EVOLUTION OF SHELL STRUCTURE

W A RICHTER

ITHEMBA LABS

UNIVERSITY OF THE WESTERN CAPE

Focus points:

1. **Single-particle structure of nuclei**

2. **Elastic scattering**

3. **The Interface between Nuclear structure & Astrophysics**

4. **Computing capabilities required**

The final energy of the RIB's on target will range from few MeV/u up to ~ 10 MeV/u for A=130. Allows overcoming Coulomb repulsion.

Opens up new possibilities for experimental studies of neutron-rich nuclei employing different reaction mechanisms such as Coulomb excitation, inelastic scattering, single-and multiple-nucleon transfer, fusion reactions, etc.

Such reactions will allow reaching nuclei far away from the stability line, thus providing very valuable information on nuclear structure and dynamics.

The interest in the study of nuclei with large neutron excess is not only focused on the location of the drip line but also on the investigation of the density dependence of the effective interaction between the nucleons for exotic N/Z ratios.

Changes of the nuclear density and size in nuclei with increasing N/Z ratios are expected to lead to different nuclear symmetries and new excitation modes e.g. oscillations of a neutron skin against the core.
This information is needed to enable a quantitative description of compact systems like neutron stars.

It is very important to study experimentally how the single-particle levels shift or re-order with neutron excess, inducing changes in shell gaps and even the breakdown of the standard magic numbers (so-called shell quenching).

A different scenario has been recently suggested where the evolution of the shell structure in going from stable to exotic nuclei is described in terms of a mean field which includes the tensor force explicitly (Otsuka).

The tensor-force is responsible for the strong attraction between a proton and a neutron in spin-flip partner orbits.

One-particle transfer reactions e.g. (p,d) or (d,p) are an important tool to study the evolution of shell closures far from stability.

They allow determination of the position of the single-particle states and also the occupation probabilities via spectroscopic factors.

The latter provide detailed information on the mixing of single-particle states with more complicated configurations.

Reactions where one neutron is added for determining the single-particle location and strength are perhaps the most important information needed for the extrapolation of nuclear models to properties of nuclei out to the neutron drip line.

A recent example is ^{132}Sn(d,p)^{133}Sn studied at ORNL (Oak Ridge) where the exotic beam production is limited to a few isotopes such as Sn.

Reactions such as (d,p) in inverse kinematics on other exotic isotopes that could be produced at the new facility are crucial.

These will be easiest to interpret for nuclei near the magic numbers such as ^{68}Ni, ^{80}Zn, ^{82}Ge, ^{132}Sn and ^{134}Te.

ELASTIC SCATTERING ON NEUTRON-RICH NUCLEI

A Workshop (Annual FRIB workshop August 8 - 12, 2011, U Washington, Seattle) was held on the topic of "Interfaces between nuclear structure and reactions".

During that workshop several talks emphasized the need for data on the optical-model parameters for neutron-rich nuclei.

