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ЛАБОРАТОРИЯ ЯДЕРНЫХ ПРОБЛЕМ

ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

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IONIZATION POTENTIALS OF ATOMS

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* A more detailed paper will be published in JETP

I. INTRODUCTION

Ionization energy losses of fast particles traversing matter are described by the well-known formula of Bethe-Bloch

$$-\frac{dE}{dS}=\frac{2\pi(ze^2)^2n}{\rho mc^2\beta^2}\left\{\ln\frac{2mc^2\beta^2T}{I^2(1-\beta^2)}-2\beta^2+\frac{2}{Z}\sum_{K,L}C_i-\delta\right\} \qquad (1)$$

From the values forming the relation the ionization potential I is the only value which cannot be computed accurately on the basis of the modern theory of atomic shells. In this connection formula (1) is of the semi-empirical character.There are two ways of the experimental determination of the ionization potential by measuring the stopping power of a thin layer of matter and by simultaneous measuring the total range of particles in matter and their energy. The most direct method is the first one, since it allows to find the value I directly from relation(I). At the same time this method is more difficult as it is concerned with the necessity of accurate measuring small changes of particle energy. Up to now in the high energy region only one measurement of the value of ionization losses (at 18 MeV proton energy/1/) has been performed. The second method is considerably easier from the experimental point of view but it is connected with great difficulties in the interpretation of experimental results because in the first case one has to take into consideration a number of phenomena (scattering, nuclear interaction, etc.) concerned with the passage of particles through a thick layer of matter. And this method permits to determine only the value I averaged over a large energy range but not the value of the ionizatization potential at a definite energy.

Besides the abovesaid difficulties, the problem of accurate determination of the value of ionization potential is complicated by the fact that I depends exponentially upon the measured values and as a consequence of it the relative error of the determination of I turns out to be 6-10 times higher than the experimental error of the value dE/dS .

According to the existing theory (see, e.g./2/) the ionization potential should not depend upon the energy of incident particles. However, on analysing the obtained experimental values of I for alluminium Sachs and Richardson have pointed out the possible existence of dependence of the ionization potential upon the velocity of particles/3/. Later Caldwell showed/4/ that if one correctly takes into account the electron binding in an atom at K- and L-shells, the experimental data lead to a conclusion on the independence of I upon the velocity of particles. At the same time Caldwell called in question the results obtained by Mather and Segre[5] at the proton energy highest by that time ($E_{eff.}$ = 200 MeV) in connection with the fact that in the quoted paper proton energy was determined by measuring the angle of Cerenkov radiation but the theoretical relation between this angle and the value of particle velocity is proved experimentally not enough accurately. The conception on the constancy of the ionization potential was predominating up to now and was used in all the latest papers (see, e.g.[6]). The data of Zrelov and Stoletov[7] published recently proved the correctness of experimental results of Mather and Segre. However, they did not eliminate Caldwell's objection since they were obtained in the same way as in [5].

The above disrepancies urged us in 1957 to carry out systematic measurements of the ionization potentials of various atoms in a large energy region of incident particles. In order to determine the value I we have measured both the ionization losses dE/dS and the total ranges of protons, deuterons and α-particles, i.e. we have made use of both the methods discussed above. The experiments have been performed at the 6-meter synchrocyclotron of the Laboratory of Nuclear Problems (JINR).

2. MEASUREMENT OF IONIZATION LOSSES

In order to determine the values of ionization losses we have made use of the apparatus employed earlier[8] in the investigations of the energy characteristics of the external beam which passed through a number of collimators and was deflected by the magnet. The deflected beam was registered by a detector consisting of a thin (0.1 - o.2cm) plastic scintillator with a photomultiplier under it. Electric pulses of the photo - multiplier were integrated with the unit RC and the current value was measured by a self-recording potentiometer. With the help of a synchronous motor the detector could move perpendicularly to the beam. In this way the function of the beam density distribution was registered on the recorder tape. This function is well described by the Gauss curve and this permitted us to find the location of the beam center with great accuracy. The particle beam energy was determined with an accuracy better than 0.1% by means of a current-carrying wire (see the details in [8]). In the measurement of ionization losses value a thin sample of matter under study was placed on the beam path and the energy difference of the initial and the slowed down beams was found. This was made many times. The values dE/dS obtained for copper in this way are given in Table I. In all the measurements except the point 615 MeV one and the same sample of copper was used.

TABLE I

Kind of particles	p	p	p	d	α
Incident particle energy, MeV*	662	662	283	397 /198/	765 /190/
Effective particle energy, MeV*	651	615	267	376,8 /188,5/	691 /173,9/
dE/dS MeV/gr/cm^2	1,74$\pm$0,02	1,772$\pm$0,008	2,61$\pm$0,03	3,15$\pm$0,01	3,337$\pm$0,015

* Equivalent proton energy is given in brackets.

