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The Production of Charged Mesons by the Bombardment of Beryllium and Carbon with 660 MEV Protons

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The energy spectra of positive and negative pions released in p + Be and p + C collisions was measured with a magnetic spectrometer at an angle 24° to a 660 mev proton beam. The π^+ – meson spectrum has a clearly defined maximum at an energy of about 210 mev in the laboratory system, whereas the spectrum for the π^- – mesons varied only slightly over a range from 60 to 250 mev. The probability of positive pion formation when protons collide with protons bound in Be and C nuclei was discovered to be at least three times less than where protons act on free protons. The maximum of the π^+ – meson spectrum in the center-of-mass coordinate system is situated near 100 mev. The ratio of positive to negative pion emission was determined for Be and C over the whole spectral range. The ratio of total emission of positive to negative pions for these two elements is equal, respectively, to 5.3 ±0.6 and 7.0 ±0.8.

1. INTRODUCTION

THE present article is devoted to research on the energy spectra of positive and negative pions released during the bombardment of beryllium and carbon with protons whose energy was sufficient to excite one of the colliding nucleons to the state with an angular momentum of 3/2 and an isotopic spin of 3/2 (i.e., a $P_{3/2,3/2}$ state). The proton energy was not so high that the process of forming two pions in a single collision occurred to any appreciable degree.

2. THE EXPERIMENTAL PROCEDURE

A magnetic spectrometer was used to obtain the energy distributions of the pions. Those pions which are emitted at an angle 24° to the proton beam pass through the spectrometer and are recorded with a telescope of three scintillation counters. Information on the proton beam and magnetic spectrometer was presented in a previous paper[1]. The method for determining the contamination of the pion beam by μ – mesons and electrons upon exit from the spectrometer was described in the same paper. The influence of pion absorption in the target, as well as in the crystals and filters, was evaluated in the light of current data on total cross sections of pion-nucleus interaction[2-5]. For the beryllium and carbon targets, with thicknesses selected so that the energy loss suffered by the 660 mev protons was 3.7 mev in both, this correction varied from 3% at the bottom of the spectrum to 6.6% at 200 mev and then dropped again to 3.5% at 420 mev. In calculating the correction for pion disintegration in flight, the lifetime of π^+- and π^-- mesons was taken to be $(2.54 \pm 0.11) \times 10^{-8}$ sec[6,7].

3. THE ENERGY SPECTRA OF THE PIONS

Figures 1 and 2 show the energy distributions of the π^+- and π^-–mesons in the laboratory system as obtained for beryllium and carbon. The errors indicated in the measured points allow for statistical errors of measurement and for all uncertainties in the evaluation of the corrections for negative pion disintegration in flight and for determining the contamination by μ–mesons and electrons. The spectra were normalized to the value of the area under the peak belonging to the π^+–mesons from the $pp \to d\pi^+$ reaction[8].

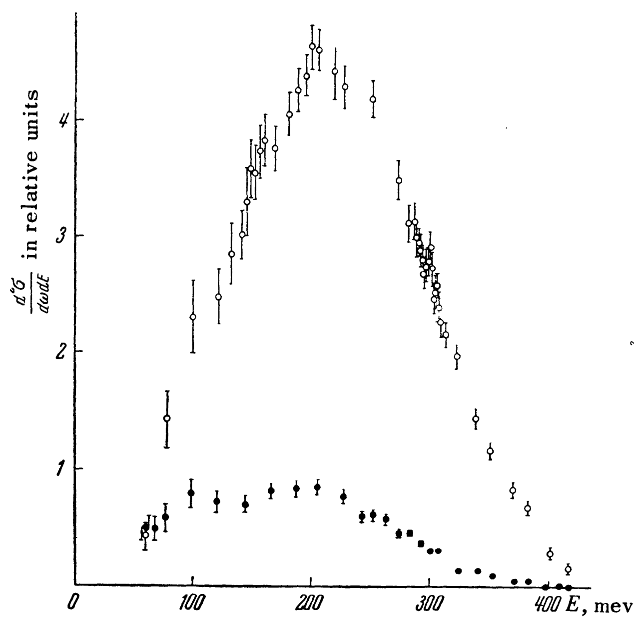

FIG. 1. Energy distributions of pions from Be at an angle of 24° in the laboratory system. O represents π^+- mesons and ●, π^- – mesons.

