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A Remark on Pion Capture in Heavy Nuclei

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Abstract. The yield of neutrons from the (π^-, xn) reactions on ^{165}Ho is calculated with a two nucleon absorption mechanism followed by (nucleon, xn) reactions using experimental input only. The comparison with the experimental yield curve supports this simple two-step model for heavy nuclei.

1. Introduction

Recent experiments on γ rays following π^- capture in heavy nuclei [1, 2] indicate that emission of neutrons dominates and that high spin states are excited in the residual nucleus. These observations do not seem to depend on the deformation of the target nucleus [2]. The standard picture of pion absorption is a two step process [3]. First, the pion is absorbed on two nucleons (single nucleon absorption is suppressed by the high momentum transfer imposed on the one nucleon wave function) then the absorbing nucleons interact with the remaining ones. For heavy nuclei this interaction proceeds mainly through the formation of highly excited compound states [4] which subsequently decay, mostly by the emission of neutrons.

In this note we want to show that the experimental observations are completely consistent with the two step model. In particular the model implies that the yield curve $Y(x)$ for the (π^-, xn) reaction on heavy nuclei is closely connected to the shape of the energy spectrum of fast nucleon pairs emitted in pion absorption on light nuclei. The experimental situation regarding this second spectrum is controversial. Our results for the pion induced yield agree with the nucleon spectra from Ref. [5, 6] and disagree with Ref. [7].

2. The Model

To calculate the yield $Y(x)$ for the reaction (π^-, xn) on ^{165}Ho we have to specify the two steps of the model. The energy spectrum of the two nucleons originating from the elementary capture process $\pi^-(NN) \to NN$ on two bound nucleons will be taken directly from experiments on light nuclei. The experimental energy spectrum of two correlated nucleons escaping a light nucleus should fairly accurately reflect the effects of Fermi motion. The collective interactions of the second step leading to nucleon evaporation are not important in light nuclei and can essentially be cut out of the spectrum by requiring a corresponding minimal energy ($E_{\min} \gtrsim 10$ MeV) for the two observed nucleons. Moreover, only the shape of the spectrum is needed and not the absolute value, to calculate the yield curve in holmium.

Neglecting Fermi motion the two nucleon absorption mechanism of the pion predicts two nucleons emerging typically back to back and with energies $E \approx m_\pi/2 - E_{\text{binding}} \approx 60$ MeV. The 180° angular correlation of the two nucleons is indeed seen in all experiments [5–7]. The experimental energy spectrum $f(E)$ of correlated pairs shows a Fermi broadened peaking around 60 MeV in Ref. [5, 6] whereas Ref. [7] gives a monotonically falling energy distribution.

The second step involves the interaction of the energetic nucleon pair with the recoiling (excited) nuclear core. We shall approximate this process by free nucleon–nucleus cross sections [8]. Experiment shows that up to about 90 MeV incident kinetic energy (particle, xn) reactions dominate [8–13]. The following properties of the excitation functions in heavy nuclei are important in our context:

(a) The shape of excitation functions depends to a good approximation only on the type and number of emitted particles (neutrons, neutrons and protons, neutrons and α particles, etc.). Shape and relative normalization are practically universal with known scaling factors [13]. Illustrative examples for our energy range are given in fig. 1 of Ref. [9] and in fig. 4 of Ref. [11].

(b) Only the kinetic energy injected into the nucleus matters. In particular the type of the exciting particle n, p, d, ^{3}He, α is irrelevant [8–11]. (This holds for $20 < E < 90$ MeV if allowance is made for small binding corrections in the energy scale.) The presence or absence of target deformation is also unimportant [10–12].

(c) For fixed incident energy, the (particle, xn) reactions select a well defined number of neutrons x in the final state.[1]) For protons of $E = 50$ MeV, e.g., the $5n$ channel dominates [8]. Neighbouring channels are down by at least a factor seven.

(d) Coulomb effects suppress charged particle emission by an order of magnitude [9] or more for $E < 90$ MeV. At $E = 90$ MeV α particle emission is about 15%, proton emission about 10%.

It is clear from the preceding observations that the peak multiplicity in π^- absorption determines directly the most probable energy in the spectrum of the intermediate two nucleons (dominantly two neutrons). The selectivity of (p, xn) reactions is illustrated in Figure 1.