The values of ionization losses for other , differing from copper matters were determined by a relative method by means of comparing energy losses in samples of matters under study and of copper. The measured relative losses $q_x = (dE/dS)_x / (dE/dS)_{Cu}$ are enlisted in Table II. The values determined in other experiments are shown also there; this allows to follow the changes of the relative stopping power with increasing energy of incident particles.

3. RANGES AND ENERGIES OF PARTICLES

In order to measure the particle range use was made of the ionization chamber. The beam was slowed down with a wedge-shaped copper absorber. The current of the ionization chamber was registered with a self-recording potentiometer. The thickness of the filter changes synchronously with the movement of the potentiometer tape and owing to this the Bragg curve was continuously recorded. The measurement was repeated many times to achieve high accuracy. At the same time by means of the current-carrying wire kinetic energy of particles T was determined. Obtained by the above method the ranges of various particles in copper R are shown in Table III. In the calculation of the average range unlike in /5,7/ the scattering of particles in the filter was taken into account. The corresponding correction was included also in the data taken from the quoted papers and given in Table III for the sake of comparison.

TABLE II

Relative ionization losses q_x

Particles	p	p	p	α	d	p	p	p	p	p
Effective particle energy, Mev*	19,8	20	70	691 (173,9)	376,8 (188,5)	267	300	615	635	651
Reference	/9/	/10/	/11/	Present paper	Present paper	Present paper	/12/	Present paper	/7/	Present paper
H**	–	–	–	3,1$\pm$0,1	3,10$\pm$0,04	–	3,01$\pm$0,15	3,06$\pm$0,04	3,02$\pm$0,15	–
C	–	–	–	1,31$\pm$0,01	1,316$\pm$0,003	1,29$\pm$0,01	1,265$\pm$0,013	1,256$\pm$0,003	1,268$\pm$0,013	1,271$\pm$0,005
Al	1,218$\pm$0,002	1,196$\pm$0,007	1,221$\pm$0,012	1,17 $\pm$ 0,01	1,167$\pm$0,003	–	1,143$\pm$0,011	1,154$\pm$0,003	–	1,161$\pm$0,005
Sn	0,828$\pm$0,002	0,835$\pm$0,005***	–	–	0,870$\pm$0,005	–	0,858$\pm$0,009	–	0,870$\pm$0,009	0,874$\pm$0,004
Pb	0,677$\pm$0,004	0,679$\pm$0,007****	0,747$\pm$0,007	0,749$\pm$0,007	0,748$\pm$0,003	0,736$\pm$0,017	0,754$\pm$0,007	0,763$\pm$0,003	–	0,768$\pm$0,004

* The equivalent proton energy is given in brackets.

** Determined by the subtraction method "CH_2 – C".

*** Obtained from the data on the neighbouring element Cd under the assumption that I = kZ and the coefficient k is similar for Cd and Sn.

**** The same for Au and Pb.

TABLE III

Particles	T, MeV	R, gr/cm^2 Cu	Particles	T, MeV*	R, gr/cm^2 Cu
p	663,5±0,7	263,0±0,2	p	190,1±0,8	36,4±0,1
p	658 ±2 [7]	258,3±1,2	p	148,6±0,8	23,8±0,1
p	473,3±0,6	157,9±0,1	d	394,4±0,5	75,7±0,1
				/197,3±0,3/ [x]	
p	340 ± 1 [5]	93,4±0,2			
p	279,9±0,6	68,6±0,1	α	774,2±1,0	37,5±0,1
				/195,0±0,3/ [x]	

* The equivalent proton energy is given in brackets.

4. IONIZATION POTENTIALS

a) Ionization potential for copper

The values of ionization potential for copper I_{Cu} have been found from the data of Table I and are presented in Table IV.

TABLE IV

Particles	p	p	p	d	α
Effective* energy, MeV	651	615	267	376 /188,5/	691 /173,9/
I_{Cu}, ev	301±27	302±11	288±22	333±7	318±9

* In brackets the equivalent proton energy is given.

The comparison of all the data determined by direct measuring the values of ionization losses (paper[1] and the present research) shows that if formula (I) is justifiable and the corrections C_1 and δ are calculated by Walske[13] and Sternheimer[14] correctly, it is necessary to assume the existence of the ionization potential dependence upon incident particle velocity (see Fig.I).

In order to obtain an additional information on the value of ionization potential in the high energy region use was made of the relations between the range and energy enlisted in Table III of the present paper. Ionization potentials obtained by the "range-energy" method (see Table V) confirm the conclusion on the existence of the dependence of the value I_{Cu} upon the velocity of particles.

TABLE V *

Particles	Effective energy, MeV	I_{Cu}, ev	Particles	Effective energy, MeV	I_{Cu}, ev
p	400	322±7	α	117[x]	351±10
p	282	312±5	p	115[x]	338±12
p	168	320±6	p	90	341±18
d	118[x]	323±12			

* The equivalent proton energy is given.

