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Photoneutron emission from Li, Be, V, Mn, Co, Ni, Pb and Bi

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SEZIONE II

(Fisica, chimica, geologia, paleontologia e mineralogia)

Fisica. — *Photoneutron emission from* Li, Be, V, Mn, Co, Ni, Pb *and* Bi. Nota (*) di RAFFAELLO GARFAGNINI (**), GUIDO PIRAGINO (**) e ALBA ZANINI (**), presentata dal Socio G. WATAGHIN.

RIASSUNTO. — Vengono confrontati i dati, ottenuti misurando lo spettro energetico dei fotoneutroni per $0.8 < E_n < 12$ MeV prodotti dal ^{7}Li, ^{9}Be, ^{51}V, ^{55}Mn, ^{59}Co, Ni, Pb e ^{209}Bi, a 135° da un fascio di raggi γ di bremsstrahlung di $E_{\gamma\,\mathrm{max}} = 85$ MeV, con i dati ottenuti da altri autori [1] per $E_n > 10$ MeV con fasci di raggi γ di bremsstrahlung di 55 ed 85 MeV. Dall'analisi dei risultati si nota che la formazione di un nucleo composto per assorbimento di [raggi] γ con successiva evaporazione di un neutrone è molto improbabile. Qualitativamente il modello a nucleo « precomposto » di Griffin (23, 25) meglio si adatta ai risultati sperimentali per i fotoneutroni emessi nella regione della risonanza gigante. Ad energie di raggi γ superiori alla risonanza gigante (quando la lunghezza d'onda ridotta dei fotoni è circa uguale ai raggi nucleari) il modello a quasi-deutone per la fotodisintegrazione dei nuclei, come recentemente calcolato da Gabriel ed Alsmiller (26), sembra spiegare l'emissione dei fotoneutroni veloci ($E_n > 8$ MeV) dai nuclei.

Recently the energy spectra of fast photoneutrons at 67.5° from different elements were measured by Kaushal *et al.* [1] at bremsstrahlung energies 55 and 85 MeV. The neutron difference spectra effectively due to photons between 55 and 85 MeV were obtained for neutron energies greater than 10 MeV. These experimental data were compared to the predictions of the quasi-deuteron model as recently modified by Levinger [2] and the authors found good agreement as regards absolute cross sections for fast neutron emission as well as a dependence of the cross-sections and neutron energy shape.

We have measured the energy distribution at 135° of the photoneutrons, produced by a bremsstrahlung γ-ray beam of 85 MeV for neutron energy E_n higher than 0.8 MeV, for ^{7}Li [3], ^{9}Be [4], ^{51}V, ^{55}Mn, ^{59}Co, Ni [5] Pb and ^{209}Bi [6]. In the case of ^{7}Li and ^{9}Be the measurements were performed also at 90° [7]. The targets were irradiated with the γ-ray beam of the Turin synchrotron and the photoneutrons were detected with a diffusion cloud chamber filled with helium. The details of the method have been previously described [8]. In this paper we compare our results for neutron energy E_n between 0.8 and 12 MeV with those of Kaushal *et al.* [1] to search at which energy the quasi-deuteron model predictions begin to agree with the experi-

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mental data. The energy spectra were normalized to the same dose incident on the targets and to the same solid angle of acceptance of the neutron detector. So the total number of photoneutrons of each spectrum is proportional to the proper (γ, n) yield. The number of photoneutrons with $E_n > 12$ MeV results negligible in our measurements for statistical reasons. We have divided the spectra in four energy regions: the first $0.8 < E_n < 2$ MeV and the second $2 < E_n < 4$ MeV, because the maximum of the spectra for all the elements falls in the interval $(1.5 \div 2.5)$ MeV and the photoneutrons in these energy regions are strongly connected with the gigant resonance (g.r.); the third $4 < E_n < 8$ MeV, where usually in the literature [9] one supposes the "direct" reaction becomes dominant, and the fourth $8 < E_n < 12$ MeV where all the photoneutrons should be only "direct". In fig. 1 we report the percentage of the photoneutrons in the respective energy intervals as a function of Z. In the case of ^{7}Li and ^{9}Be are also reported the data of spectrum measurements [7] at 90°, but the behaviour of the energy distribution is practically the same. As we can see the low energy photoneutron emission for the heavy-weight nuclei is relatively higher but for the light elements the emission of fast photoneutrons is relatively richer. More interesting conclusions can be deduced from fig. 2. In this figure are reported the number

