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RESONANCE PHENOMENA IN THE ELASTIC SCATTERING OF PHOTONEUTRONS WITH ENERGIES OF 0.1, 0.2, 0.3 AND 0.4 MeV BY ATOMIC NUCLEI

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The cross sections for the elastic scattering of photoneutrons having energies of $E=0.1$, 0,2, 0.3 and 0.4 MeV by atomic nuclei have been measured. Regular variations of the cross sections have been found with the change of E. Both for light and heavy elements the maxima and minima are separated by energy intervals of the order of 100 keV. This result is in conflict with the exponential decrease of energy intervals between levels with increasing atomic numbers of the element, although the character of the variations observed makes one suppose that they are due to the resonance interaction of neutrons with nuclei. The hypothesis is advanced that the surface layer of all nuclei is of the same structure and this layer is supposed to consist of α-particles.

Introduction

Numerous studies (1-11) are devoted to the elastic scattering by atomic nuclei of neutrons having various energies. As a result of these studies, the cross sections (for the sake of brevity designated further as σ) were found to vary in an irregular manner in passing from element to element, *i. e.* if σ is treated as a function of the atomic number Z $[\sigma=f(Z)]$, and to vary apparently in a regular fashion when regarded as a function of the energy of the scattered neutrons, E $[\sigma=F(E)]$. These regular oscillations have a low amplitude, about $0.5\cdot10^{-24}$ cm^2, when D, D neutrons having energies from 2.14 to 2.9 MeV are scattered; however, for medium energies ranging from 100 to 400 keV these amplitudes become as high as $5\cdot10^{-24}$ cm^2, *i. e.* 10 times as large on the average.

The impossibility of changing the neutron energy over a wide range without disturbing the energy uniformity, unfortunately makes it difficult to carry out an investigation of the fluctuations of σ within the energy ranges from 0 to 0.1 MeV and from 0.4 to 2.0 MeV. But without an investigation of these energy ranges, it is very difficult to build up a definite theory of the observed variations of σ. As far as we are aware, it was only in MacPhail's work (10) that an attempt was made to offer a theoretical interpretation of the variations of σ found for Mg and Al. The method employed by MacPhail to construct the phase curve seems, on our opinion, to be much of an arbitrary matter. At any rate, this method could be justified only if it would be applied successfully to many elements and many measurements with these elements. The attempt to employ this method in the measurements described here had failed.

Although the number of cross sections measured by various investigators at various neutron energies exceeds 300, almost nobody took up a study of the variation of σ even within the accessible energy ranges. The numerous data available in the literature, refer almost solely to the domain of elements with small Z where several wide maxima and minima are observed within the energy range 2—3 MeV. As is known, the intervals between the energy levels of the nuclei of these elements cannot be theoretically calculated on the basis of the statistical theory. Therefore, the assumption as to these intervals being able to become as high as several hundred keV is merely probable without a strict foundation; experimental results that appear to support this postulate would be of a great value. On the other hand, from **Bethe**'s computations based on the nucleus drop model ([12]), it follows that for the heavier nuclei the variations of σ with neutron energy changing by 100 keV must vanish, because the energy intervals of such nuclei are hardly above 10—100 eV. Thus, it is very desirable to measure the cross sections σ with monochromatic neutrons in the region of the heavier elements. It was with this aim that the present work was undertaken, it being an extension of the cross section measurements made for six heavy elements already published ([4]). Further that work shall be called Part 1 and the present—Part 2 of the study.