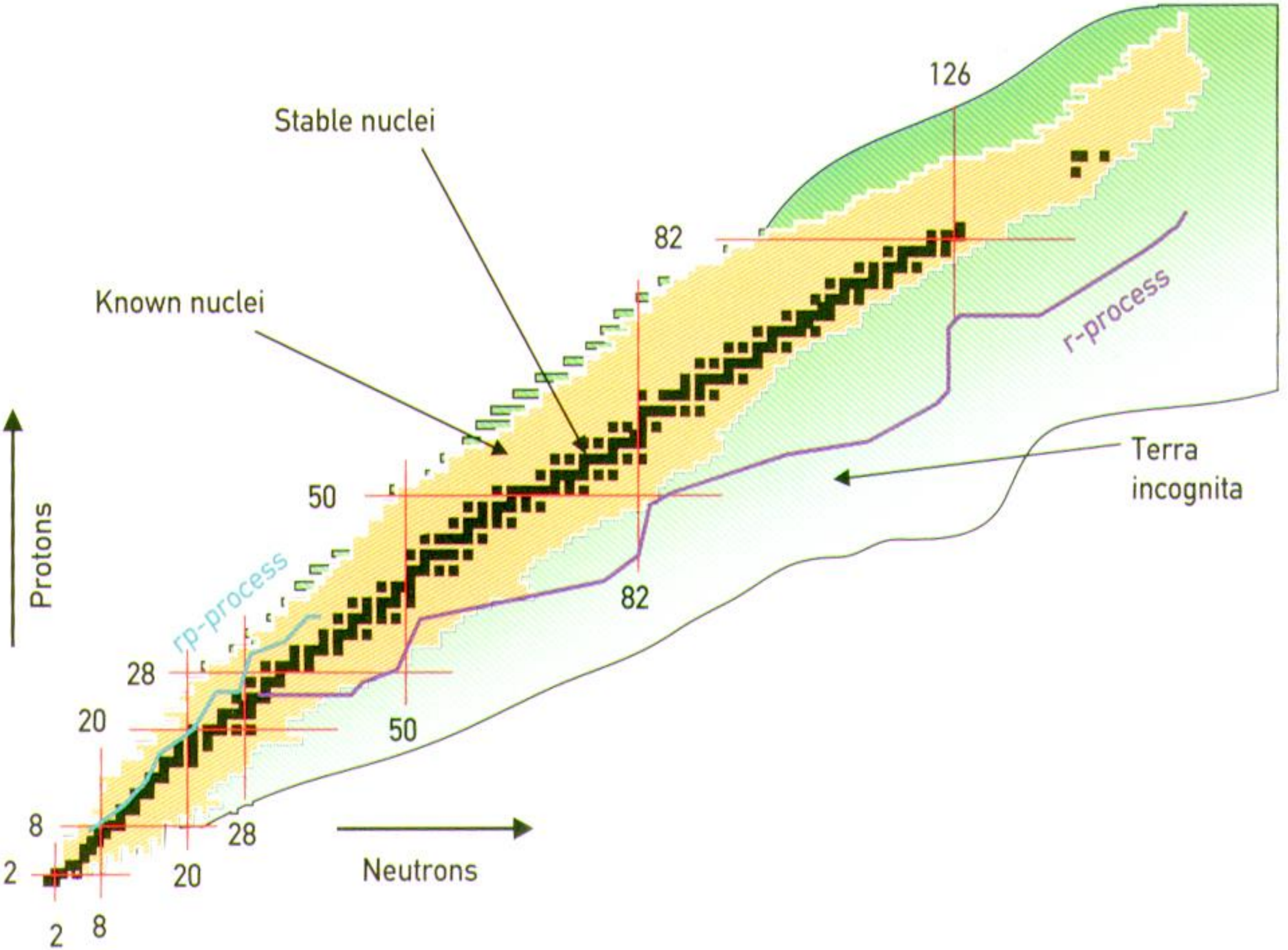
This is needed as input to reactions such as (d,p) in order extract information related to spectroscopic factors.

Thus there is much need for a systematic set of data for proton, deuteron, ^{3}He and alpha elastic and inelastic scattering in inverse kinematics over the wide range of neutron – rich nuclei that can be produced at the new facility.