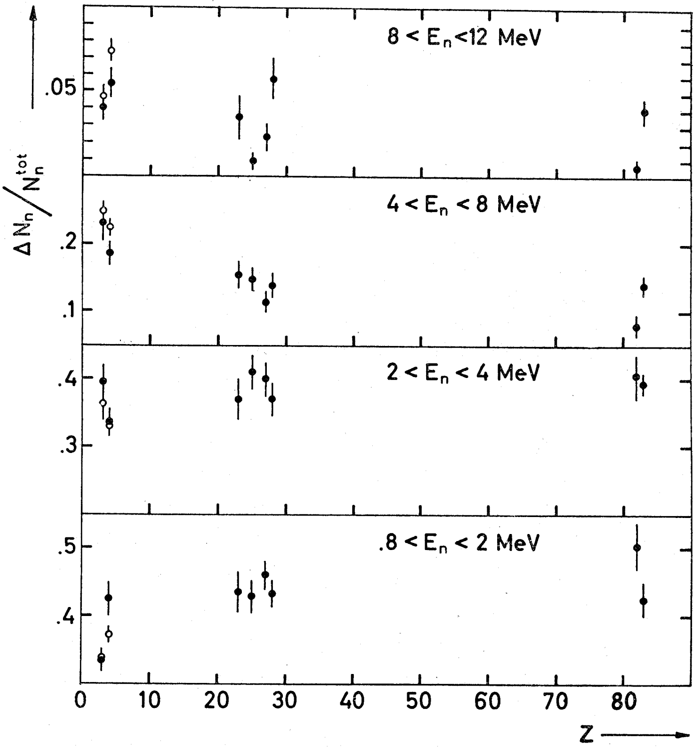

Fig. 1. – Percentage of the photoneutrons emitted at 135°, in the respective energy interval as a function of Z, by a γ-ray bremsstrahlung beam with $E_{\gamma\,\max} = 85$ MeV. The open circles represent the values obtained at 90° for ^{7}Li and ^{9}Be.

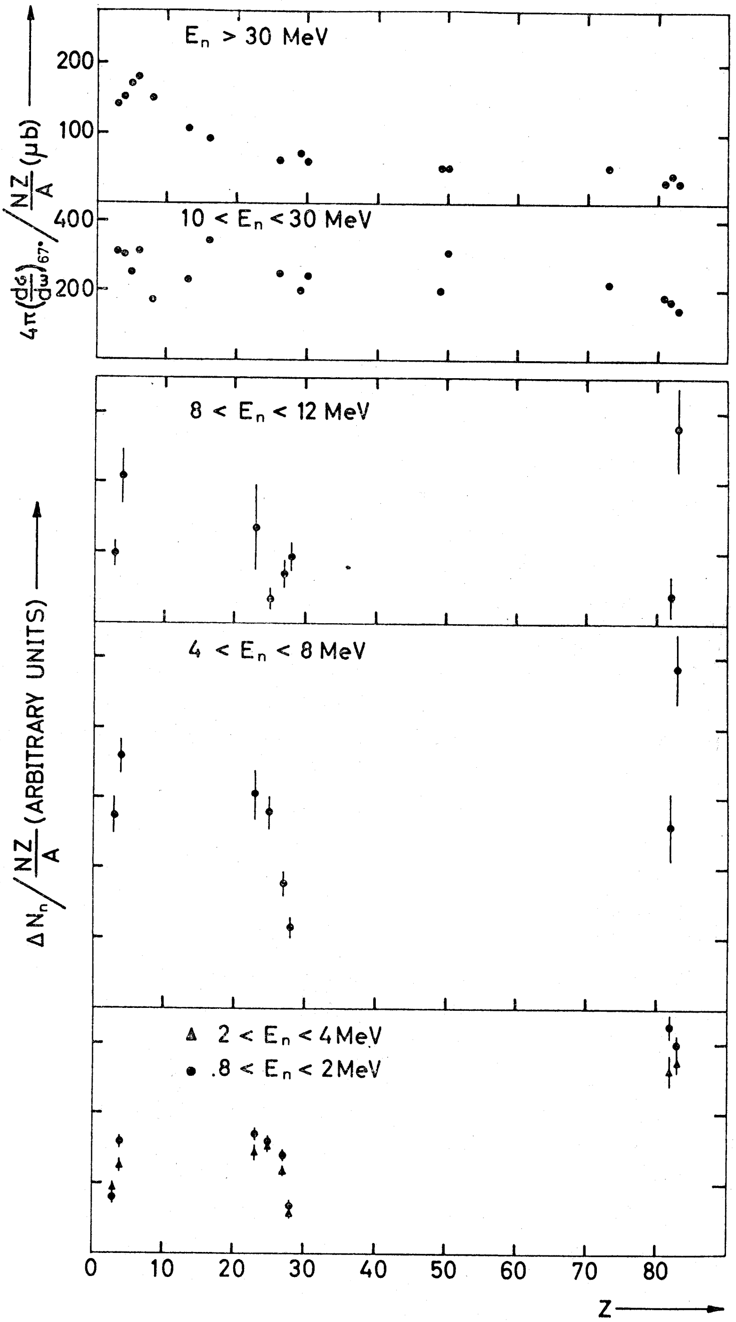

Fig. 2. – Number of photoneutrons emitted at 135°, normalized to the sum rule factor NZ/A, as a function of Z. In the upper part is reported the effective cross section divided by NZ/A for photoproduction of fast neutrons by 55–85 MeV bremsstrahlung photons as deduced by Kaushal *et al.* [1].

