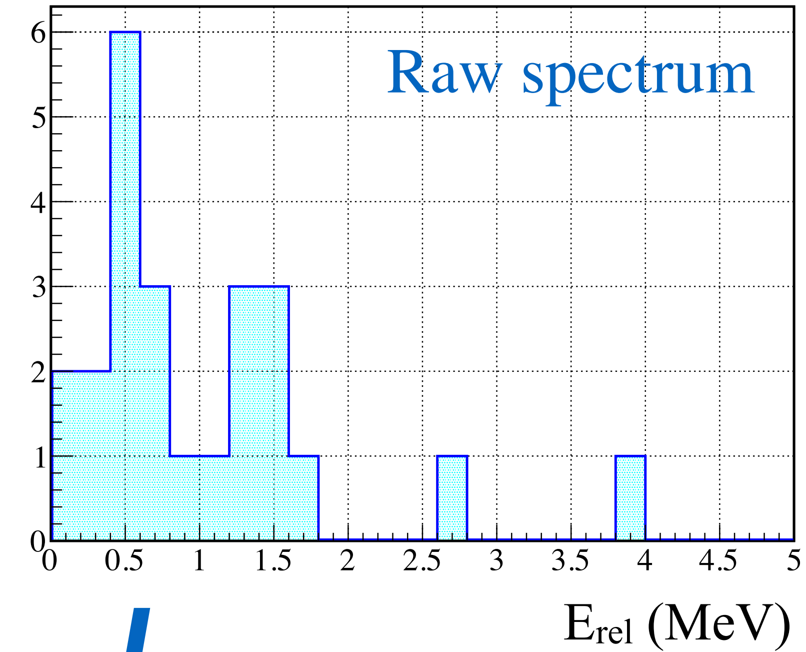
$$\frac{d\sigma}{dE_{rel}} = \frac{n_{scat}}{n_{beam} \cdot n_{target}} \frac{1}{\epsilon_{FDC} \cdot \epsilon_{neutron} \cdot \epsilon(E_{rel}, k_F) \cdot \Delta E_{rel}}$$