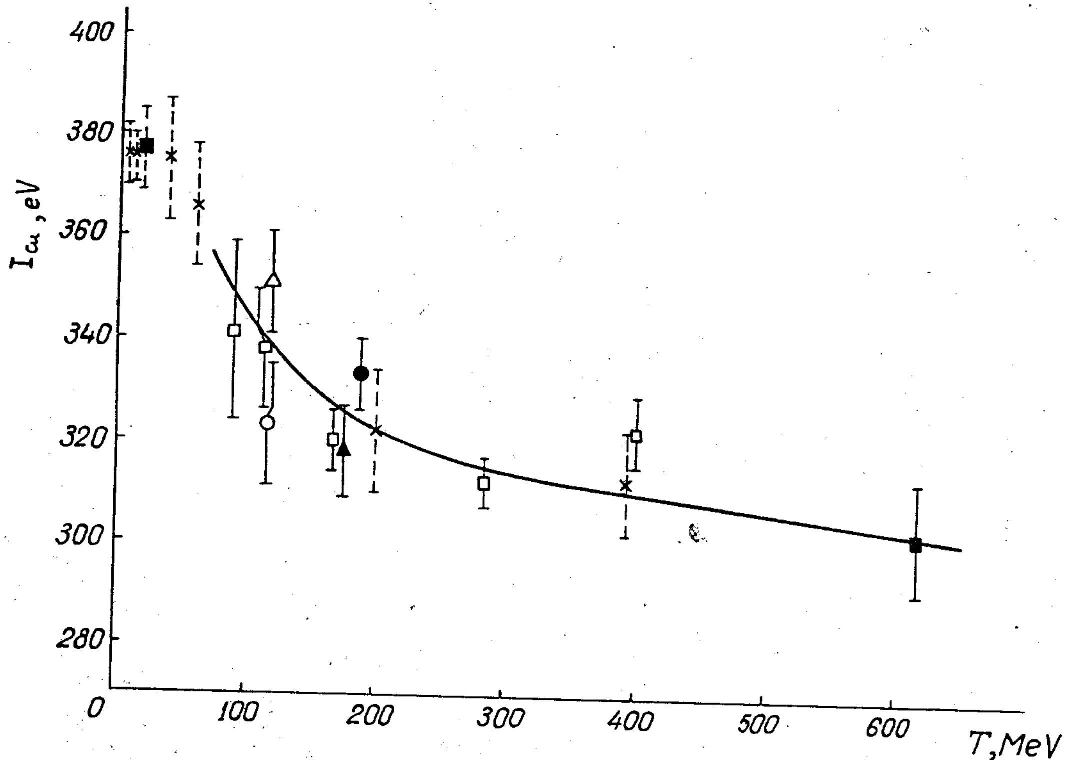

Fig.1. Dependence of the ionization potential of the copper nucleus I_{Cu} upon the energy of bombarding particles T. Black points show the results of the direct measurements of ionization losses. Light points indicate the values obtained by the "range-energy" method. , , , , and are the data of the present paper, obtained with proton, deuteron and α -particle beams, respectively. is taken from paper[1], -according to the data of papers[15,9,11] (in the order of energy increase), obtained with a proton beam. The approximating curve is drawn by the least squares method.

b) Ionization potentials of other matters

The values of ionization potentials I_x of various matters obtained from the data of Tables II, IV and V are shown in Table VI together with the data of other papers.

TABLE VI

Ionization potentials I_x (in eV)

Particles	Effective energy, MeV*	Reference	H*	C	Al	Cu**	Sn	Pb
p	6–18	/15/	-	-	166±1	376±20	622±43 x/	1076±104 x/
p	18	/3/	-	-	163±3	377±8	708±59	1179±104 x/
p	19,8	/9/	-	-	166±1	366±5	621±7 x/	1070±24
α	691 /173,9/	наст. работа	18±6	86±6	157±13	325±8	-	778±43
d	376,8 /188,5/	наст. работа	17,0±2,4	81,2±3,1	158±5	323±8	473±20	795±23
p	200	/5,4/	-	-	155±5	322±8	-	-
p	267	наст. работа	-	88±7	-	316±8	-	918±131
p	300	/12/	18±7	87±8	170±13	314±8	514±38	789±49
p	615	наст. работа	11,7±2,1	89±4	145±7	302±11	-	786±30
p	635	/7/	14±7	84±9	-	301±12	488±38	-
p	651	наст. работа	-	79±5	136±8	300±12	463±23	753±37

* See the note under Table II.
** The averaged values I_{Cu} are given here (see the curve in Fig.I).

As is seen from Table VI the ionization potentials of elements heavier than copper decrease with increasing energy faster than I_{Cu} . On the contrary for lighter elements (alluminium) a comparatively slow change of the value of the ionization potential with increasing energy is observed.

In conclusion the authors take an oppotunity to express their thanks to V.P.Zrelov for the discussion of the results of the present paper.

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