# Production at SPES of a $^{94}$Nb radioactive source for studying the quenching of the weak interaction axial-vector coupling constant


*Francesco Cappuzzello on behalf of the ASPCT-BET collaboration*

*INFN-LNL 13 May 2025*

M. Biassoni(1), T. Bradanini(1)(2), C. Brofferio(1)(2), S. Capelli(1)(2), G. Gagliardi(1)(2), A. Nava(1)(2), I. Nutini(1), L. Bernardini(3)(4), M. Carminati(3)(4), F.C* (5)(6), M. Cavallaro (6), V. Soukeras (6)

(1) INFN, Sezione di Milano-Bicocca
(2) Dipartimento di Fisica G. Occhialini, Università di Milano-Bicocca, Milano
(3) DEIB, Politecnico di Milano, Milano
(4) INFN, Sezione di Milano
(5) Dipartimento di Fisica e Astronomia 'Ettore Majorana', Università di Catania, Catania
(6) INFN, Laboratori Nazionali del Sud

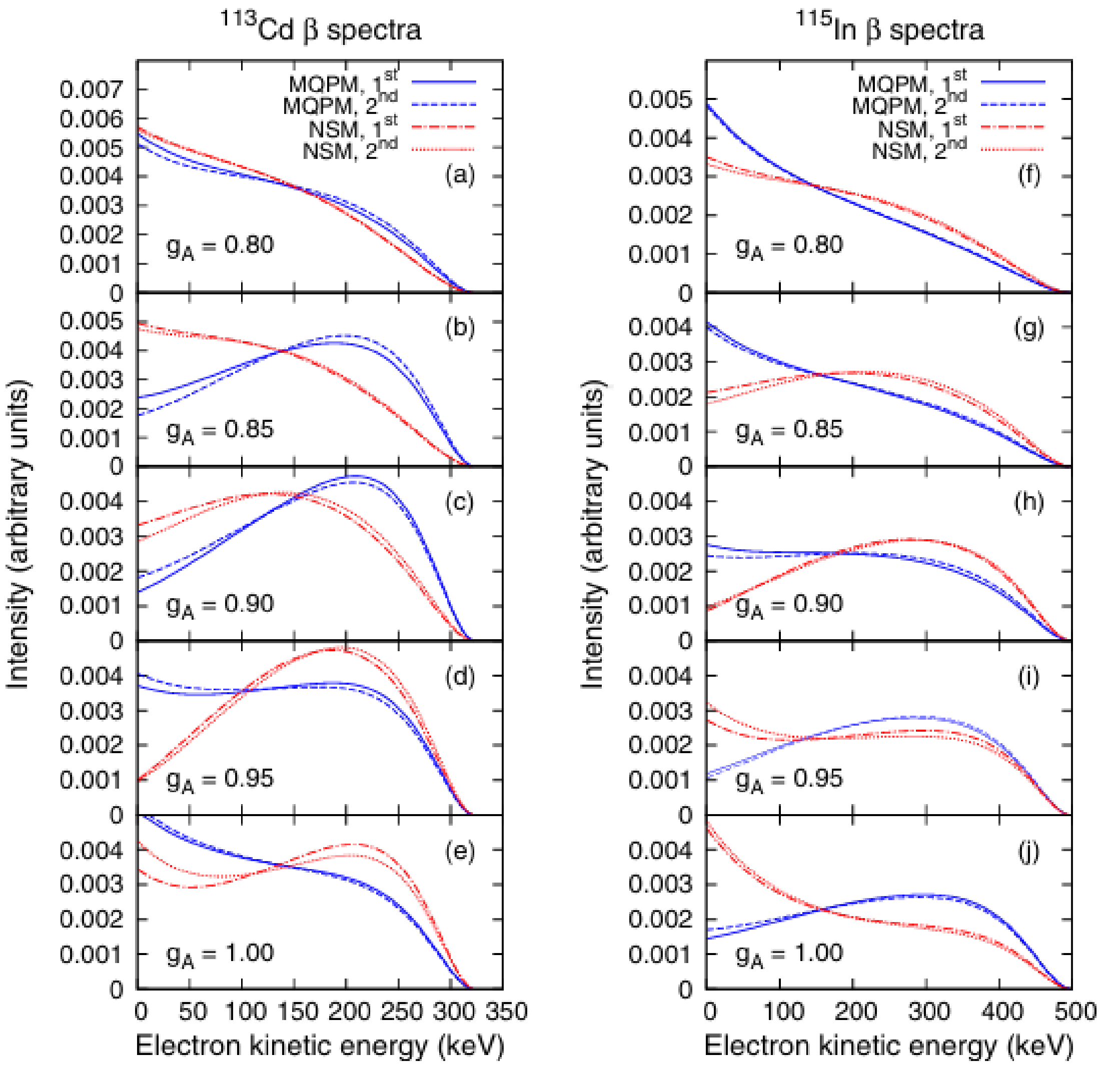

# Challenges in beta decays spectral shapes

- ✓ Recent theoretical studies have highlighted the sensitivity of beta decay parameters in **complex decays**