THE INTERFACE BETWEEN NUCLEAR STRUCTURE AND ASTROPHYSICS

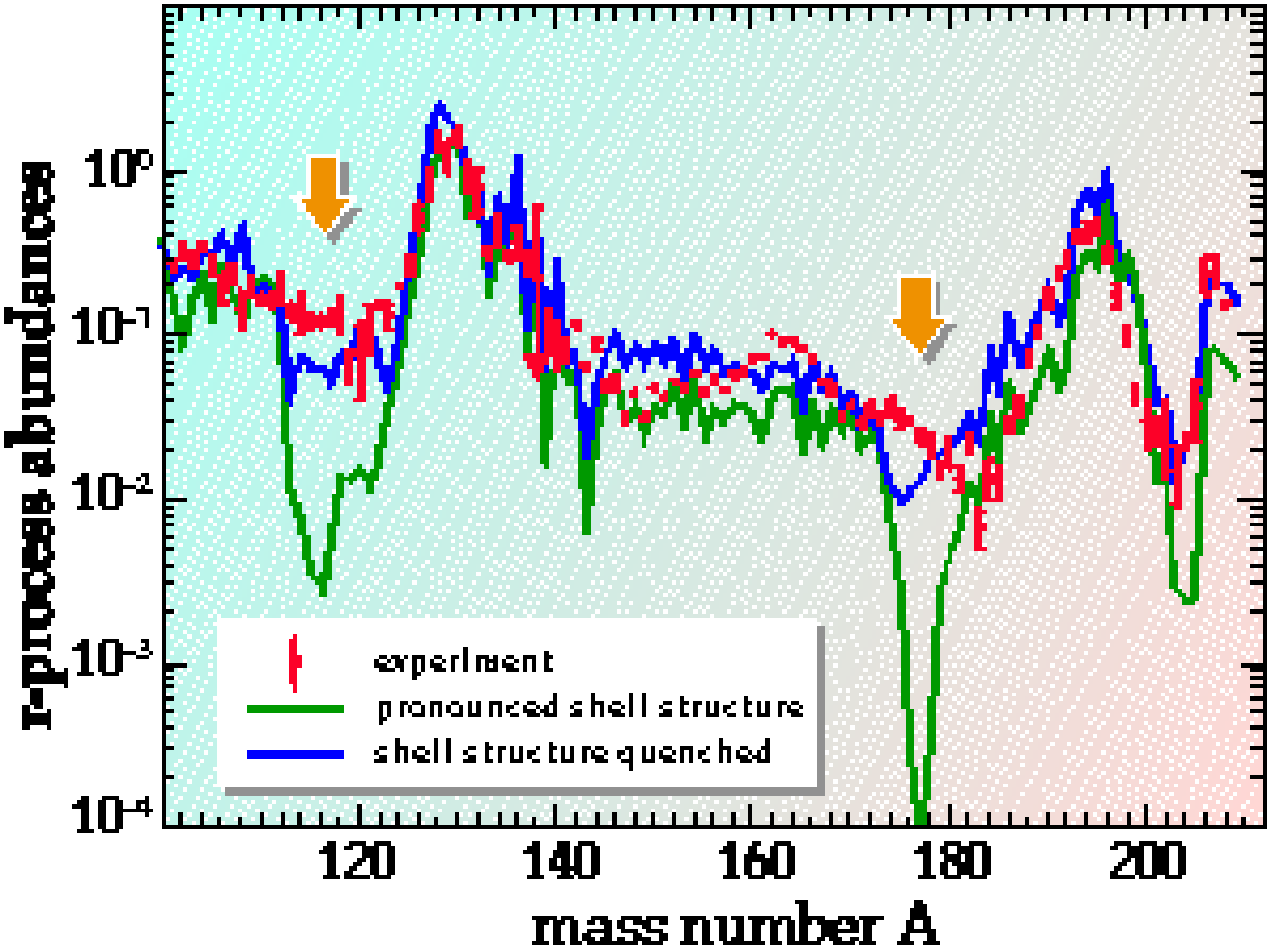
Rapid (r) process path along very neutron-rich nuclei; several neutrons added before β decay terminates sequence, i.e. nuclear decay time long. High density, temperature needed, e.g. supernova explosion

Some proton-rich nuclei not formed via either the r- or s-processes – rapid proton burning or rp process e.g. in explosive H burning on surface of neutron stars in binary systems, accretion discs of black holes and supernovae


126
Stable nuclei
82
Known nuclei
r-process
Terra incognita
50
82
Protons
rp-process
28
20
50
8
28
2
20
Neutrons
2
8

The key role of radioactive beams in the field of nuclear astrophysics is mainly related to the problem of nucleosynthesis. This involves measurements of beta-decay, gamma, and n-capture rates in medium-mass very n-rich nuclei along the so called r-process path.

The study of abundances of nuclei along the r-process path of heavy elements, as shown in the next figure, points also to the existence of shell quenching effects. A quenching of the shell effects at N=82 and N=126 can lead to substantial improvements between the calculated and exp determined abundances.



r process exp abundance (in red) & 2 calcs with differing spin-orbit strength - weaker does better

For r process network calculations need:

Nuclear masses (or BE)
n capture rates (n, γ)
inverse rates (γ,n)
β-decay halflives
neutron separation energies
probability for β-delayed neutron emission (Pn)

It is of key importance to determine the neutron separation energy and β-decay half-lives at and around the major neutron shell closures, i.e. at N = 50, 82 and 126, associated with the r-peaks in the abundance distribution.

