Isospin splitting of the GDR and photoproton reactions on isotopes of molybdenum

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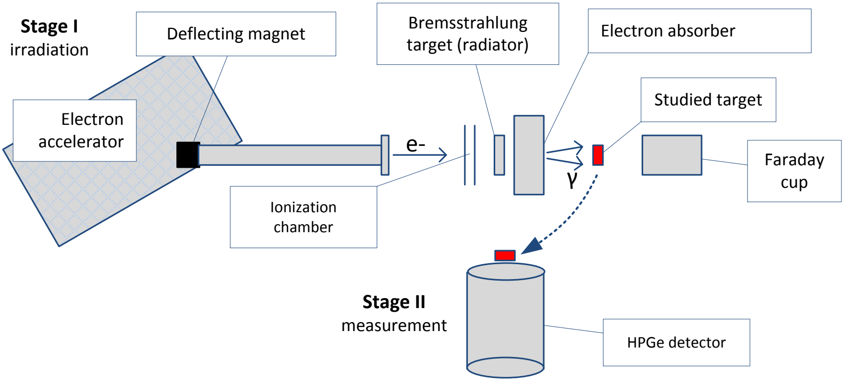
ND-2016, September 15, 2016

Motivation

- Natural molybdenum isotopes: $A = 92, 94, 95, 96, 97, 98, 100$
- ^{100}Mo is a convenient tool to test normalization methods due to multiple measurements of ^{100}Mo (γ, n) in literature
- Photoproton reactions observable using photon activation technique on consequitive isotopes to demonstrate isospin splitting as a function of A
- Production of ^{99m}Tc medical isotope used in radiography
- *p*-nucleus ^{92}Mo

Photon activation technique



- RTM-55 racetrack microtron, $E_e = 55.5$ MeV, 10 mA pulsed current, no. of orbits: 11. Average current measured by a Faraday cup and charge collected from the target. Normalized using a copper monitor target.
- Induced gamma-ray activity measured continously by a low-background HPGe detector.

Measurement results

Reaction	Конечное ядро, (спин четность)	$T_{1/2}$, тип распада конечного ядра	Порог, МэВ	Эксперимен-тальный выход (ошибка эксперимента)		
^{100}Mo(γ, n)	^{99}Mo$(1/2^{+})$	67 ч (β^{-})	8.29	100(6)		
^{100}Mo(γ, pn)	^{98m}Nb(5^{+})	51 мин (β^{-})	18.10	0.31(0.03)		
^{98}Mo(γ, p)	^{97}Nb$(9/2^{+})$	72 мин (β^{-})	9.79	6.6(0.1)		
^{97}Mo(γ, p) ^{98}Mo(γ, pn)	^{96}Nb(6^{+})	2.4 ч (β^{-})	9.23 17.87	11(1)		1
^{96}Mo(γ, p) ^{97}Mo(γ, pn)	^{95}Nb$(9/2^{+})$	35 сут (β^{-})	9.3 16.72	5.1(0.4)	10.6(0.5)	1
^{96}Mo(γ, p) ^{97}Mo(γ, pn)	^{95m}Nb$(1/2^{-})$	3.6 сут (IT $+ \beta^{-}$)	9.53 16.95	5.5(0.3)		
^{94}Mo(γ, pn) ^{94}Mo(γ, pn)	^{92}Nb(7^{+}) ^{92}Nb(7^{+})	$3.5 \cdot 10^{7}$ лет (ϵ) 10.2 сут (ϵ)	17.32 17.45	2.60(0.02)		
^{92}Mo(γ, n)	^{91}Mo$(9/2^{+})$	15.5 мин (ϵ)	12.68	34(5)		
^{92}Mo$(\gamma, 2n)$	^{90}Mo(0^{+})	5.6 ч (ϵ)	22.78	5.1(0.4)		
^{92}Mo(γ, pn)	^{90}Nb(8^{+})	14.6 ч (ϵ)	19.51	14(5)		
^{92}Mo$(\gamma, p2n)$	^{89}Nb$(9/2^{+})$	2.0 ч.	[illegible]	[illegible]		