The basic properties of the measured spectra are the following:

a) At the upper part of the spectra the number of π^-–mesons becomes zero for lower energies than for the π^+–mesons;

b) For both elements the average energy of π^+- mesons is equal to about 215 mev, and the average energy of π^-– mesons is about 180 mev;

c) Both π^+– meson spectra have a clearly defined maximum at an energy of about 210 mev, whereas the number of π^-– mesons in the spectra of both elements shows only slight variation over a range from 60 to 250 mev. One should not rule out the possibility that the negative pion spectra has a slight indentation in the region of 100-130 mev;

d) In the π^+– meson spectra there is a certain distortion in the smooth variation in the number of mesons with energy in the interval from 140-200 mev, i.e., for those energies where the cross section of π^+– meson-proton interaction attains its maximum value. This circumstance is cause for assuming that the reason for the distortion of the smooth variation in the spectrum in the indicated region is the interaction of the π^+– meson with the nucleons in the original nuclei.

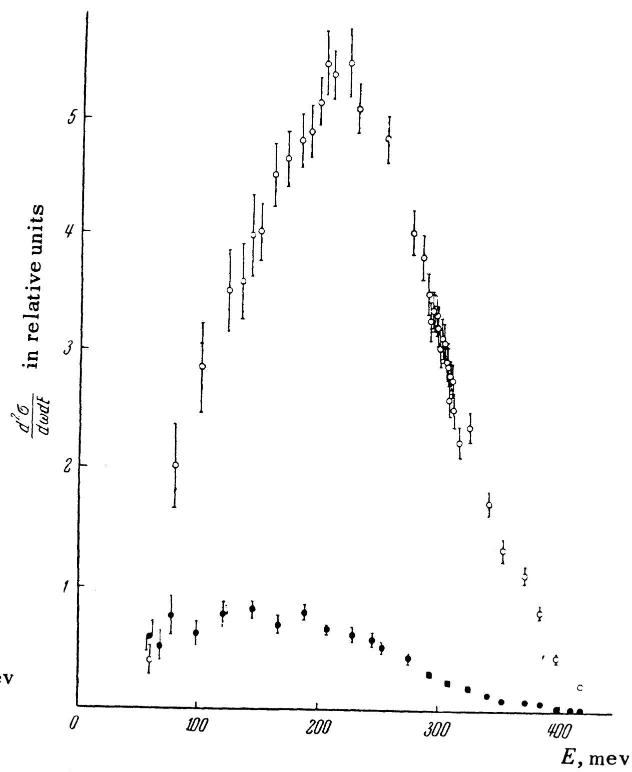

FIG. 2. Energy distributions of pions from C at an angle of 24° in the laboratory system. O represents π^+– mesons and ●, π^- – mesons.

Special attention was given to measurements of the π^+– meson spectra in the 300 mev region, where a peak can be observed for π^+– mesons from the $pp \to d\pi^+$ reaction. If this peak should be discovered in the present experiments, this might mean that the protons within Be and C nuclei spend an appreciable time at the surface of the nuclei, i.e., outside the region of strong interaction with other nucleons. In this case the protons must exhibit a small dispersion in momentum. As may be seen from Figs. 1 and 2, the results obtained give no indication of the existence of observable deviations from the monotonic decrease in the number of π^+– mesons throughout the studied energy range other than deviations within the limits allowed for by experimental error.

4. COMPARISON OF PION YIELDS FROM FREE AND BOUND PROTONS

The values of positive and negative pion yields for an angle of 24° were determined by integrating the spectra over energy. Shown below are the yields per target nucleus and the total yield of positive pions from the $pp \to np\pi^+$ and $pp \to d\pi^+$ reactions measured under the same conditions and taken as unity.

