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

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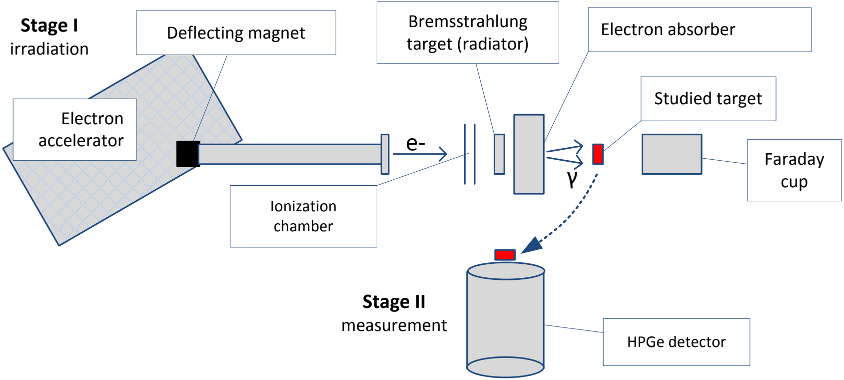
Introduction

- Molybdenum isotopes: 92, 94, 95, 96, 97, 98, 100
- Isospin splitting as a function of A
- Production of ^{99m}Tc medical isotope used in radiography
- ^{92}Mo is a p-nucleus
- Study different normalization techniques with multiple measurements results of ^{100}Mo (γ, n)

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.

Measurement results

Reaction	Конечное ядро, (спин четность)	$T_{1/2}$, тип распада конечного ядра	Порог, МэВ	Экспериментальный 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.	20.50	1.0(0.2)		

Cross sections per equivalent photon

- Photonuclear reactions induced by bremsstrahlung beams are widely used as a general tool for nuclear research,
- medical isotope production
- inspection systems
- ADS reactors (accelerator driven systems)

Typically reported quantity is the reaction yield, i.e. number of produced reactions in target, and its variations. A method of presentation of results that is independent of the specific experiment is needed.

Cross section per equivalent photon

1) Bremsstrahlung experiments report results in different forms: yields (number of reactions per 1 e^-), flux-integrated cross sections, σ_{-1}. At the same E_e may use different radiators so the yields need to be normalized to be directly comparable.
2) One widely used normalization is the cross section per equivalent quantum (photon)

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

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

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

—is the number of equivalent photons, i.e. the number of photons that could be emitted per 1 e^- if the spectrum was monochromatic with $E_\gamma = E_e$. N_q is not sensitive on low-energy part of the bremsstrahlung spectrum. Thus, σ_q is independent on the radiator.

Cross section per equivalent photon with E_{eff}

1)

$$Y_{\text{exp}} = n \int_0^{E_m} L(E, E_m)\sigma(E)dE$$

2)

$$\sigma_q(E_m) = \frac{1}{N_q(E_m)} \int_0^{E_m} N(E, E_m)\sigma(E)dE$$

$$N_q(E_m) = \frac{1}{E_m} \int_0^{E_m} EN(E, E_m)dE$$

$$N(E, E_m) = n_s \sigma_{SB}(E, E_m)$$

3)

$$L(E, E_m) \sim N(E, E_e ff)$$

in the required energy range, or

$$L(E, E_m)\sigma(E) \sim N(E, E_e ff)\sigma(E)$$

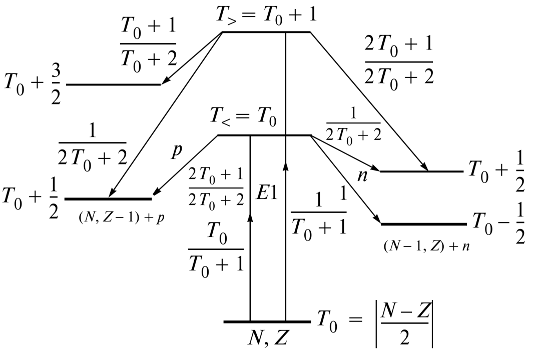
4) then find C, E_{eff} such as to minimize $L(E, E_e ff)\sigma(E) - CN_{\text{SB}}(E, E_e ff) \to 0$ 5)

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

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 $p(T \to T'$ 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