These magic nuclei, that represent the waiting points in the r-process chain, have also life-times longer than their non-magic neighbours and regulate the mass-flow and rp duration .

The nuclear properties of r-process isotopes, in particular M, $T_{1/2}$, and P_n, are currently the subject of intense experimental investigation at the already existing facilities.

Within the next few years it is expected that several radioactive beam facilities, now in construction or in the designing phase, may allow extension of measurements deep into the r-process region.

For rp network calculations need:

Nuclear masses (or BE) ⇒ S_p or S_{2p}
p capture rates (p, γ)
inverse rates (γ,p)
β^+ -decay and electron capture rates

Two types of thermonuclear explosions relevant:

X-ray bursters (hydrogen accretion onto a neutron star)

Nova (hydrogen accretion onto a white dwarf)

Example: The ^{30}P(p,gamma)^{31}S reaction

In nova outbursts on oxygen-neon (ONe) white dwarfs, the reaction plays a crucial role in the synthesis of heavier nuclear species, from Si to Ca.

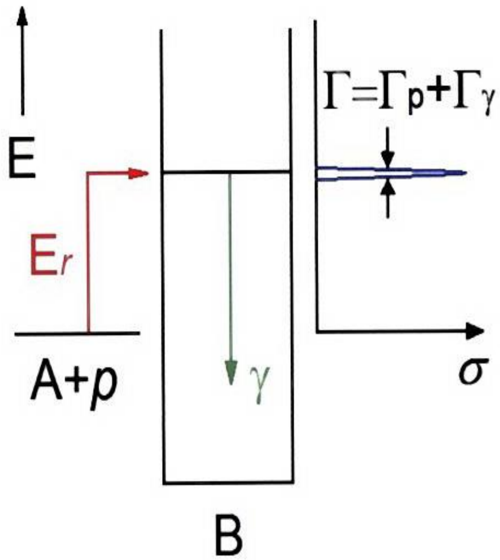
Its reaction rate, however, is not well determined due to uncertainties in the properties of key resonances.

This lack of knowledge of inhibits the interpretation of observables associated with the underlying astrophysics.

The uncertainties in the reaction rate stem from unmeasured quantities, ambiguities in level properties measured in different experiments, and problems with theoretical calculations (mainly negative-parity states).

Thermonuclear radiative proton-capture reaction rates in novae

$$N_A \langle \sigma \upsilon \rangle = N_A \left(\frac{2\pi}{\mu k T} \right)^{3/2} \hbar^2 \sum_r (\omega\gamma)_r e^{-E_r/kT}$$



$$\omega\gamma = \frac{(2J_r+1)}{(2J_p+1)(2J_P+1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma}$$

$$\Gamma = \Gamma_p + \Gamma_\gamma$$

Determination of (p,gamma) reaction rates for the rp process

Crucial properties of the proton-rich nucleus are partial **gamma-decay widths** above the proton-emission threshold, the **proton decay widths** of states (which depend on the relevant spectroscopic factors) and level energies.

A special workshop was convened in July 2014 in Debrecen, Hungary as part of the Classical Novae in the Cosmos to discuss the P-30(p,gamma)S-31 reaction rate problems.