- ✓ A pertinent example is the study of the axial-vector coupling constant $g_A$ in nuclear decays, which **is expected to be different from that extracted from neutron decay** $\frac{g_A}{g_V} = -1.27641(45)\text{stat}(33)\text{sys}$

- ✓ **For allowed beta decays**, namely Fermi ($\Delta l = 0; \Delta s = 0$) and Gamow-Teller ($\Delta l = 0; \Delta s = 1$) $g_A$ controls the half-life of the decay, being the spectral shape unaffected. Typically, **the weak interaction operators need to be renormalized**, by quenching the $g_A$, to account for missing physics in many body calculations

- ✓ **For forbidden ($\Delta l > 0$) beta decays also the spectral shape depends on $g_A$**, especially for highly forbidden non-unique decays




M. Haaranen et al., Phys. Rev. C **93**, 034308 (2016)

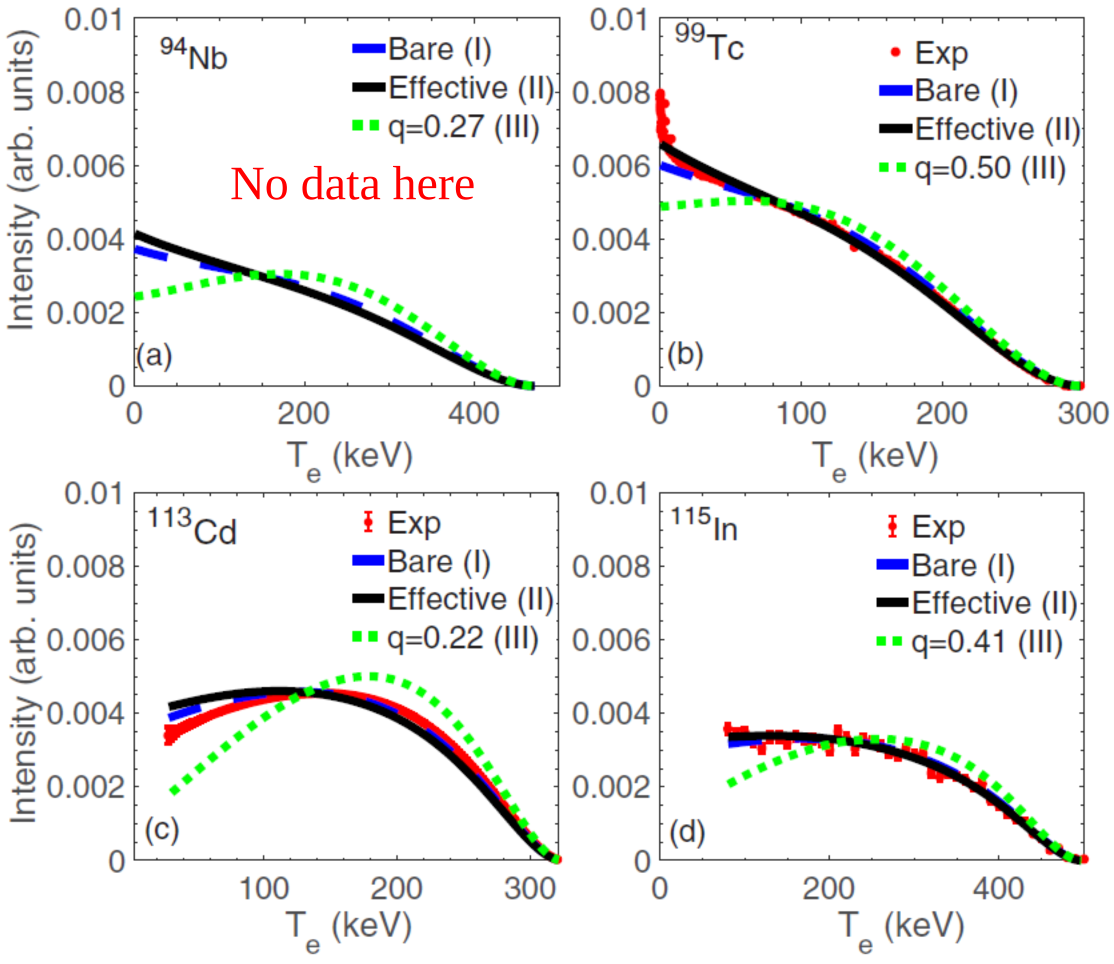
# Challenges in beta decays spectral shapes

