design, construction, and upgrade of ERNA to ERNA2

what does work and what does not

some old and some new results

conclusions and outlook
NaBoNA – Naples [Gialanella et al. NIMA 1996]

Fig. 1. Schematic diagram of the setup at the 3 MV tandem accelerator in Naples including a windowless gas target and a recoil separator (S = X–Y steerers, SL = slits, FC = Faraday cup, MQPD = magnetic quadrupole doublet, MQPT = magnetic quadrupole triplet).
Achievements:

- measurements without $\gamma$-ray coincidence
- first albeit incomplete documentation of the recoil acceptance
- investigation of charge exchange

Open issues:

- missing documentation of the angular acceptance
- good suppression only for recoil charge states unaccessible to beam ions
- no extensive optical calculations

$$p(\overline{7}\text{Be}\gamma) \overline{8}\text{B} \ E_{\text{cm}} = 992 \text{ keV}$$

> dedicated, specifically designed facility
> one additional filter element
> all analysis elements bend on the same plane
> partially computer controlled

From NABONA to ERNA
$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$
$$^3\text{He}(\alpha,\gamma)^7\text{Be}$$
Energy acceptance: change beam energy

Δ E / E₀ [%]

transmission

experimental

calculated

L. Gialanella, NARRS, GSI March 13-15, 2018
Investigation of the charge state of the recoils

\[ q_{\text{rec}} = q_{\text{beam}} + 2 \]

\[ q_{\text{rec}} = q_{\text{beam}} \]

\( ^{16}\text{O}^{3+} \text{ 9.60 MeV in } ^{4}\text{He} \)

L. Gialanella, NARRS, GSI March 13-15, 2018
$^{16}\text{O}^3$+ 7.2 MeV in Ar

$^{16}\text{O}$ in Ar post stripper

$^{16}\text{O}$ equilibrium charge state distribution in Ar
If you measure a transmission of 80% with an $\alpha$ source for a specific target:

- Recoil LOSS: 47%
- E1: 66%
- E2: 23%

for a specific target:

- 21%
- 36%
- 7%

LG and D. Schuermann PoS(ENAS 6)058v
Recoil detection

Full acceptance

Suppression
Separator: $10^{-10}$-$10^{-13}$
Detector: $10^{-3}$-$10^{-6}$

Mass resolution is not a good design parameter for ERNA
Achievements:
> cross section measurements without $\gamma$-ray coincidence (optional)
> documentation of the full recoil acceptance
> control of charge exchange using a post stripper
> good suppression with a nearly free choice of the recoil charge state
> extensive optical calculations

Open issues:
> extensive experimetal tuning required, scaling possible over relatively small ranges
> poor suppression and background production for low recoil charge states
From ERNA to ERNA2

> one more (charge filter) before strong focusing added
> full computer controlled
> both extended and jet gas target
> more complex ancillary detectors (gamma ray, e⁺, e⁻)
Background and leaky beams at low recoil charge state

$q = 3$
Background and leaky beams at low recoil charge state
Background and leaky beams at low recoil charge state

$\mathbf{q} = 3$
\[ S_{17}(0) = 20.8 \pm 0.7 \text{(expt)} \pm 1.4 \text{(theor)} \text{ eV b.} \]

Adelberger et al 2011
H$_2$ gas target

Intense beam
normalization

Energy loss

Charge state distribution
Angular acceptance

The resulting overall systematic uncertainty is 4%
$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$, again

Tracking detector - J. G. Duarte

Cauldrons in the Cosmos – Nuclear Astrophysics, Claus E. Rolfs
$E_{\text{CM}} = 2780\,\text{keV}$
Detector design

- MCPs
- Carbon foil
- Mirror grids
- Acceleration grids
- $x_0 - y_0$ position
- $x_1 - y_1$ position
- Delay line parallel grid detector
- Flight length

incident ions

High Vacuum
Isobutane ($C_4H_{10}$)

not in scale
New He jet target
D. Rapagnani

- full CFD
- jet profile tailoring
- optimized for gamma-ray and e+e- detection

2 mbar Ar (similar with selfconfinement)

100 mbar Ar
Compact rotating scanning unit
Conclusions and outlook

> ERNA2 has considerably improved performances
> for the first time p capture could be studied
> scaling does not work yet, we are working on that
> still remain the problems of a very challenging approach, requiring a lot of skilled manpower

Collaborating Institutions: Atomki, INFN, University of Edinburgh, University of Naples, University of Campania, University of Perugia, University of Sao Paulo, Ruhr University Bochum