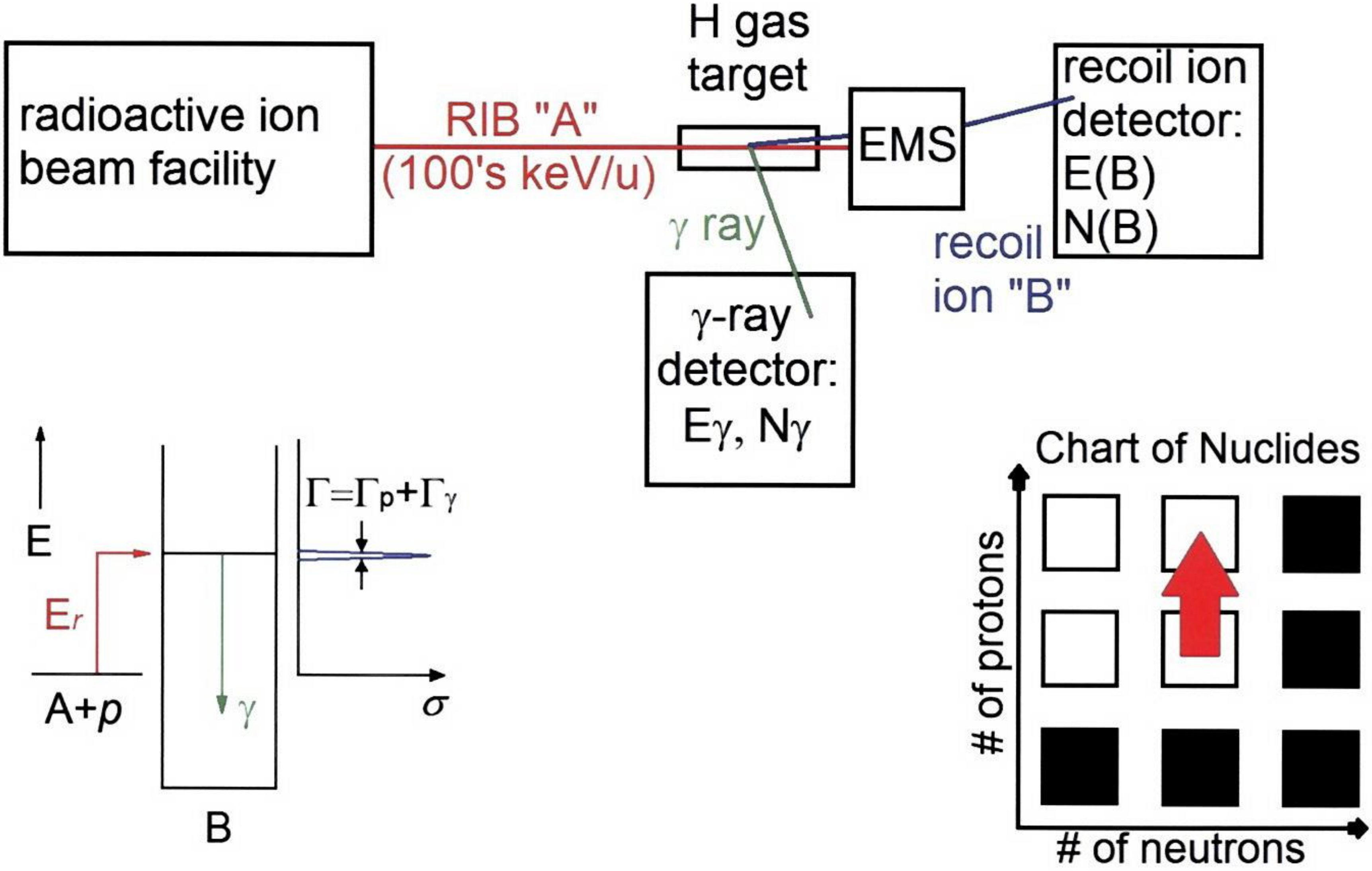
Experiments to determine the reaction rate for P-30(p,gamma)S-31.

Halflives: P-30 ~ 2.5 min. S-31: 2.55 s

Thus direct reaction expts generally not feasible, so use stable targets and light-ion transfer or charge exchange

S-32(d,t)S-31 Irvine MLL Munich
(p,d) Ma ORNL
P-31(He-3,t)S-31 Wrede Yale
Parikh MLL Munich
Si-28(α,n)S-31 Doherty Gammasphere

Also P-30(p,γ)S-31 in inverse kinematics
Kankainen NSCL



H gas target

radioactive ion beam facility

RIB "A"
(100's keV/u)

EMS

recoil ion detector:
E(B)
N(B)

γ ray

recoil ion "B"