- ✓ Recent realistic shell model calculations have emphasized **a challenging situation** for a simultaneous description of the decay half-life and spectral shape for highly forbidden non unique decays

- ✓ **Renormalizing the $g_A$** to get an accurate description of the half-life **spoils the theoretical description of the measured spectra**

- ✓ This topic is quite hot since $g_A$ enters with its 4th power in the expression of the decay rate for $0\nu\beta\beta$ decay. **A factor of 2 of "quenching" would reduce the rate of factor 16!!!**

- ✓ **Experimentally the challenge is to provide energy spectra, free from distortions** due to background, down to very low energy ($T_e < 100\ keV$), where the sensitivity to $g_A$ is the highest



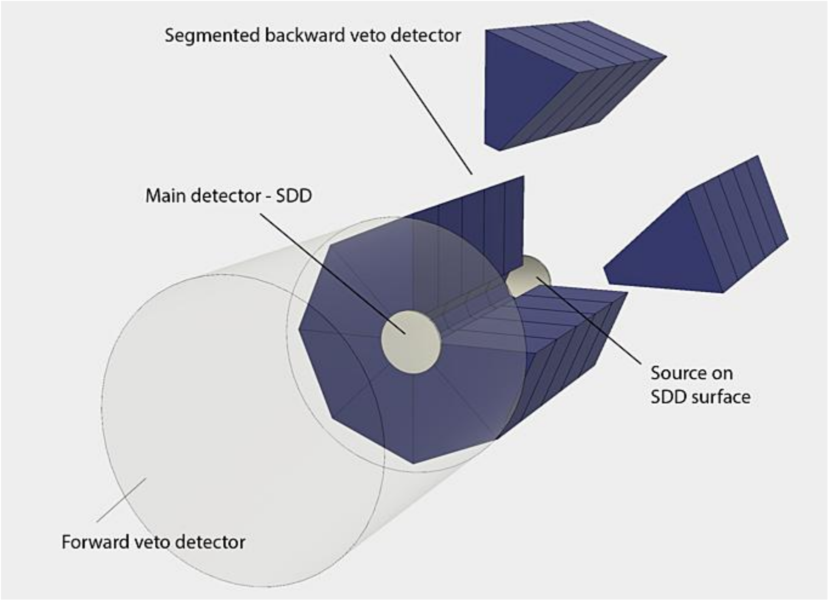

G. De Gregorio et al., PRC **110**, 014324 (2024)

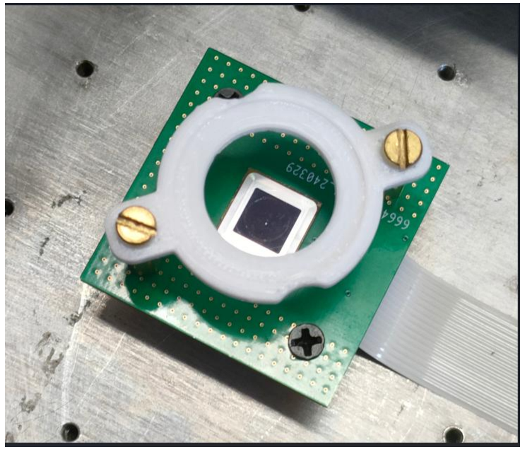
# The ASPECT-BET project

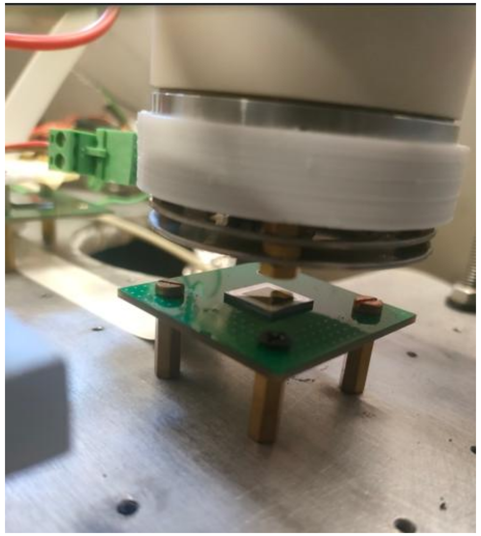
This proposal is part of the PRIN-2022 ASPECT-BET (An sdd-SPECTrometer for BETa decay studies) project [A. Nava et al., Sensors 24 (2024) 8202]