Element	Y^+	Y^-
H	1.0	–
Be	1.4	0.26
C	1.7	0.24

Because of charge independence the total cross sections $\sigma(pn \to nn\pi^+)$ and $\sigma(np \to pp\pi^-)$ must be identical, and the π^+– meson yield at an angle θ in the first reaction must be equal in the center-of-mass system to the π^-– meson yield at the angle $(180° - \theta)$ for the second reaction. For an energy of about 660 mev we have $\sigma(pp \to d\pi^+) = (3.1 \pm 0.2) \times 10^{-27}$ cm^2 [8], $\sigma(pp \to np\pi^+) = (10.2 \pm 1.2) \times 10^{-27}$ cm^2 [1], $\sigma(pp \to pp\pi^0) = (3.4 \pm 0.4) \times 10^{-27}$ cm^2 [9] and $\sigma(pn \to pn\pi^0) = (7.8 \pm 1.6) \times 10^{-27}$ cm^2 [10]. From the relation

$$\tfrac{1}{2}[\sigma(pp \to d\pi^+) + \sigma(pp \to np\pi^+)]$$
$$= \sigma(pp \to pp\pi^0) + \sigma(pn \to pn\pi^0) - \sigma(pn \to nn\pi^+)$$

it follows that $\sigma(pn \to nn\pi^+) = \sigma(np \to pp\pi^-) = (4.6 \pm 1.8) \times 10^{-27}$ cm^2. This estimate is compatible with the Y^+/Y^- ratio obtained for the 24° angle. Bearing all this in mind, we cannot be too far wrong in assuming that in the studied energy region positive pion formation inside a nucleus occurs mostly in $(p-p)$-collisions. If the values for Y^+ obtained for Be and C refer to a single proton in a target nucleus, then it turns out that the probability of π^+-meson formation in $(p-p)$-collisions inside the nucleus is at least three times less than the probability of π^+– meson formation where the protons are free.

This large reduction in the probability of π^+– meson formation in collisions with bound protons is caused to a certain degree my meson absorption in the original nuclei, and also by the slowing-down and scattering of impinging protons in the nuclear matter. The effect of these processes is such that the nucleons situated on the surface of the nucleus participate principally in meson formation. The presence of nuclear bonds in the nuclear matter may also prove to be one of the additional reasons for the reduction in the probability of meson formation inside the nucleus, even at high energies.

5. ANALYSIS OF THE PION ENERGY SPECTRA

On the assumption that pion formation in compound nuclei occurs through the interaction of an impinging proton with one of the bound nucleons and that pion scattering in the original nuclei is insignificant, the spectra obtained were transformed to the center-of-mass system of the two nucleons. In this system the kinetic energy of the two nucleons is equal to 305 mev when one of them has an energy of 660 mev in the laboratory system. The values of $d^2\sigma^*/d\omega^* dE^*$ in the center-of-mass system were found by calculating the invariant expression $(1/p)d^2\sigma/d\omega dE$, where p is the momentum of the pion. Figures 3 and 4 show the spectra obtained in this way for positive and negative pions, with the angles at which the pions of a given energy were emitted*. It is apparent that the angular interval 48° to 42° corresponds to the energy interval 50-200 mev. For both elements the average total energy of a π^+– meson proved equal to 242 mev, which comes close to the value found under similar circumstances for free $(p-p)$-collisions[1]; the average total energy of π^-– mesons in both cases is equal to 225 mev. These figures indicate that in

* These values for the angles are approximate, since motion of the nucleons in the nucleus was disregarded in the calculations.