γ-ray detector:
$E\gamma$, $N\gamma$

E

E_r

A+*p*

γ

B

$\Gamma=\Gamma_p+\Gamma_\gamma$

σ

Chart of Nuclides

# of protons

# of neutrons

Calculation of the reaction rate:

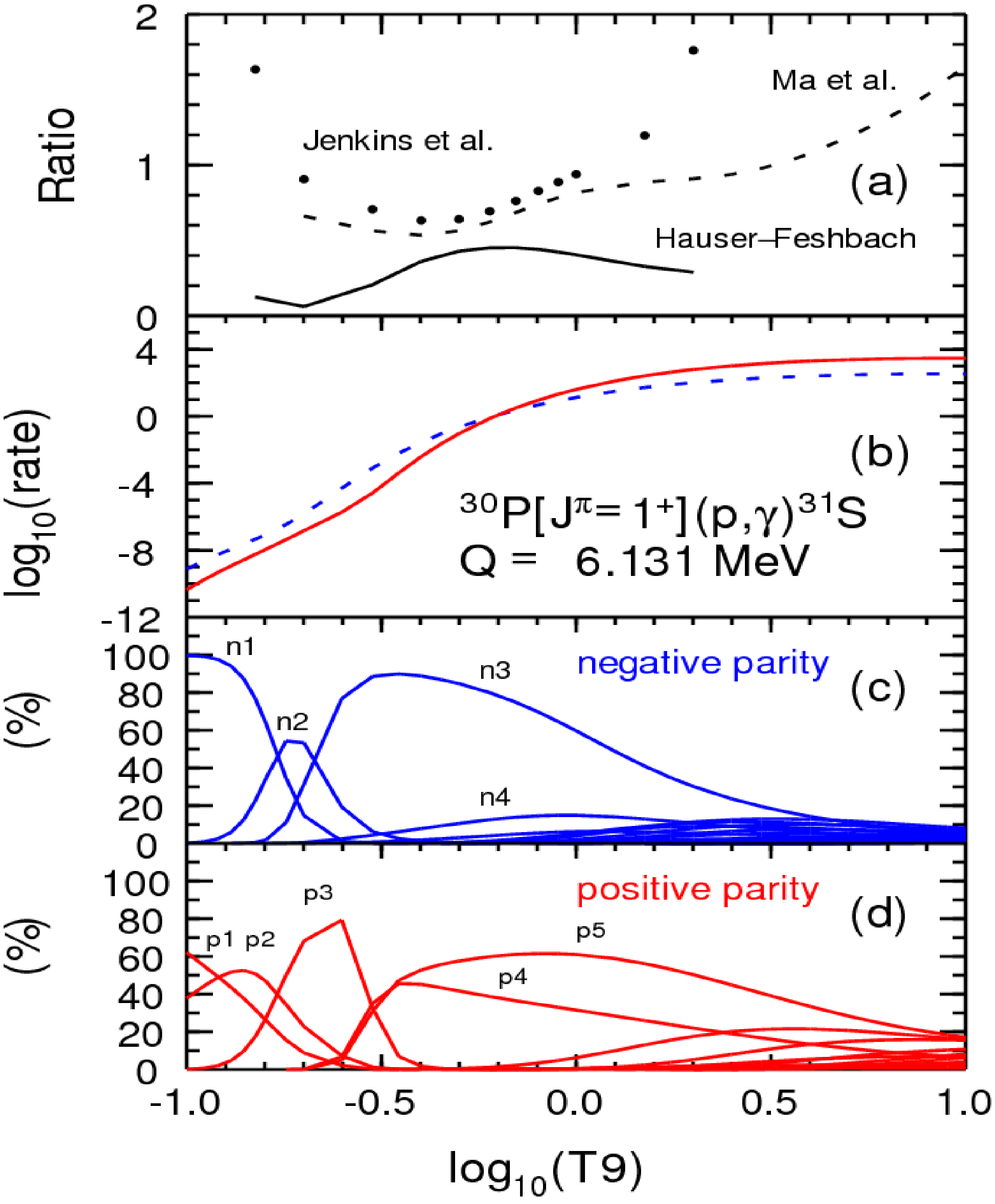
We obtained results for the first time of calculations in a full 1ħω model space for several negative parity states in the resonance region, using the interaction WBP.