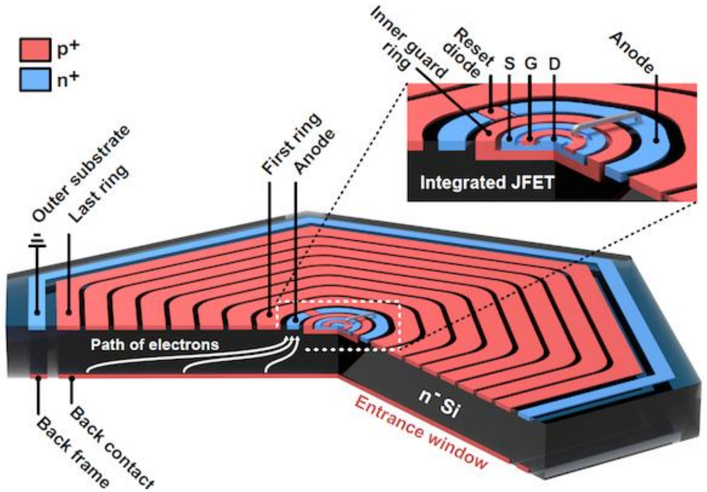
**We have developed an innovative and versatile spectrometer to enable state of the art measurements of beta energy spectra, almost background free**

The spectrometer uses Silicon Drift Detectors (SDD) technology to detect electrons in the 10 keV - 1 MeV range, a crucial energy region for beta decay studies