of photoneutrons emitted at 135^0 in the same energy intervals of fig. 1, normalized to the sum rule factor NZ/A, as a function of Z. In the upper part of fig. 2 we have reported, as a function of Z, the effective cross section divided by NZ/A for photoproduction of neutrons with $10 < E_n < 30$ MeV and $E_n > 30$ MeV by $55 - 85$ MeV bremsstrahlung photons as deduced by Kaushal *et al.* [1]. As we can see, the photoneutron emission in the peak energy region of the spectra ($0.8 < E_n < 4$ MeV) is strongly connected to the γ–ray absorption in the g.r. for medium-weight nuclei. In fact to the anomalous low γ–absorption in the (γ, n) channel for the ^{58}Ni [10] (explained [11] to be due to the strong shell effect in the g.r. region on the nuclear level density near $N = Z = 28$ shells) corresponds the anomalous emission we see in fig. 2. This nuclear shell effect is still noticeable in the emission of photoneutrons in the energy interval $4 < E_n < 8$ MeV where usually [9, 12] the neutrons are considered as "direct" but mostly produced by photons in the region of g.r., giving experimental evidence that the g.r. can be attributed to single particle transition and to a collective type of photon absorption [9]. In the case of light nuclei several theoretical analyses of photoabsorption explain the noticeable structure found experimentally [14, 15, 16, 17] in the gigant resonance, for ^{6}Li, ^{7}Li, ^{9}Be, ^{12}C (respectively refs. 18, 19, 20, 21). These analyses, in fairly good agreement with the experimental photoabsorption measurements, deduce also a noticeable low energy photoneutron emission in agreement with our spectrum measurements for Li and Be. Also in the case of medium-weight nuclei better agreement between theory and experiment is obtained, near the threshold of the (γ, n) reaction, treating explicity the dipole states in the particle-hole frame-work [13]. At this point one can conclude that in the g.r. region the compound nucleus formation with the evaporation of one neutron [22] is very improbable. A mechanism of nuclear emission like that proposed by Griffin [23] may explain qualitatively the strong correlation between the behaviour of the emission spectra of photonucleons and the nuclear structure and may suggest that the photoemission is mostly direct also at low neutron energy. This author assumes that the decay may occur into a state with the particle (direct or quasi-direct) in the continuum and with the residual nucleus at an energy shared by remaining "excitons" (particles or holes) in the residual nucleus. Finally, an equilibrium distribution results among the various independent-particles states, which is considered to describe "the average-compound-nuclear state". In the case of light nuclei as ^{7}Li and ^{9}Be the g.r. is very large up to about 40 MeV [14, 15, 16], but it was pointed out [19, 20, 21, 7] as also for high photon energy ($20 < E_\gamma < 40$ MeV) the resulting spectra of photoneutrons is soft. In this energy interval the decays of the most intensive high dipole states proceed via the emission of neutrons into high lying states of the residual nucleus. The higher excited states decay may also occur through the emission of many different particles (for example $^7\text{Li} - {}^3\text{He} + {}^3\text{H} + n$ [19]), but there is no experimental evidence [9] of noticeable multiple photoneutron emission. For the medium and heavy-weight nuclei the energy interval

$20 < E_\gamma < 40$ MeV corresponds to the tail of the g.r. where the multiple and single photoneutron emission cross-sections have about the same values [10]. Bergère *et al.* [24] pointed out that all photoneutrons from $(\gamma, 2n)$ and $(\gamma, 3n)$ reactions are to be classified as "boiled" off neutrons. Consequently the photoneutrons from these reactions are emitted with low energy E_n giving a negligible contribution in our spectrum measurements and their emission may be explained in the Griffin model [25] for time-dependent formation of a compound nucleus by the evaporation of the residual nucleus. As we can see in fig. 2 for $8 < E_n < 30$ MeV the emission of photoneutrons becomes practically independent of the nuclear structure. This fact shows that these photoneutrons are emitted by γ–rays with energy above the g.r. The experimental data of Kaushal *et al.* [1] show for the light nuclei that the emission probability of photoneutrons with $E_n > 30$ MeV presents a peak (see fig. 2) for the ^{12}C. This fact, in our opinion, may be explained by a strong direct emission of high energy photoneutrons from the lp shell [28] superposed on the spectrum due to the quasi-deuteron nuclear photodisintegration. Recently Gabriel and Alsmiller [26] have calculated the photoproduction spectra using the quasi-deuteron model [27] and taking into account all secondary interactions. These authors show by comparing with the data of Kaushal *et al.* [1] that their calculational model is capable of yielding reliable results over a large range of atomic mass numbers ($\gtrsim 12$). From our analysis of the experimental data, one can conclude that high energy photoneutron tail ($E_n > 8$ MeV) of the spectra is due to the high energy γ–rays above the g.r.; in the case of light nuclei for $E_\gamma > 30 \div 40$ MeV and in the case of medium – and heavy – weight nuclei for $E_\gamma > 20 \div 30$ MeV. These E_γ values correspond to photon reduced wave lengths about equal to average nuclear radius for $A < 40$, and $A > 40$ respectively, and may be considered the lower limits of applicability of the quasi-deuteron nuclear photodisintegration model, in agreement with the results obtained by Gabriel and Alsmiller [26]. For the light nuclei the inner shell direct photoneutrons may give a noticeable contribution at high energies.

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