USDB-cdpn was used for positive parity.

Gamma- and proton-decay widths were calculated for input into the reaction rate. Available experimental data was used in conjunction with the calculations to obtain an estimate for the reaction rate.

TABLE I. Properties of levels in ^{31}S between 5.9 and 7 MeV. See text for details.

n		Experiment					Theory						
	E_{res} (kev)	E_x (kev)	$(2J)\pi$				USDB-cdpn			$1\hbar\omega$			
							$(2J)\pi$	k	E_x (kev)	$(2J)\pi$	k	E_x (kev)	
		NDS 2013 [5]	NDS 2013 [5]	Wrede 2014 [28]	Doherty *et al.* 2012 [8]	Parikh *et al.* 2011 [9]							
1		5896	3+,5+				3+(t)	6	5965				
2		5959	3+,5+	*			5+(t)	7	6044				
3		5978	(9+)				9+(g)	3	5829				
4	8	6139	(7+)	(b)	(3,7)+	9	3+(t)	7	6141				
5	29	6160	(5−,7+)	(b)	7[+]	5				5−(t)	2	5825	
6	124	6255	1+	1+		1+	1+(g)	5	6259				*p*1
7	149	6280	3+	3+		3+	3+(g)	8	6280				*p*2
8	196	6327	(3)	(b)	3[−]	1+				3−(t)	2	6327	
9	226	6357	(5−)	(b)	5[−]	3+							
10	246	6377	(9−)	(9)	(5,9) [9−]	9[−]				9−(g)	1	6313	*n*2
11	261	6392	(5+)	(a),(5+)	5+		5+(g)	8	6402				*p*3
12	263	6394	(11+)	(a),(11)	11[+]	[11+]	11+(g)	1	6364				
13	270	6401		(a,c)			7+(t)	6	6298				
14	289	6421	(1+,3+,5+)	*									
15	411	6542	(3−)	(b)	3[−]	(7,9)				3−(t)	3	6757	*n*3
16	451	6583	(7)	(7)	(3,5,7)[−]	7				5−(t)	3	6792	
17	505	6636	(9−)	(9)	(5,9)[9−]	9[−]				9−(g)	2	6682	


2
1
0
Ratio
Jenkins et al.
Ma et al.
Hauser–Feshbach
(a)
4
0
-4
-8
-12
log10(rate)
(b)
30P[Jπ= 1+](p,γ)31S
Q = 6.131 MeV
100
80
60
40
20
0
(%)
n1
n2
n3
n4
negative parity
(c)
(%)
p1
p2
p3
p4
p5
positive parity
(d)
-1.0
-0.5
0.0
0.5
1.0
log10(T9)

Conclusions regarding the P-30(p,gamma)S-31 reaction rate:

The experimental inconsistencies and uncertainties make it very difficult to obtain a one-to-one correspondence with theory.

The reaction rate will be uncertain to within about an order of magnitude until the position and decay widths of several of the key states in the region of 6.0 to 6.6 MeV are experimentally determined.

There remains much experimentation to be done.

FW: What's this?

Flashback Photo. Try to guess what this is!

...This picture was taken in 1956...

It's a hard disk drive back in 1956... With 5 MB of storage.

In September 1956 IBM launched the 305 RAMAC, the first "SUPER" computer with a hard disk drive (HDD). The HDD weighed over a ton and stored a "whopping" 5 MB of data.

P.S. It would take 3200 of these units to equal the capacity of a little 16-Gig stick plugged into the side of your PC or laptop.

Summary:

1. Nuclear structure aspects of neutron-rich nuclei – especially single-particle info and elastic scattering
2. Experiments related to astrophysics – the r- and rp- processes
3. Our computing capabilities in association with SKA will be on par with any in the world

Cost ~ R 1 Bn. We should motivate the creation of our RIB facility at iThemba on the basis of a “security upgrade”.

Security against obsolescence!

Alternative: Produce S-31 from β+ decay of Cl-31 via e.g. Ar-36 + Be-9 NSCL Bennett

Populating *L* = 0 ^{30}P(p,γ)^{31}S resonances with ^{31}Cl decay