Cross section per equivalent quantum

1. Photonuclear reactions in bremsstrahlung beams are ubiquitous:
   - general-purpose nuclear research
   - medical isotope production
   - accelerator safety applications
   - cargo inspection systems
   - accelerator driven reactors
   - nuclear waste transmutation
   - *etc.*
2. However, existing measurements are hard to compare. Results are reported in different forms: yields (number of reactions per 1 e^-), normalized yields, flux-integrated cross sections, σ_{-1}.
3. Furthermore, different radiators can be used so the same E_m may correspond to different bremsstrahlung beams. A consistent normalization method is needed to make results directly comparable.
4. A (once) widely used normalization scheme is the cross section per equivalent quantum σ_q.

Cross section per equivalent quantum

Standard definition

By definition

$$\sigma_q = \frac{1}{N_q} \int\limits_0^{E_m} \sigma(E_\gamma) N(E_\gamma, E_m) dE_\gamma, \qquad (1)$$

where $\sigma(E_\gamma)$ is the reaction cross section, E_m is the electron beam energy, $N(E_\gamma, E_m)$ is the bremsstrahlung spectrum, i.e. mean number of photons with the energy $E_\gamma \in [E_\gamma, E_\gamma + dE_\gamma)$ per 1 e^-,

$$N_q = \frac{1}{E_m} \int\limits_0^{E_m} E_\gamma N(E_\gamma, E_m) dE_\gamma$$

is the number of equivalent photons, i.e. number of photons emitted per 1 e^- if the spectrum was monochromatic with $E_\gamma = E_m$.
N_q is insensitive to the low-energy part of the bremsstrahlung spectrum that depends on the radiator choice. Thus, σ_q is independent on the radiator.
Above definition can be used to calculate σ_q for the thin target case ($h \ll L_e$). If not, the yield definition in (**??**) is incorrect.

Cross section per equivalent quantum

Proposed estimation using E_{eff}

For the thick target case the experimental yield can be represented as

$$Y_{\text{exp}} = n \int_0^{E_m} L(E_\gamma, E_m)\sigma(E_\gamma)dE_\gamma,$$

where $L(E_\gamma, E_m)$ is the total length travelled by photons with the energy E_γ in the irradiated target, n is the concentration. In the σ_q definition

$$\sigma_q(E_m) = \frac{1}{N_q(E_m)} \int_0^{E_m} N(E_\gamma, E_m)\sigma(E_\gamma)dE_\gamma, \quad N_q(E_m) = \frac{1}{E_m} \int_0^{E_m} E_\gamma N(E_\gamma, E_m)dE_\gamma$$

it is assumed that the bremsstrahlung spectrum is calculated using the Seltzer-Berger cross sections: $N(E_\gamma, E_m) = n_s\sigma_{\text{SB}}(E_\gamma, E_m)$.

Find such E_{eff} that $L(E_\gamma, E_m) \sim N(E_\gamma, E_{\text{eff}})$ in the energy range where the reaction cross section is large, or

$$L(E_\gamma, E_m)\sigma(E_\gamma) \sim N(E_\gamma, E_{\text{eff}})\sigma(E_\gamma).$$

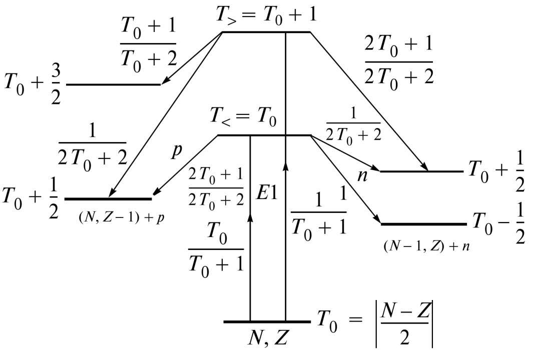
This is done by minimizing the norm $||L(E_\gamma, E_m)\sigma(E_\gamma) - aN(E_\gamma, E_{\text{eff}})\sigma(E_\gamma)||$ with respect to a, E_{eff}. Then the experimental σ_q is estimated as

$$\sigma_{q_{\text{exp}}}(E_{\text{eff}}) = \frac{1}{N_q(E_{\text{eff}})} \frac{Y_{\text{exp}}}{na}$$

