PHOTODISINTEGRATION OF HELIUM. III

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Results of an investigation of the $He^4(\gamma, pn)D$ reaction, and a summary of results on photodisintegration of He^4 are presented. The dependence of the cross section for the (γ, pn) reaction on γ-ray energy, the angular distributions of the protons and neutrons from this reaction, and the correlations between the directions of emission of protons, neutrons and deuterons were measured. $\sigma_{int} = (95 \pm 7)$ Mev · mbarn and $\sigma_b = (2.4 \pm 0.15)$ mbarn are computed from the cross section curves for the (γ, p), (γ, n) and (γ, pn) reactions on He^4. The results are discussed from the point of view of finding a model for the interaction with He^4 of γ-quanta of varying energies, and are also compared with theoretical computations of the photodisintegration of He^4.

1. INTRODUCTION

In preceding papers[1,2]* we discussed in detail the properties of the $He^4(\gamma, p)H^3$ (I) and $He^4(\gamma, n)He^3$ (II) reactions, which lead to the emission of two particles — a proton and an H^3 nucleus, and a neutron and an He^3 nucleus. Here we shall consider the third reaction which occurs after absorption of a photon by the helium nucleus — the $He^4(\gamma, pn)D$ reaction, which leads to emission of three particles — a proton, a neutron and a deuteron.

The investigation of this reaction has a special interest from the point of view of testing the validity of the two-nucleon model for the absorption of high energy photons by nuclei, which was proposed in papers by Khokhlov[3] and Levinger.[4] According to this model, high energy photons are absorbed by a pair of nucleons in the nucleus which are located at a relatively small distance from one another. Having absorbed the photon, the high energy proton and neutron either both leave the nucleus or, before emergence, undergo a series of collisions in the nuclear matter and excite the residual nucleus.

Many experimental papers have already been published whose results can be interpreted from the point of view of the quasideuteron model. Among these, we mention papers[5-12] on the angular and energy distributions of high energy photoprotons, in which there were observed characteristic kinks in the energy spectra of the photoprotons at an energy about half the maximum energy of the bremsstrahlung, and a marked forward peaking in the angular distribution of the photoprotons. However no quantitative agreement between the predictions of the quasideuteron model and experiment was found. In addition to this, experiments[13-15] were done to detect directly the correlation in the emission of fast protons and neutrons in the nuclear photoeffect. In these experiments, coincidences between neutrons and photoprotons were observed from lithium, carbon and oxygen, and the kinematics were the same as for the photodisintegration of the deuteron. The angular distributions of the neutron-proton pairs were practically the same as the corresponding distributions in the case of the deuteron. The authors of Ref. 15 arrive at the conclusion that the quasideuteron model is applicable for photon energies from 140 to 300 Mev, but are unable to say whether the quasideuteron process can be responsible for all the high energy photoprotons which are not associated with the production of real mesons.

Since we can, by applying the conservation laws, use the angles of emission and momenta of the proton and deuteron from the $He^4(\gamma, pn)D$ reaction to calculate the energy of the photon and the angle of emission and momentum of the neutron, the study of this reaction enables us to draw conclusions concerning the correlation in the emission of the neutron and proton, and to get some idea of the role of various processes in the photodisintegration of helium.

2. TREATMENT OF PHOTOGRAPHS

We have already said in I that the $He^4(\gamma, pn)D$ reaction is characterized by the appearance of two

*These will be cited as I, II.

tracks of different density in the Wilson chamber (the more dense track being that of the deuteron), and these tracks are at at arbitrary angle to one another and to the direction of the γ-quanta. A cloud chamber photograph of a $He^4(\gamma, pn)D$ reaction was given as Fig. 3 in paper I. We should mention that two arbitrarily oriented tracks of different density can also be formed in the $He^4(\gamma, 2p\,2n)$ reaction. However, as the results of photometering and measurement of momenta showed, almost all cases of a pair of tracks with random orientation are due to the $He^4(\gamma, pn)D$ reaction. In a series of 23,000 photos taken with maximum bremsstrahlung energy from 170 to 260 Mev, the number of cases recorded of the $He^4(\gamma, pn)D$ and $He^4(\gamma, 2p\,2n)$ reactions were 1,370 and 120, respectively. Thus the relative yield of the $He^4(\gamma, 2p\,2n)$ reaction compared to $He^4(\gamma, pn)D$ does not exceed 10%. The yield of reactions of the type of $He^4(\gamma, pn)D$ and $He^4(\gamma, 2p\,2n)$ is 10% compared to that of reactions with two particles in the final state.