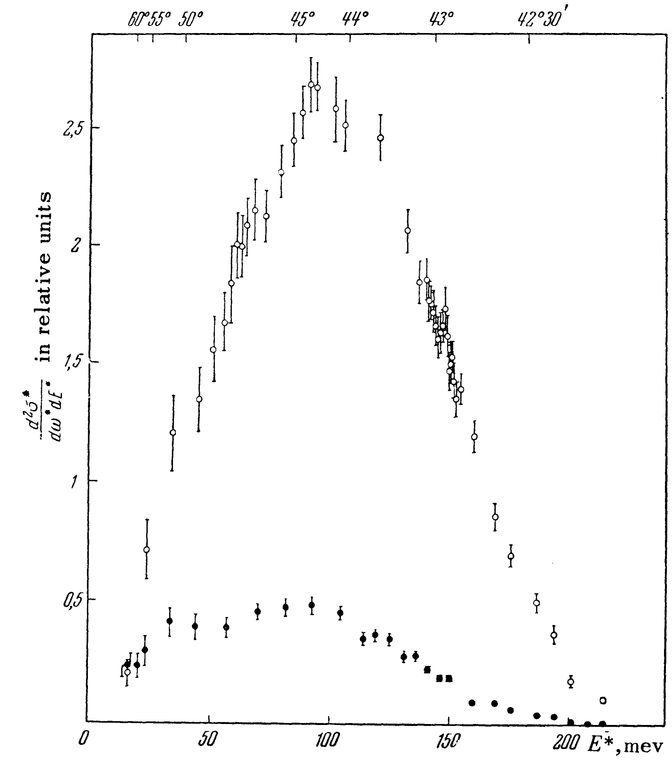

FIG. 3. Energy spectra in the center-of-mass system for Be. O represents π^+–mesons and ●, π^-–mesons.

a single act of pion formation an average of about 75% of the energy available in the center-of-mass system is expended.

Both π^+–meson spectra disclose a maximum near 100 mev. If the recoil energy of the nucleon and the rest energy of the meson are added to this most probable value of the π^+–meson energy, then the most probable value of the total energy released in the elementary act of positive pion formation will be equal to about 260 mev. The value obtained for the total energy is only slightly less than the resonance energy of the excited $P_{3/2,3/2}$ state.

It is of considerable interest to compare the π^+–meson spectra obtained in these experiments with spectra measured at far greater energies. According to Yuan and Lindenbaum[11] the maximum for the π^+–meson spectrum formed by the action of 2300 mev protons on beryllium and measured at an angle of 32° to the primary beam is close to 130 mev. It is also known that for the π^+– and π^-–meson spectrum from the $np \to np\pi^+\pi^-$ reaction at an energy of 1720 mev, the average energy is 112 mev and 120 mev, respectively[12].

The cited facts are evidence that with the increase in energy from 660 to 2300 mev, the maximum in the π^+–meson spectrum changes its position only slightly, remaining always close to the resonance energy of the $P_{3/2,3/2}$ state. On this basis it may be assumed that throughout the entire energy interval investigated the main effect is due to the same specific mechanism of pion formation. This mechanism may be taken to consist of a transition in the energy region of 600-1000 mev of one,or where the energy is greater, of both the colliding nucleons to an excited state, from which the nucleons, acting almost like free particles, return to their ground state by emitting pions. A similar supposition was used by Fowler, Shutt et al.[12] to explain the predominant formation of two pions in one elementary act and the angular correlations of particles in the reaction $np \to np\pi^+\pi^-$ at 1720 mev.

The questionof the reasons for the striking difference in the forms of the spectra of positive and negative pions deserves to be treated separately. Let us assume that nucleonic collisions inside nuclei possess the same properties as collisions

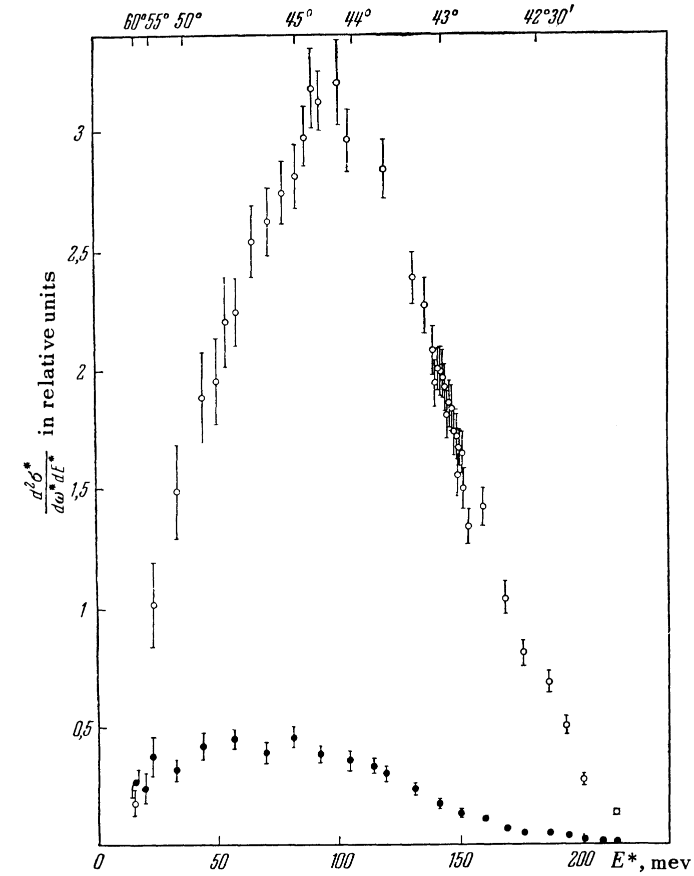

FIG. 4. Energy spectra in the center-of-mass system for C. O represents π^+—mesons and ●, π^-—mesons.