After Part 1 had been published some investigators in their discussions called my attention to the fact that the maxima observed at energies of 0.3 MeV are questionable, in so far as the method for determining this energy for photoneutrons (γRaC, Be) is without rigid foundation. This method consists in that in measuring σ the radioactive detector of thermal neutrons is surrounded in one case by a paraffin sphere 6 cm in diameter, and in the other—by a paraffin sphere 10—12 cm in diameter. As the radioactive source use was made of RaC known to have six γ-lines with energies above the binding energy of Be^9 nuclueus (1.69, 1.75, 1.82, 2.09, 2.20 and 2.42 MeV). In a special investigation I showed ([13]) that with a paraffin sphere, cm in diameter, a sharp break point is observed on the curve showing an increase in the number of thermal neutrons with increasing paraffin sphere diameter. This break point is undoubtedly due to the fact that with such a filtering paraffin layer for the photoneutrons ejected by the most intense γ-line with 1.75 MeV energy, equilibrium sets in between the neutrons that have attained thermal velocity and those absorbed in the paraffin (the maximum on Bjerge-Westcott's curve). In this case activation is brought about mainly by these neutrons. The faster neutrons generated by the two lines coming next in intensity with energies 2.20 and 2.42 MeV, will be, by an amount of about 30—40 per cent mixed to the neutrons with 0.1 MeV energy generated by the line 1.75 MeV. With the paraffin sphere 12 cm in diameter it was shown in Part 1 that the neutrons released by the γ-lines with energies 2.20 and 2.42 MeV, are most of all responsible for the activation of the detector. The mean energy of these photoneutrons is found to be 0.3 MeV, by comparing the position of the maxima of the Bjerge-Westcott curves for photoneutrons (γRaC, Be) and (γThC″, D). As well known, the energy of the deuterium photoneutrons has been determined with great precision and on the most recent data is 0.22 MeV ([14]). The maxima of these two curves have been found with precision and are almost in exact agreement, so that the magnitude of 0.3 MeV is the highest for this group of photoneutrons (γ RaC, Be)*.

Besides the results of this special work, as outlined here, measurements of the angular distribution were made with two groups of photoneutrons (γRaC, Be) ([15]). As a result of these measurements it was found that group *1* (energy 0.1 MeV) has a spherically symmetrical distribution, whereas the amount of neutrons in group *2* (energy 0.3 MeV), emitted at the angle φ = 90° relative to the direction of the incident γ-rays, is by 42±3% greater than at the angle φ=0°. This effect of non-uniform angular distribution for different neutron energies was for some time the sole case. Only quite recently **Myers** and **von Atta** ([14]) discovered a similar effect for the photodisintegration of deuterium. With an energy of photoneutrons close to

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* As the energy of the γ-rays is 2.20 and 2.42 MeV and the binding energy of the Be^9 nucleus on the most recent data and from many earlier measurements is found to be 1.63 MeV, the energy of photoneutrons, when emitted from the ground state, must be 0.51 and 0.7 MeV. The assertion that the energy of these photoneutrons does not exceed 0.3 MeV is based only on the above mentioned comparison of the positions of the maxima on curves of the Bjrege-Westcott type. So far this inference has never been confirmed by anybody; however, a similar inference as to photoneutrons (γ ThC″, Be), having an energy of about 0.4 MeV instead of the universally accepted value 0.9 MeV, has been substantiated by direct measurements of the energy of recoil protons in an ionization chamber with a proportional counter. These measurements wree carried out by D. V. Timoshuk at the Nuclear Laboratory of the Ukrainian Physical Technical Institute, Kharkov, but have remained unpublished. The reduction in the energy of Be^9 photoneutrons appears to be due to an excited state with energy of the order of 0.4 MeV, this state at present being still undiscovered.

the binding energy of the deuterium nucleus, the distribution is found to be spherically symmetrical, whereas with energy of 0.22 MeV about 90 per cent of all the neutrons are ejected at a right angle.

The evident asymmetry of the photoneutrons of the second group is an unquestionable proof that their energy is greater than that of the photoneutrons of the first group; but in separating these two groups the admixture of each one is probably as great as 40 per cent, so that σ measured with these groups are not the true values. If σ_1 is less than σ_2 as for example, for Mg, by $1.5 \cdot 10^{-24}$ cm^2, the difference actually has to be greater because the admixture of neutrons of the first group diminishes σ_2 and the admixture of neutrons of the second group increases σ_1. However, in establishing whether a maximum exists, this fact is of no importance. It affects only its magnitude.

Experimental procedure

The experiments were carried out by the method of passing a beam of neutrons through a scattering substance placed 9 cm away from the source and 14 cm away from the detector, when making measurements with the first group of photoneutrons. These spacings were 10 and 18 cm respectively when measuring with the second group. As the neutron source use was made of a beryllium sphere 4 cm in diameter in the centre of which there was placed a small ampulla containing 200 mC of Rn in the measurements with the first group of photoneutrons and 200 to 100 mC of Rn in the measurements with the second group of photoneutrons. To avoid the introduction of two corrections, one for the irradiation of the detector and the other for the decay of Rn, the irradiation was always carried on for 8 hours and the activity of the dysprosium detector was measured with a Geiger-Müller counter continuously for 2 or 2.5 hours. The counter background was measured within one hour prior to starting the detector activity measurements and within 2 hours after they were over. To control the stability of the counter operation, the activity of a uranium standard was measured for 10—20 minutes. The background of the counter surrounded with 10 cm of lead, was 6—7 readings per minute. The initial activities of the detectors were in various cases 5—10 times greater than the background. An irradiation of a detectors both in presence and in absence of the scatterer, and all the measurements were completed within 24 hours. To avoid saturation of the 2.5 hour half-life of Dy, use was made of two identical cylindrical detectors. To reduce the statistical errors the σ values were, for each element and each group of neutrons, measured several times. These repeated measurements served also as a check of the measurement precision. The values of individual cross sections never departed from the mean values listed in Table 1 by more than ±20%. In most of measurements the deviation was only ±10%. The correction to the neutron beams being non-parallel was calculated from the formula