As the free particle–nucleus cross sections are successfully described by a stochastic sequence of incoherent nucleon–nucleon interactions (see Ref. [4, 9–13]) we shall assume that the two intermediate nucleons trigger two independent particle-nucleus cascades. Our model for the neutron yield in pion absorption from a heavy nucleus is therefore

$$Y(x) \propto \int_0^{m_\pi} dE\, f(E)\, \sigma_E(N, xn). \tag{1}$$

The energy spectrum $f(E)$ of the intermediate nucleons is taken from experiment [5–7] as has been discussed earlier. For the excitation function σ_E we take the experimental values for protons incident on ^{181}Ta from [8] and also interpolated values for ^{163}Dy (p, xn), using the tables of Ref. [13], with no significant change in the resulting pion induced yield.

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[1]) We thank H. K. Walter for having drawn our attention to this point.

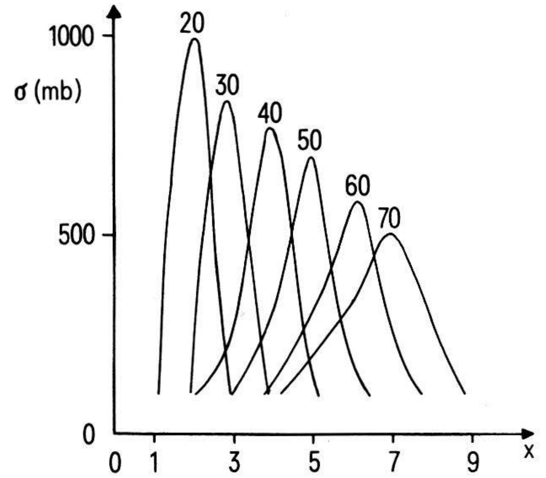

Figure 1
Cross sections for ^{163}Dy(p, xn) interpolated from the tables in *Landolt–Börnstein* [13] and connected with eye-guiding lines. The parameter on the curves is the incident proton energy in MeV. A similar figure obtains from the experimental values [8] for ^{181}Ta(p, xn).

3. Discussion

In Figure 2 we compare the calculated neutron yield of pion capture in ^{165}Ho with experiment [1]. The calculated curves are normalized to equal height and correspond to three different energy spectra of the intermediate nucleons as described in the figure caption. It is clear that the spectrum of Ref. [5] agrees with the observed width $\Delta x \approx 6$ of the pion induced yield (see curve *a*). The peak multiplicity in ^{165}Ho is about $x = 6$ with a similar (slightly higher) value [14] for ^{175}Lu. As the width of a nucleon induced interaction at fixed incident energy is about $\Delta x \approx 1.5$ [8] (see Fig. 1),

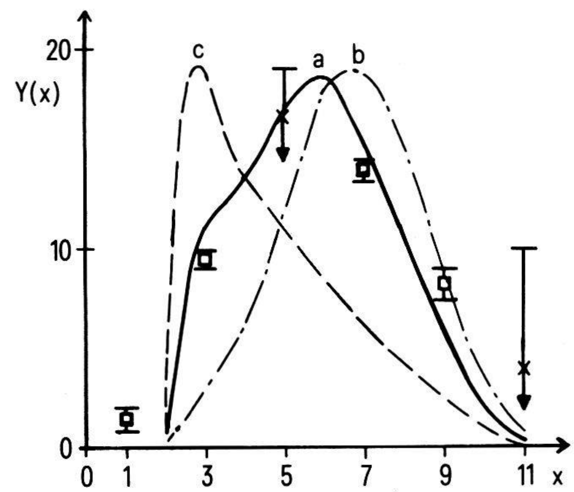

Figure 2
The neutron yield $Y(x)$ for the reaction (π^-, xn) on ^{165}Ho (in % per capture). The experimental points are from P. Ebersold et al. [1]. There are special background problems with the two points showing error bar arrows. The crosses indicate the most probable value [1]. The curves are obtained from equation (1). The calculated points are connected with eye-guiding lines and normalized to equal height. They differ in the experimental input for the intermediate nucleon energy spectrum and correspond to the values given in Nordberg et al. [5] (curve *a*), to fig. 7 of Calligaris et al. [6] (curve *b*) and to Lee et al. [7] (curve *c*).

the yield curve c based on the spectrum of Ref. [7] is incompatible with pionic neutron yields in our model.

The observed peaking value of $x = 6$ excludes, in a two step model, any significant contribution from intermediate nucleons (or heavier intermediate clusters) with energies different from 60 ± 25 MeV. Moreover, an intermediate nucleon of energy around 120 MeV, as it would arise from pion absorption on a single nucleon, would lead to considerable emission [9] of α particles and protons. In our model only a small fraction of charged particles is expected in pion absorption at rest. Due to the universality of the (particle, xn) reactions mentioned in Section 2, we expect that the shape of the yield should be similar to curves a or b of Figure 1 for all heavy nuclei.