To find the energy dependence of the cross section and to construct the angular distributions of the emerging particles, we restricted ourselves to those cases in which both tracks had projected lengths on the plane of the bottom of the chamber at least equal to 53 mm. We could then measure the radius of curvature of the track with sufficient accuracy. Having measured the angles between the γ-ray beam direction and the track projections, as well as the projected momenta, we could, from the projected length of the tracks and the depth of the illuminated region of the chamber, determine by the same method as in I and II the true spatial angles of emission of the particles and their true momenta. Furthermore, by comparing the observed visual densities of the tracks with those expected (assuming we knew the type of particle and using the measured momenta), we checked the correctness of the identification of the particles. After this, using the conservation laws, we found the energy of the photon and the angles of emission and momenta of all three particles in the center of mass system, and the angles between them.

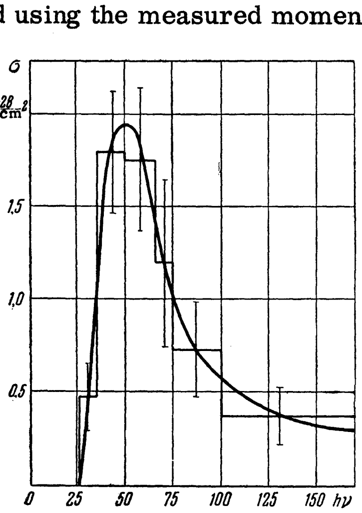

FIG. 1 Dependence of the cross section for the $He^4(\gamma, pn)D$ reaction on photon energy.

In constructing the angular distributions of the emergent particles, we introduced corrections (as described in I) to take account of the limited size of the illuminated region. In constructing the energy distributions, such corrections were not made, but the cross section curve was normalized to the total number of observed cases of the $He^4(\gamma, pn)D$ reaction.

3. RESULTS

A. Dependence of the Cross Section for the (γ, pn) Reaction on Photon Energy

Figure 1 shows the curve for the cross section of the $He^4(\gamma, pn)D$ reaction as a function of photon energy, obtained from analysis of 91 cases of this reaction in a series of 9,000 cloud chamber photographs taken with radiation having a maximum energy of 170 Mev. We see from Fig. 1 that the $He^4(\gamma, pn)D$ reaction has resonance character, with its maximum at an energy around 50 Mev. The cross section at the maximum is of the order of $2 \times 10^{-28}\,cm^2$. Comparison with the cross section curves for the (γ, p) and (γ, n) reactions shows that the cross section for the (γ, pn) reaction becomes approximately the same as those for the (γ, p) and (γ, n) reactions for photon energies of the order of 75 Mev.

To estimate the contribution of the (γ, pn) reaction to the total photon absorption cross section, we give in Table I the integral cross section of this

TABLE I*

Photon energy E_γ, Mev	$\sigma_{int} = \int \sigma(W)\,dW$, Mev·mbarn	
	(γ, pn)	$(\gamma, p) + (\gamma, n)$
$\leqslant 75$	7.2 ± 0.9	71.6 ± 2.2
75–170	4.6 ± 1.2	10.0 ± 1.9
$\leqslant 170$	11.8 ± 1.5	81.6 ± 2.9

*Only the statistical errors are given.

reaction and also the total cross sections for the (γ, p) and (γ, n) reactions.

We see from the table that, for energies below 75 Mev, the contribution of the (γ, pn) reaction to the total photon absorption cross section is less than 10%, while in the energy region above 75 Mev its contribution increases to 30%.