$$\sigma = \frac{1}{N\delta} \ln \frac{1-\alpha}{(a/b)-\alpha} . \qquad (1)$$

This formula was derived in our previous papers. N is the number of nuclei per 1 cm^3 of scattering matter, δ — the thickness of the latter in centimetres, a — the number of the counter readings proportional to the number of neutrons that activated the detector in presence of the scattering substance, b — the same number obtained in its absence, and α — the correction to the non-parallel directions of the neutrons.

Table 1

Neutron energy (MeV)	$\sigma \cdot 10^{24}$ cm^{-2}							
	Li	B	Mg	S*	Ni*	Zn	As	Tl*
0.1	0.9±0.2	4.7±0.4	6.5±0.5	1.1±0.2	5.7±0.5	5.1±0.4	8.2±0.6	11.3±0.8
0.2	2.2±0.4	4.2±0.5	3.9±0.4	2.4±0.3	6.6±0.5	4.0±0.4	6.3±0.5	6.5±0.6
0.3	1.0±0.2	6.5±0.5	8.3±0.6	1.0±0.2	6.3±0.5	6.0±0.6	7.0±0.6	10.0±0.8
0.4	2.3±0.5	2.9±0.3	3.6±0.4	2.3±0.3	3.6±0.4	2.8±0.3	5.8±0.7	6.8±0.7

Discussion

In Table 1 and in Fig. 1 are presented the measurement results. The values of σ as measured with photoneutron energies of 0.2 and 0.4 MeV are taken from previous studies accomplished in collaboration with Prof. A. I. Leipunsky. The data, marked by asterisks, were measured in the present work for the second time. All the other values of σ were measured in the present work. On the curves in Fig. 1 the triangles indicate the σ taken from the work of Amaldi and others ([5]) with (C, D) neutrons. As in those measurements the neutron energy ranged from 0.1 to 0.18 MeV, the position of the points was determined within ±50 keV. For some elements, for example, B, As, these σ fall onto the minima of the curves, for other elements the position of σ is intermediate. The points on the ordinate axis are σ measured by Goldhaber and Briggs ([11]) with thermal neutrons.

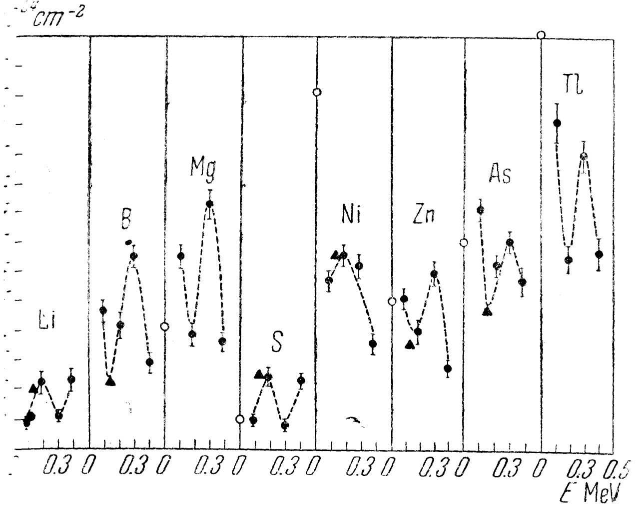

Fig. 1

It was mentioned in the introduction, that the inexact position of the first and third points on the ordinate (σ) has no material effect on the question whether the maximum and minimum are real. Of greater importance is their position on the abscissa axis (E). In the objections to the results of Part 1 of the present study it was pointed out that to place the σ obtained with neutrons of group 2 on the curve to the right of σ obtained with neutrons (γThC″, D) cannot be justified and that in reality this cross section must agree with the σ obtained with neutrons of group 1. In this case the maxima vanish and the curves fall off smoothly as required when the intervals between nuclear levels are much less than 100 keV.