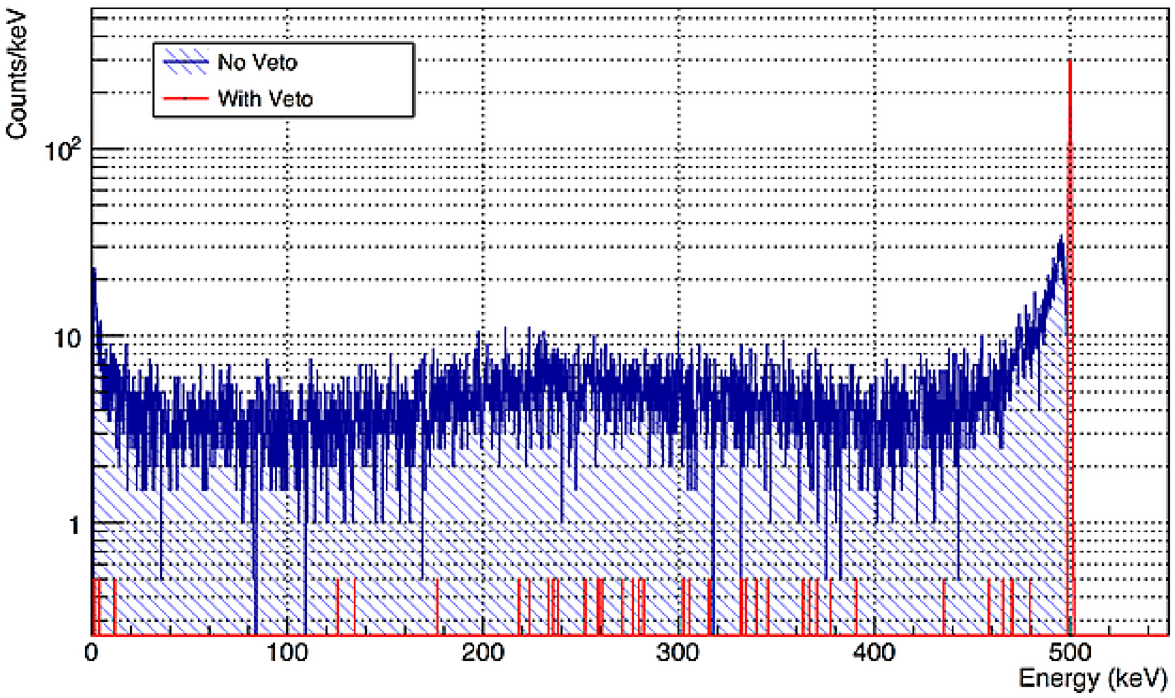


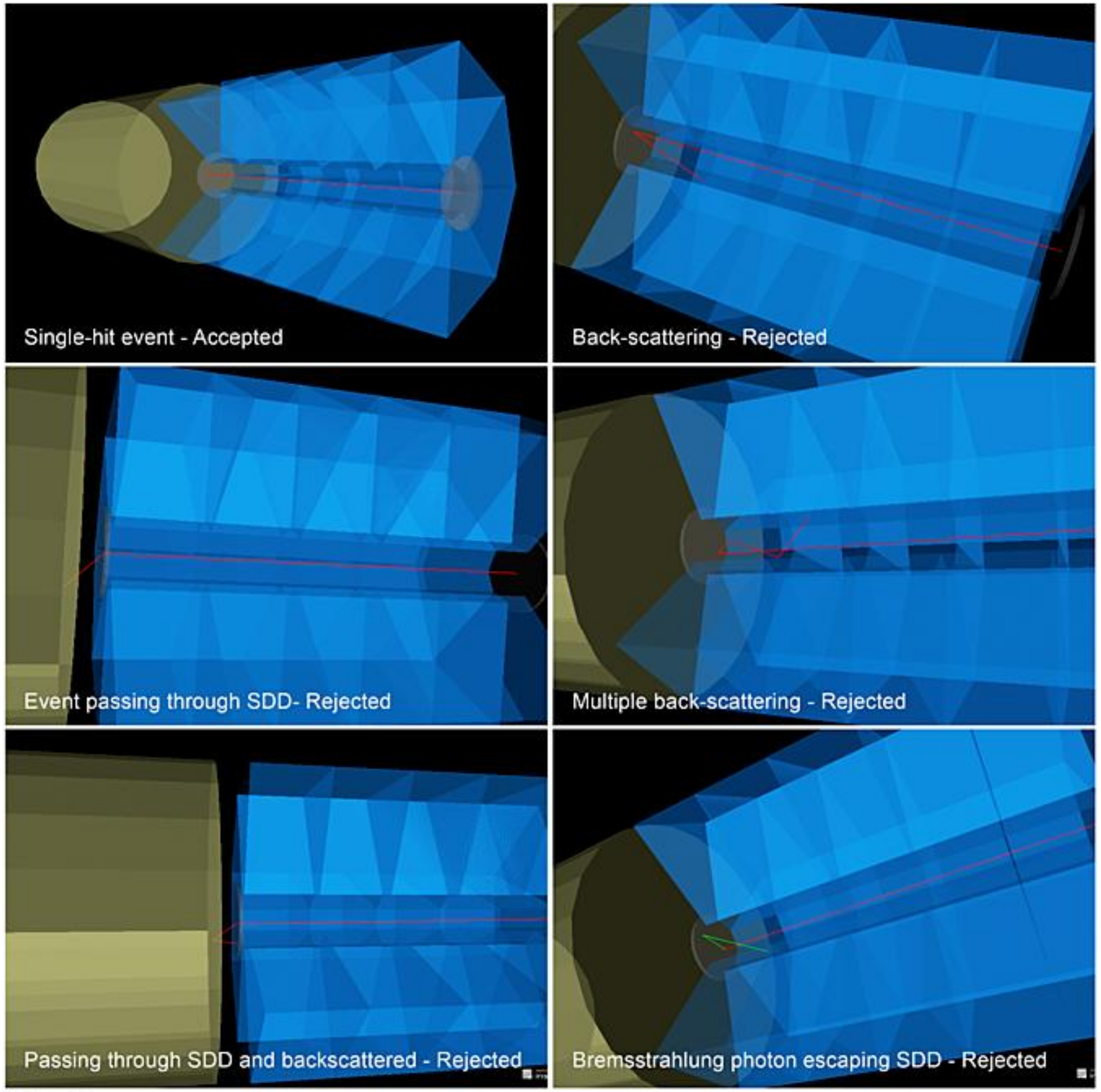


# The ASPECT-BET project

The use of forward and backward **VETO detectors allows to suppress the background**

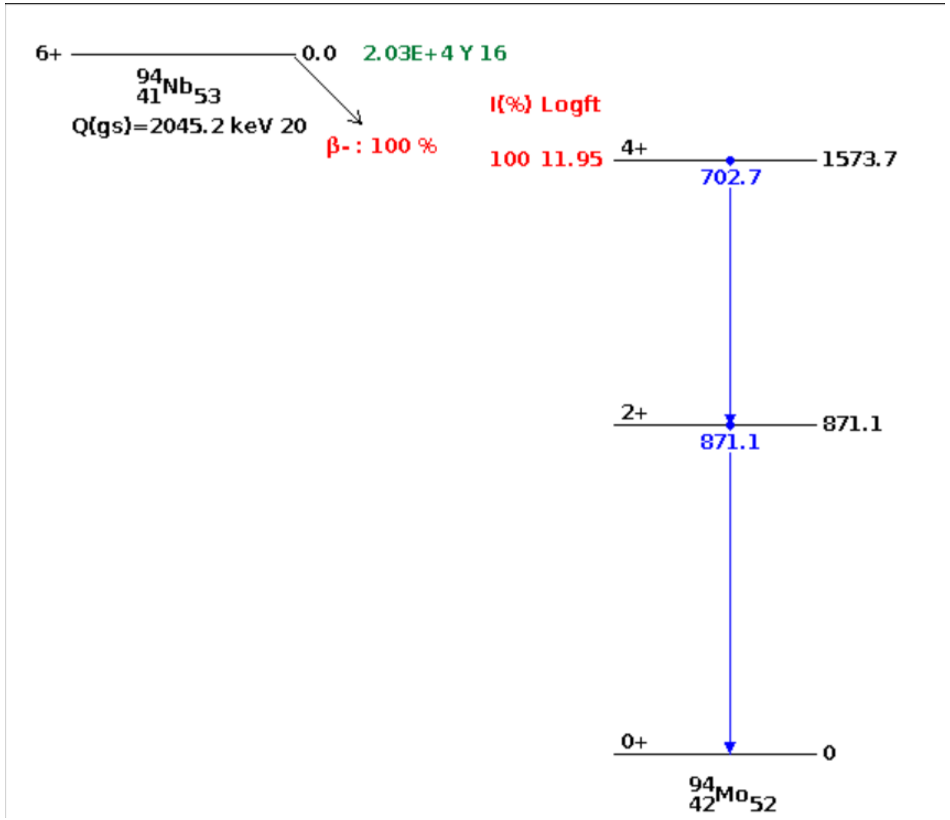
**The careful characterization of the radioactive source allows to correct for tricky distortion effects** due to self-absorption of slowly moving electrons