of free nucleons with regard to the nature of particle interaction in the final nucleonic system, conservation of the isotopic spin and the predominant emission of mesons in the p-state. Now the mentioned difference in the spectra of positive and negative pions may be qualitatively explained, if it is borne in mind that for the $pp \to np\pi^+$ and the $pn \to pp\pi^-$ reaction, there is a difference in the relative contribution of the transitions to the final P and S states of the two-nucleon system and and that the form of the pion spectrum is sensitive to nucleon interaction in the final state. It is for this reason that transitions to P states, where nucleons interact weakly, should lead to a softer spectrum than transitions to $^1S_0$ and $^3S_1$ states, which are characterized by strong nucleon interaction.

6. THE π^+/π^- RATIO

The dependence of the ratio of positive and negative pion yields on energy was determined from the measured values of $d^2\sigma^*/d\omega^* dE^*$. As can be seen from Figs. 5 and 6, for both elements at energy $E \simeq 15$ mev, $\pi^+/\pi^- \leq 1$. In the region from 160-180 mev the π^+/π^- ratio attains its maximum value of 14 ± 1.9 for Be and 17.7 ± 3.2 for C. For these same elements the ratio of integral yields of positive to negative pions is equal to 5.3 ± 0.6 and 7.0 ± 0.8, respectively. According to Sidorov[13], the ratio of integral yields of positive to negative pions for $p + C$ collisions at an energy of 660 mev is 5.0 ± 0.7 at a 90° angle in the laboratory system. The large increase in the yield of positive pions over that of negative pions is due to the fact that the impinging nucleon is a proton and also to the comparatively low probability of pion formation when the two-nucleon system is in a state where the isotopic spin is equal to zero.

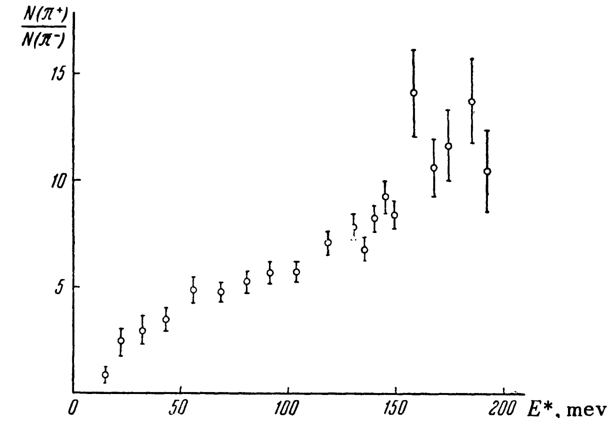

FIG. 5. The energy dependence of the ratio of positive to negative pion yields for Be in the center-of-mass system.

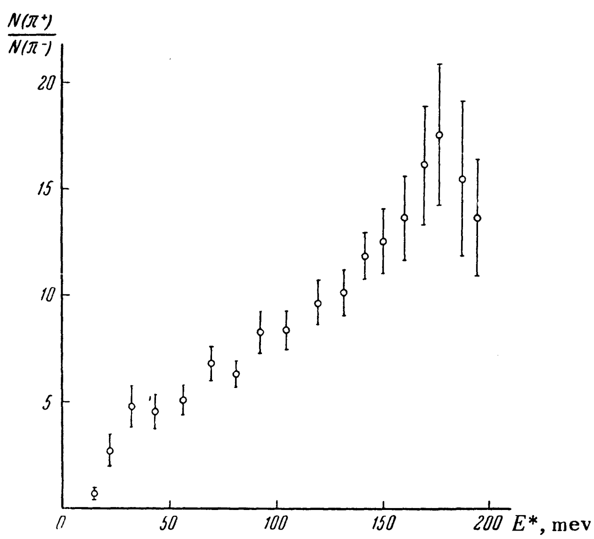

FIG. 6. The energy dependence of the ratio of positive to negative pion yields for C in the center-of-mass system.