The arguments and facts concerning the difference in the energies of neutrons of the first and second groups, as presented in the introduction, seem to rest on a sound foundation. Besides, it can be pointed out that for some elements the difference in the cross sections as measured with neutrons of group 1 and group 2 is much above random measurement errors, so that it is absolutely impossible to dispose them at a single place on the curve. And finally, for some elements, both heavy and light ones (Cr, Ni, Li, S) σ, falling on the maxima, were measured with photoneutrons (γThC″, D). In such cases the coalescence of the two σ values obtained with the two groups of photoneutrons (γRaC, Be) will all the same not give rise to a curve that falls off monotonously.

Thus we arrive at the conclusion that the results of the cross section measurements presented in Table 1 and in Fig. 1 as well as the results of the Part 1 of the study cannot be accounted for by any reasonably founded regular errors. The existence of regular variations of σ within energy intervals of the order of 100 keV is a real fact both for light and heavy elements. In the domain of light elements such variations were found also in the energy range of 2—3 MeV in the investigations of Aoki ([7]) and MacPhail ([10]). The cross section determinations made by Nonaka ([16]) for heavy elements by means of a (D, D) neutron source have also proven that the maxima and minima do exist. However Nonaka found the interaction of the neutrons with the nuclei to be inelastic, so that it is not clear whether in the 2—3 MeV range there exist regular variations of σ for an elastic interaction of the neutrons with nuclei. In the 0.1—0.4 MeV range inelastic interaction is entirely ruled out. Several investigators have shown that with such neutron energies the inelastic interaction is either very small or zero ([6,17]).

At present when a precise theory of the atomic nuclei structure is lacking, it is impossible to set up a theoretical foundation for the variations of σ found to have the form of resonance phenomena. It is quite obvious that the mechanism of the scattering, responsible for the observed variations in σ must be in principle other than the mechanism governing the distribution of nuclear levels. As the latter mechanism is a consequence of the conception that the whole nucleus becomes excited by the energy of the incoming neutron, such a treatment will necessarily lead to the familiar picture of the levels becoming closer with increasing atomic number Z, which rules out all possibility for maxima and minima to appear separated by energy intervals of the order of 100 keV.

However, it is now already possible to advance more or less probable suggestions. The principal feature of the phenomenon discovered is, besides of the variations in σ, also the monotonous increase of σ with increasing Z of the scattering element. The deepest minimum for any element with large Z lies above the minimum of any element with small Z. In other words, for all cross sections σ there is a lower limit which rises monotonously with increasing Z. This limit can be with great probability identified with the geometrical dimensions of nuclei. The existence of this boundary seems to be an indication that the processes of elastic scattering (and quite possible other processes, too) occur solely at the surface layer of a nucleus, the thickness of which is probably of the order of the effective radius of action of nuclear forces. If such be the case, these surface layers must for all of the nuclei be of the same constitution.

The second hypothesis that can be advanced as to the structure of this surface layer, will already be less evident. The most probable seems the supposition that the surface layer of the nuclei is made up of α-particles. It is well known that one of the difficulties, that hinders a nucleus model to be set up from α-particles as the stable constituents, is the great binding energy of a nucleon in the nucleus.

This energy is on the average the same as that in an α-particle. Inside a nucleus an α-particle would, therefore, burst. At the surface the conditions are other inasmuch as here the binding forces are in the first approximation unidirectional in their action, and the possibility for α-particles to exist in stable state is not precluded. In this case the centres of the heavy nuclei are taken up mainly by the surplus neutrons.

Verification of this hypothesis would greatly simplify the building up of a rational atomic nucleus theory, as it would involve a definite structure without depriving the nucleus of its distinguishing features of a liquid drop. These features would become yet more distinguishable, because the surface energy which is quite analogous to the energy of the surface tension in a liquid drop would be less than the volume energy, as required by the liquid drop model of the nucleus. It seems that such a confirmation should be expected only from further measurement of the cross section for elastic scattering. Theoretical computations, being based on a statistical theory, can be only approximate. Because of the impossibility of building up a precise theory of the nucleus, *i. e.* of obtaining an exact solution of the many-body problem, the impression is created that only one way is left over for investigating the nuclear structure, the setting up of semi-empirical models and verifying them by experiment.

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