Comparison ^{100}Mo

Comparison ^{97}Nb

Isospin splitting



Isospin conservation leads to inhibited neutron yield from the $T_> = T_0 + 1$ branch. Probabilities given by coupling of states with different T via Clebsch-Gordan coefficients.

Isospin splitting in statistical model calculations

[B. S. Ishkhanov and V. N. Orlin, Phys. At. Nucl. **74**, 19 (2011)] General expression for the rate of decay ($|E, T\rangle_i \to |E', T'\rangle_f$) via nucleon emission with the energy ε:

$$\lambda_k(\varepsilon, E, T \to T') = \frac{2s+1}{\pi^2\hbar^3}\mu\varepsilon\sigma_k(\varepsilon)\frac{\omega_f(E', T')}{\omega_i(E)}p(T' \to T),$$

where $T = \{T_0, T_0+1\}$, $T' = \{T_0', T_0'+1\}$, μ is the reduced mass of the nucleon, $\sigma_k(\varepsilon)$ is the inverse reaction cross section, $\omega_i(E) = \omega_i(E, T_0) + \omega_i(E, T_0+1)$ is the total level density of the initial nucleus for particle or exciton states, $\omega_f(E', T')$ is the level density of the final nucleus with the isospin T' at the excitation energy $E' = E - B_k - \varepsilon$ (B_k is nucleon separation energy for nucleon type k), and p is the factor describing the fraction of the $|E, T\rangle_i$ states populated in $T' \to T$ transitions.

Isospin splitting

Taking into account the isospin effects in statistical model calculations

p can be calculated as follows:

$$p(T' \to T) = \frac{\omega_f(E', T')\langle T', T_{0Z} - t_{zk}, \frac{1}{2}, t_{zk}|T, T_{0Z}\rangle^2}{C},$$

where

$$C = \omega_f(E', T'_0)\langle T'_0, T_{0Z} - t_{zk}, \frac{1}{2}, t_{zk}|T, T_{0Z}\rangle^2 + \omega_f(E', T'_0 + 1)\langle T'_0 + 1, T_{0Z} - t_{zk}, \frac{1}{2}, t_{zk}|T, T_{0Z}\rangle^2$$

and T_{0Z} is the isospin projection of the initial nucleus and t_{zk} is the isospin projection of the outgoing nucleon. The level densities of heavy nuclei can be approximated with the expressions $\omega_f(E', T'_0) \approx \omega_f(E')$ and $\omega_f(E', T'_0 + 1) \approx \omega_f(E' - \Delta'_1)$, where Δ'_1 is the energy of the first excited state with the isospin $T'_0 + 1$ in the final nucleus.

Isospin splitting

Taking into account the isospin effects in statistical model calculations

Algorithm to include isospin splitting corrections in a Hauser-Feshbach + preequilibrium calculation

1. (Optional) Use microscopically calculated photoabsorption cross section σ_{abs} from CMPNR
2. Split $\sigma_{\text{abs}}(E)$ into $T_<$ and $T_>$ components using the $p(T \rightarrow T'$ coefficient
3. For the $T_<$ branch calculate the partial reaction cross sections as usual
4. Unless a proton was already emitted for the $T_>$ branch shift level densities in final nuclei by Δ_1'.
5. Total partial photonucleon reaction cross sections are given by a sum of corresponding $T_<$ and $T_>$ cross sections.

Comparison ^{95}Nb

Comparison ^{96}Nb

Conclusions