# $^{94}$Nb beta decay

$^{94}$Nb is unstable against ***$\beta^-$* decay to $^{94}$Mo**





The decay proceeds almost fully from the 6$^+$ ground state of $^{94}$Nb to the excited 4$^+$ state of $^{94}$Mo, thus resulting in a non unique angular momentum transfer dominated by $\Delta J = 2^+$ (second forbidden decay)

The measured half life is $T_{1/2} = 2.04 * 10^4 y$. The end-point energy is **471.5 keV**.

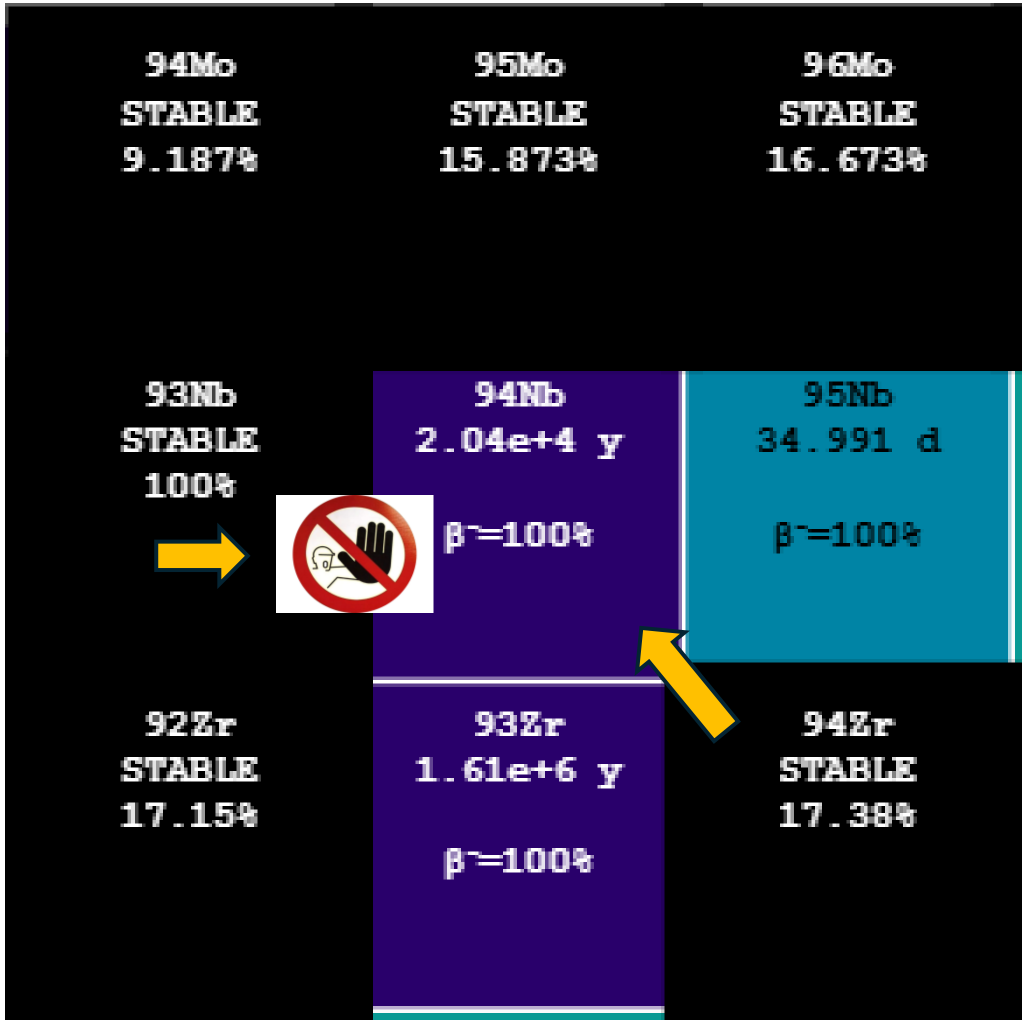
# Procurement of the $^{94}$Nb isotope

$^{94}$Nb is not easy to find in nature as it is radioactive and it is not at all commercially provided so it should be produced in laboratory