One further piece of information on pion capture in holmium is the strong interaction width of the $4f$ level [15]. This width is convertible into an f-wave scattering length for pion holmium scattering by standard methods [16]. A theoretical estimate of this quantity is difficult as the absolute rate is sensitive to the nuclear matrix element and to the f-wave projection. We obtained an order of magnitude agreement in a microscopic two step model.

There is no reliable information yet on the emission of fast neutrons from holmium. The observation [1] of γ transitions from 12^+ to 10^+ levels in ^{156,158,160}Dy (and similar levels [14] in the Yb isotopes) implies, however, a minimal number of fast neutrons by a simple argument of angular momentum conservation. In the initial state we have $l = 3$ from the pion orbital angular momentum and a target spin of $\frac{7}{2}$. To reach a final state of angular momentum 12^+ a neutron must be emitted which has angular momentum $l \approx 6$. The classical estimate $k \cdot R = l$ then demands $E_n \approx 20 \pm 5$ MeV (with $R \approx 6\,fm$). Adding up the intensities of the 12^+ to 10^+ transitions given in Ref. [1] we obtain about $10 \pm 5\%$ (normalized to the 4^+ to 2^+ transitions). This number is the estimated number of neutrons per π^- capture with energies $E \gtrsim 20$ MeV in the single neutron energy spectrum. (Assuming a ratio of 4:1 for the correlated emission of fast nn to np pairs in the first step of our model the emission of energetic protons should be about eight times less frequent.) Similar numbers of fast neutrons were observed in Ref. [17] on heavy nuclei.

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REFERENCES

[1] P. Ebersold, B. Aas, W. Dey, R. Eichler, H. J. Leisi, W. W. Sapp and H. K. Walter, Phys. Lett. *58B*, 428 (1975).
[2] V. S. Butsev, D. Chultem, J. Ganzorig, Yu. K. Gavrilov and S. M. Polikanov, Dubna preprint JINR, E6-8535, 1975.
[3] K. A. Bruckner, R. Serber and K. M. Watson, Phys. Rev. *84*, 258 (1951).
[4] N. Metropolis, R. Bivins, M. Storm, A. Turkevich, J. M. Miller and G. Friedlander, Phys. Rev. *110*, 185 (1958).
[5] M. E. Nordberg, K. F. Kinsey and R. L. Burman, Phys. Rev. *165*, 1096 (1968).
[6] F. Calligaris, C. Cernigoi, I. Gabrielli and F. Pellegrini, Nucl. Phys. *A126*, 209 (1969).
[7] D. M. Lee, R. C. Minehart, S. E. Sobottka and K. O. H. Ziock, Nucl. Phys. *A182*, 20 (1972).
[8] C. L. Rao and L. Yaffe, Can. Journ. Chem. *41*, 2516 (1963).
[9] J. Bisplinghoff, J. Ernst and T. Mayer-Kuckuk, P. Jahn and C. Mayer-Böricke, Nucl. Phys. *A228*, 180 (1974).
[10] F. Hermes, E. W. Jasper, H. E. Kurz and T. Mayer-Kuckuk, P. F. A. Goudsmit and H. Arnold, Nucl. Phys. *A228*, 175 (1974).
[11] F. Hermes, E. W. Jasper, H. E. Kurz and T. Mayer-Kuckuk, Nucl. Phys. *A228*, 165 (1974).

[12] A. DJALOEIS, P. JAHN, H.-J. PROBST and C. MAYER-BÖRICKE, KFA Jülich, Annual Report 1974, p. 44.
[13] *Landolt–Börnstein*, New Series I, Vol. 5c, Edited by H. Schopper (Springer 1974).
[14] P. EBERSOLD, thesis ETHZ (1975), unpubl.
[15] P. EBERSOLD, B. AAS, W. DEY, R. EICHLER, J. HARTMANN, H. J. LEISI and W. W. SAPP, Phys. Lett. *53B*, 48 (1974).
[16] T. L. TRUEMAN, Nucl. Phys. *26*, 57 (1961); A. PARTENSKY and M. ERICSON, Nucl. Phys. *B1*, 382 (1967).
[17] H. L. ANDERSON, E. P. HINCKS, C. S. JOHNSON, C. REY and A. M. SEGAR, Phys. Rev. *133*, B392 (1964).