- Acceptance map of NEBULA layer1

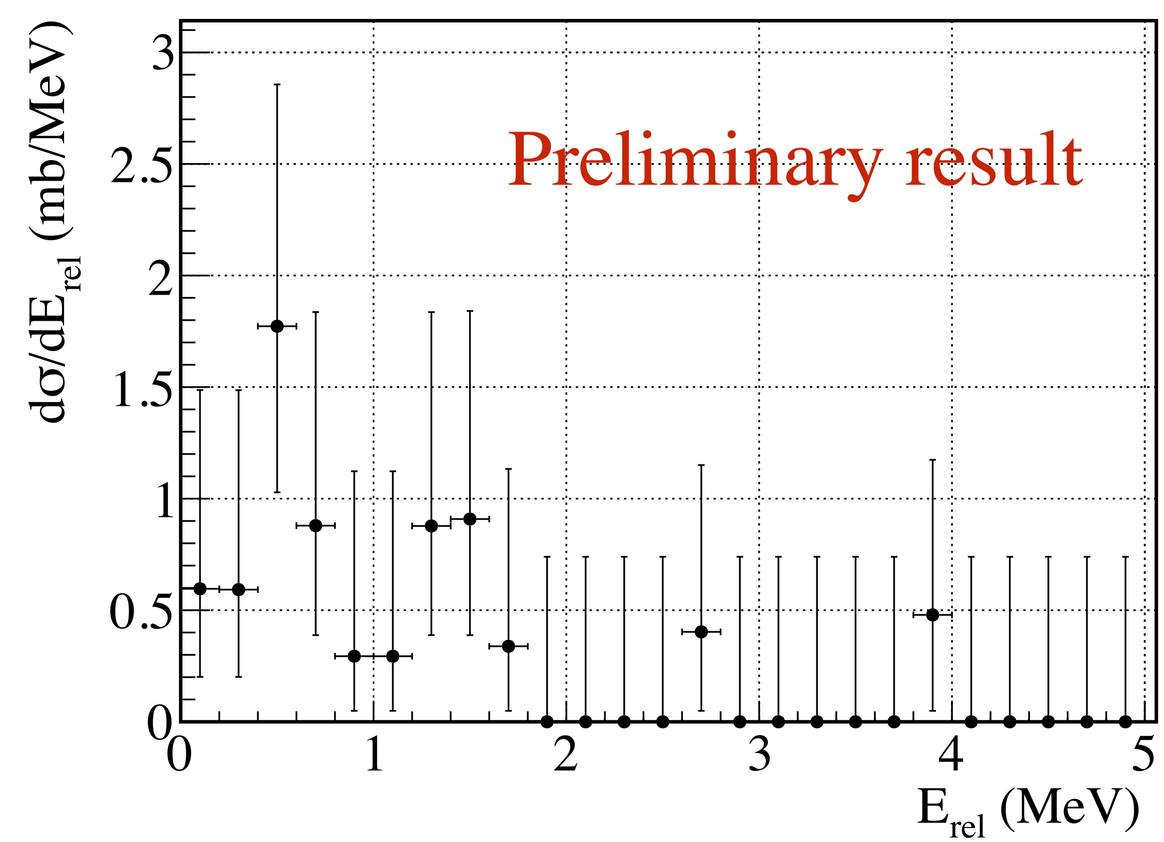


- Efficiency correction

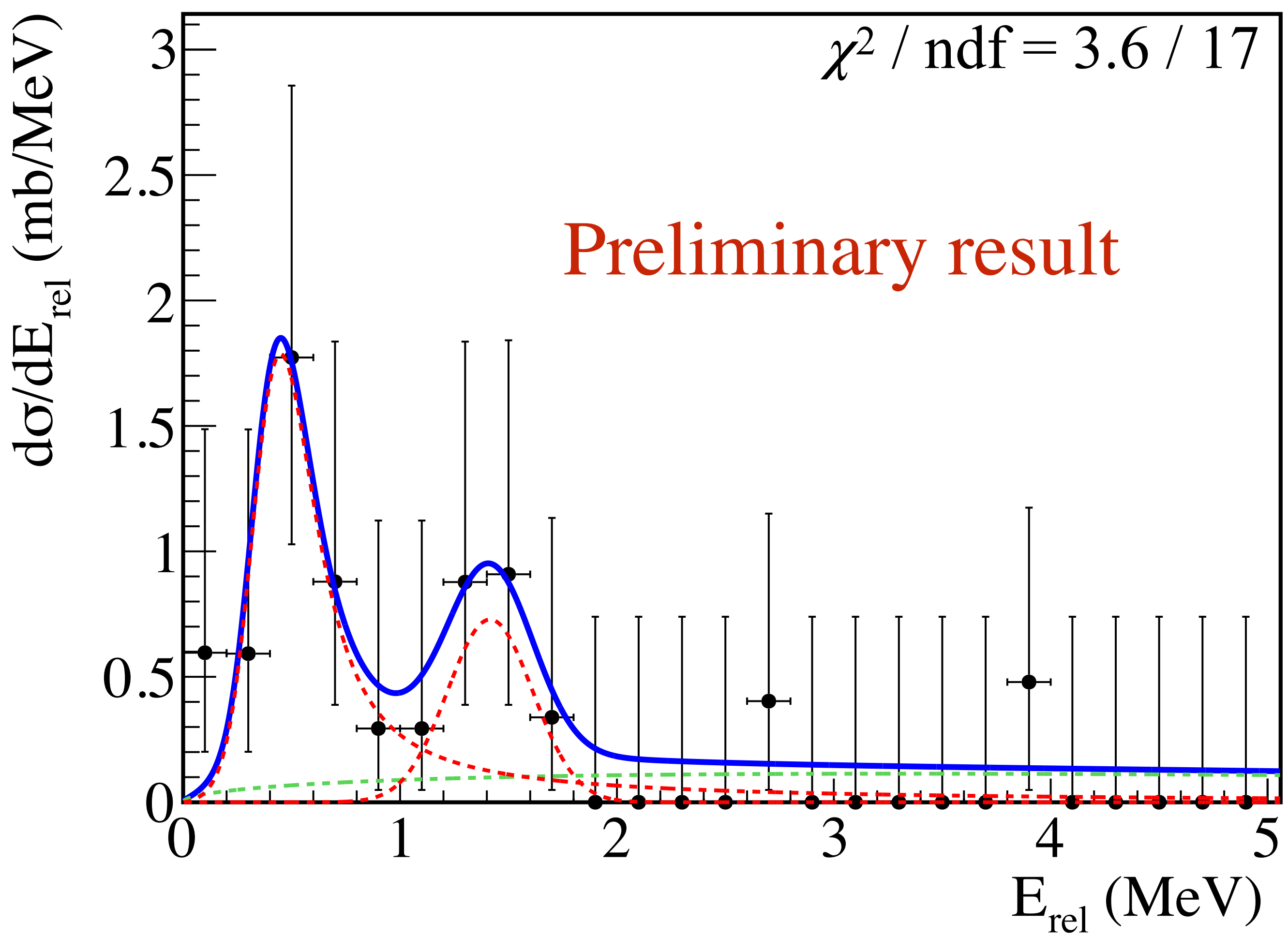
n_{beam}	n_{target} (mb^{-1})	ϵ_{FDC}	$\epsilon_{neutron}$
342598	1.08×10^{-4}	0.975	0.488



Relative energy spectrum for ^{32}Ne + n



Relative energy spectrum



Peak:

Breit-Wigner shape

$$\sim \frac{\Gamma_l(E)}{(E - E_R + \Delta_l(E))^2 + \Gamma_l(E)^2/4}$$

Background:

Maxwell-Boltzmann

$$a_0 \cdot \sqrt{E} \cdot Exp(-a_1 \cdot E)$$

	E_{rel} (MeV)	σ_{-1p} (mb)	AME2012
1st peak	0.48(17)	$1.05^{+0.63}_{-0.57}$	0.9
2nd peak	1.42(17)	$0.36^{+0.28}_{-0.36}$	

pulse height > 6 MeVee

Next plan

- Model calculations are necessary to understand the experimental results of ^{33}Ne.
  - Energy levels of ^{33}Ne
  - $1p$ knock-out cross section (σ_{-1p})
    - Spectroscopic factor (C^2S)
    - Single particle cross section (σ_{sp})

Summary

- The unbound states of ^{33}Ne, which has not been measured, are populated by 1*p* knock-out reaction performed at S027 experiment.

- Total 27 events of ^{32}Ne fragments with 1*n* coincidence are clearly identified from ^{34}Na beam with ~7 pps.

- The relative energy spectrum was reconstructed from the momenta of fragments by using invariant mass method.

- Measured S_n = -0.5 MeV is compatible with AME 2012 value of -0.9 MeV.

- Model calculations for energy levels and knock-out cross section of ^{33}Ne will help to interpret the experimental results.

Thank you!