- ✓ The possibility to produce $^{94}$Nb from neutron irradiation of the natural isotope $^{39}$Nb has been halted due to the very low cross section for neutron capture reaction, with a concern about the self absorption of the resulting thick source

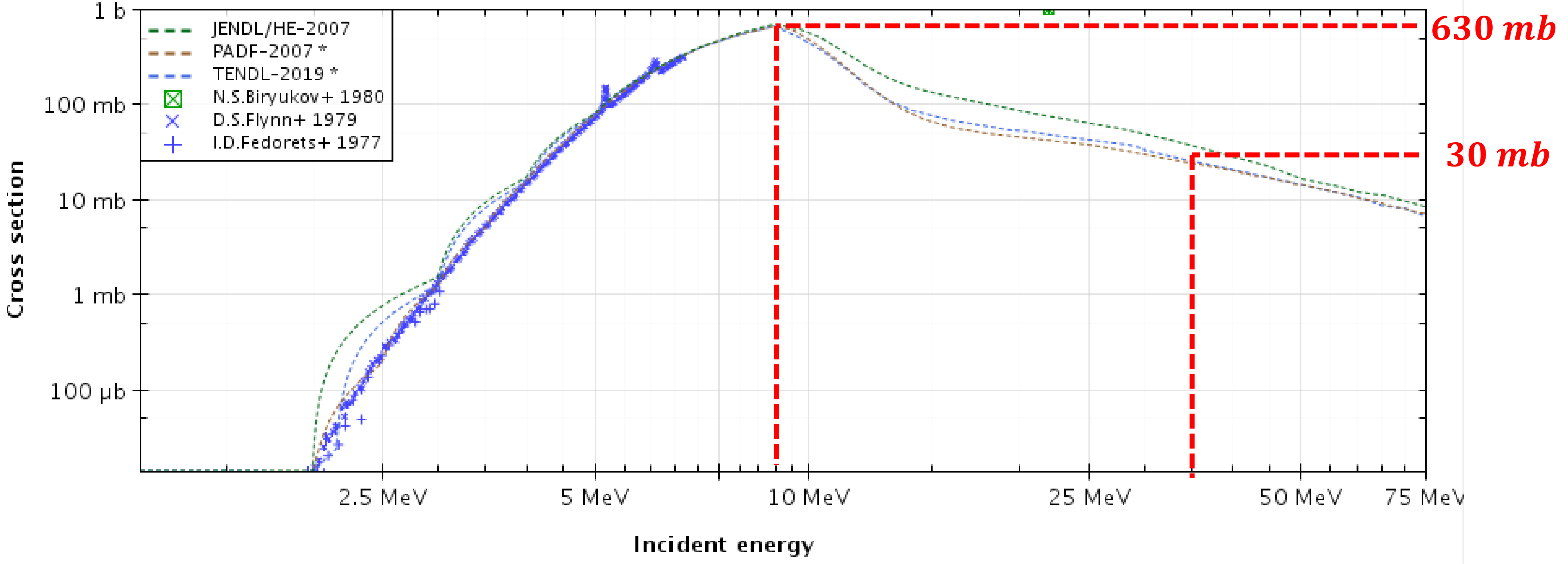
- ✓ $^{94}$Nb is not present in the REX-ISOLDE or TRIUMF databases, so it cannot be just implanted on a target backing (https://isoyields2.web.cern.ch/ https://yield.targets.triumf.ca/search/yield/data)

- ✓ A new perspective is explored from the use of (p,n) charge exchange reaction to produce $^{94}$Nb from the stable $^{94}$Zr



# The $^{94}Zr(p,n)^{94}Nb$ reaction

from https://www.oecd-nea.org/janisweb/book/protons/Zr94/MT4/renderer/9867)




Note that **the (p,n) cross section is** maximum $(\sigma(p,n)\sim 630\ mb)$ **at** $E_p \sim 8\ MeV$ reducing to $(\sigma(p,n)\sim 30\ mb)$ **at** $E_p \sim 35\ MeV$

# Experiment strategy

✓ Due to the long half-life of the $^{94}$Nb decay, $T_{1/2} = 6.4 * 10^{11}\ s$, **the number of $^{94}$Nb** to be generated by (p,n) reaction **should be at least of the order of $10^{12}$ to get source activity of the order of *Bq***

**Assuming:**

- Proton beam energy: **35 MeV**
- Beam current: **300 uA**
- Target thickness: **0.2 mg/cm$^2$** (300 nm)
- Energy loss in the $ZrO_2$ target: ~ 2 keV
- (p,n) cross section: ~ 30 mb