A theoretical attempt has been made[14] to predict the magnitude of the Y^+/Y^- ratio on the assumption that the inelastic collision of the nucleons occurs through two independent stages: excitation of one or both of the nucleons and then decay by emission of a pion. For this case, when the energy is sufficient to excite only one nucleon, the Y^+/Y^- ratio should be equal to 9 for p + Be collisions and to 11 for p + C collisions, if pion formation occurs only through the $P_{3/2,3/2}$ state. These predicted values for the Y^+/Y^- ratio are noticeably greater than the corresponding experimental values. As has already been noted elsewhere[14], this discrepancy may be obviated to some extent if due consideration is given to meson formation in a state where the isotopic spin of the meson-nucleon system is equal to ½. It is also necessary to account for the difference in the angular distributions of the π^+-mesons and π^--mesons. Furthermore, it is essential to note that the original assumption that the processes of the excitation of a nucleon and its decay are independent raises doubts simply because the width of the energy level of the $P_{3/2,3/2}$ state is not much less than the excitation energy[15].

Another approach[16] in evaluating the magnitude of the Y^+/Y^- ratio has been to assume that, in addition to meson formation through the $P_{3/2,3/2}$ state, direct formation also occurs, and that the relationship between these processes is determined by statistical weights alone. Calculations performed in this way for p + Be collisions at an energy of 100 mev give a value of 5 for the Y^+/Y^- ratio.

7. CONCLUSIONS

These experiments established the following facts regarding the formation of charged pions by the action of 660 mev protons on beryllium and carbon nuclei:

1. The probability of π^+-meson formation by a proton in a target nucleus is decreased by more than three in comparison with the probability of formation in free $(p-p)$-collisions.

2. The spectra of positive and negative pions differ in form and average pion energy. The relative softness and diffuseness of the π^--meson spectra are cause to assume that there is a weak interaction among nucleons in part of the final state of the $pn \rightarrow pp\pi^-$ reaction.

3. On the average about 75% of the available energy is expended on charged pion formation in an elementary act during nucleon-nucleon interaction.

4. Perhaps the least expected fact of all was that in these experiments the maximum of the π^+-meson spectrum was discovered in the same energy region where it was observed by experiments with the Brookhaven proton accelerator at bombardment energies of 1720 and 2300 mev. This result lends

direct support to the conclusion that both single positive pion formation in nucleon-nucleon collisions at an energy of 660 mev and pair formation of pions at energies of 1720 and 2300 mev are essentially due to strong meson-nucleon interaction in the intermediate $P_{3/2,3/2}$ state.

5. The ratio of yields of positive and negative pions increases with energy up to 160-180 mev in the center-of-mass system. The ratio of integral yeilds of positive and negative pions is noticeably lower than the values predicted by theory based on the assumption that formation and decay in the intermediate $P_{3/2,3/2}$ state are independent.

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Solution of the Fundamental Diffusion Equation for Cosmic Ray Particles Emitted by a Constant Energy Concentrated Pulsed Source

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The fundamental diffusion equation deduced by Terletskii[1] for cosmic ray protons emitted in magnetized interstellar space during a short period of time by a concentrated source of given energy is solved. It is shown that consideration of the particles which remain after collision of cosmic ray protons with protons of the interstellar gas leads to a power spectrum similar to that observed experimentally, if the source is assumed to be a supernova which appeared in the center of the galaxy over 10^8 years ago.

THE distribution function of cosmic ray protons in interstellar space $f(\mathbf{r}, E, t)$ can be found from the diffusion equation for cosmic ray particles.[2-4] In full form, with account taken of particles that remain after the collision of cosmic ray protons with the protons of an interstellar gas, this equation was found in Ref. 1 :

$$\frac{\partial f(E)}{\partial t} + \frac{f(E)}{T} - D\Delta_r f(E) + \frac{\partial}{\partial E}[\alpha E f(E)] - \frac{\partial^2}{\partial E^2}[\alpha E f(E)] - \frac{1}{T}\left[\frac{1}{a_1} f\left(\frac{E}{a_1}\right) + \frac{1}{a_2} f\left(\frac{E}{a_2}\right)\right] = Q, \quad (1)$$