**One gets:**

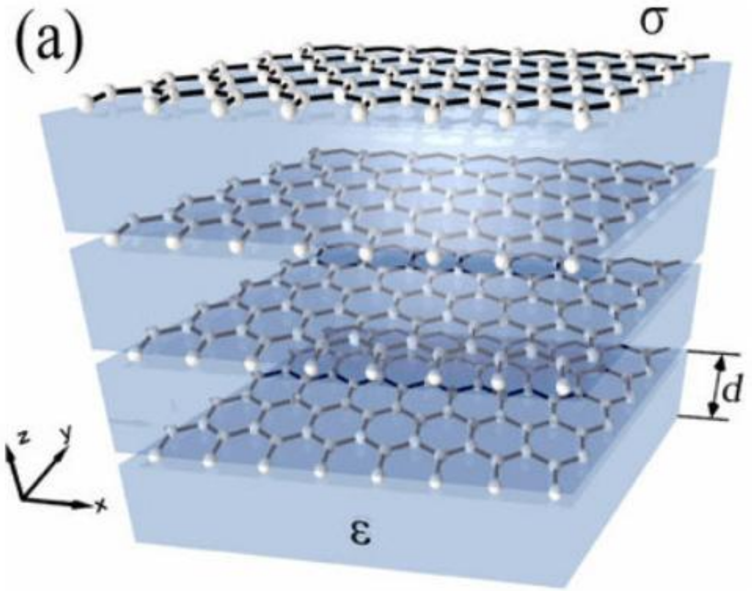
- Source activity after one day: $\boldsymbol{dN/dt \sim 6\ Bq}$
- Power dissipated in the $ZrO_2$ target: $\boldsymbol{\dot{Q} \sim 0.6\ W}$

# The heat dissipation challenge

- ✓ Although $^{94}ZrO_2$ features a high melting temperature $T_{fus} \sim 2680\ ℃$, it is a bad thermal conductor $\boldsymbol{k \sim 1.7\ \frac{W}{m*K}}$, making out target melting with $\boldsymbol{\dot{Q} \sim 0.6\ W}$ dissipated power

- ✓ An efficient heat dissipation can be guaranteed adopting the **multilayer graphene (MLG) technology**, developed by the NUMEN collaboration [F. Cappuzzello et al., Int. Jour. of Mod. Phys. A 36, 30 (2021) 2130018].

- ✓ The MLG are highly ordered thin stacks of Graphene layers used as the backing support where the $^{94}ZrO_2$ target is evaporated on. Thanks to the very high thermal conductivity of MLG ($\boldsymbol{k \sim 2200\ \frac{W}{m*K}}$), the heating of the $^{94}ZrO_2$ is maintained in the order of **300 K**, thus safely below the melting point, if a MLG foil of 2000 nm is used.



# Source purity for evaporation approach

- Since we are not using a pure $^{94}$Zr target and other processes can compete with (p,n) charge exchange reaction **we can in principle build a manyfold radioactive source whose decay pattern needs to be known with high accuracy**.

- First, we need to consider the role of **Oxigen atoms from the $^{94}ZrO_2$ oxide and the Carbon atoms from the MLG backing**. An insight on this problem shows that **Carbon and Oxygen impurities in the $^{94}$Zr target are not an issue** since the only radioactive nuclide with a long half-life (5700 y) is $^{14}$C. However, this isotope cannot be generated from C and can be hardly generated by O as it requires very suppressed processes such $^{16}$O(p, 3p)$^{14}$C or $^{17}$O(p,3pn)$^{14}$C or $^{18}$O(p,3p2n)$^{14}$C with a negligible cross section.

- **Then we need to consider** the limited purity, in terms of $^{94}$Zr, of commercial $^{94}ZrO_2$, which is about 85-90%, the main contaminants being other Zr isotopes, namely **$^{90}$Zr, $^{91}$Zr, $^{92}$Zr and $^{96}$Zr**, with about 1-2% presence each one (depending on the producer). **The main challenge comes from $^{91}$Nb**, which decays by electron capture with a half-life $T1/2=6.80*10^2\ y$, thus potentially generating a $^{91}$Nb activity comparable to the $^{94}$Nb one. **Nevertheless, the decay products from $^{91}$Nb are Auger electrons with 2.02 keV and 13.4 keV, the latter of which may be visible just above the detector threshold ($\sim 10\ keV$)**.

# Beam time request

- ✓ In conclusion, **a promising technique to produce for the first time a $^{94}$Nb radioactive source is at reach**, using the (p,n) reaction with the very intense proton beam from LNL SPES facility

- ✓ If successful, the same technique could be adopted to build other unique radioactive sources

- ✓ For the purpose of the ASPECT BET project, which is committed to measure the beta decay full spectrum with high energy resolution, low energy threshold and very low systematic uncertainties, a source activity of more than 20 $Bq$ would be ideal, which in turn means **three days irradiation time**