The value of $\sigma_b = \int \sigma(W)\,W^{-1}\,dW$ found for the

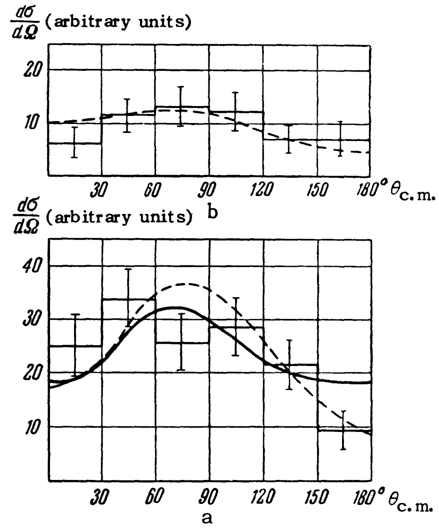

FIG. 2.

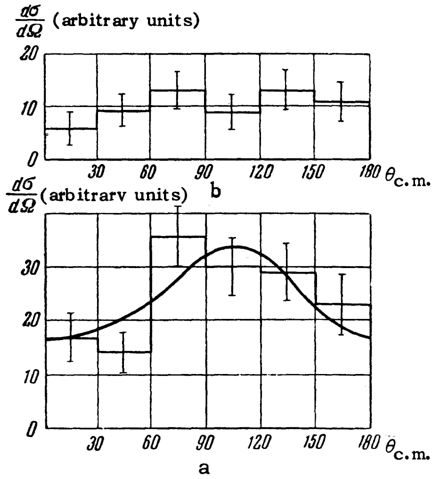

FIG. 3.

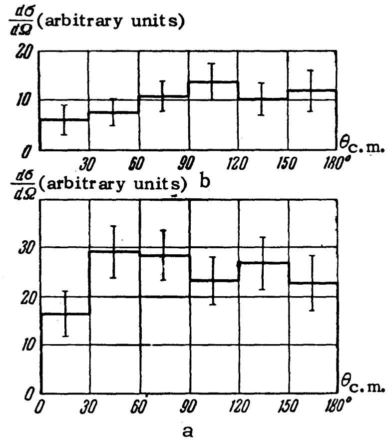

FIG. 4.

FIG. 2. Angular distributions of protons from the He^4 (γ, pn) D reaction, in the center of mass system, integrated over the bremsstrahlung spectrum for photon energies: a) $h\nu = 25.9 - 75$, b) $75 - 170$ Mev. The solid curve is a least squares fit of the functional form $\sin^2\theta + \beta \sin^2\theta \cos\theta + \delta$, with $\beta = 1.0 \pm 1.2$; $\delta = 1.6 \pm 1.0$. The dashed curves are angular distributions of protons from photodisintegration of the deuteron, for photon energies of a) 55 Mev, and b) 105 Mev.

FIG. 3. Angular distribution of neutrons from the He^4 (γ, pn) D reaction in the center of mass system, integrated over the bremsstrahlung spectrum for photon energies: a) $h\nu \doteq 25.9 - 75$ Mev, b) $75 - 170$ Mev. The solid curve is a least squares fit of the functional form $\sin^2\theta + \beta \sin^2\theta \cos\theta + \delta$, with $\beta = -0.8 \pm 0.8$; $\delta = 1.1 \pm 0.7$.

FIG. 4. Angular distribution of deuterons from the He^4 (γ, pn) D reaction in the center of mass system, integrated over the bremsstrahlung spectrum for photon energies: a) $h\nu = 25.9 - 75$, b) $h\nu = 75 - 170$ Mev.

(γ, pn) reaction was $\sigma_b = 1.8 \times 10^{-28}\,\mathrm{cm}^2$.

B. Angular Distributions

In Figs. 2 — 4 we give the angular distributions of protons, neutrons and deuterons in the center of mass system, for two ranges of photon energies, from 25.9 Mev (the threshold for the reaction) to 75 Mev and from 75 Mev to 170 Mev. These angular distributions were found from analysis of 207 cases of the He^4 (γ, pn) D reaction, which were recorded in 9,000 pictures at a maximum energy of 170 Mev and in 14,000 pictures at a maximum energy of 260 Mev.

From Figs. 2 and 3 we see that the angular distributions of the protons and neutrons produced in the (γ, pn) reaction are very similar to the angular distributions of the protons and neutrons from photodisintegration of the deuteron. Also, as in the case of the deuteron, they have an appreciable isotropic part at medium energies, and in the c.m.s. system the maximum for the protons is shifted forward to ~75° while that for the neutrons is shifted backward to ~105°. At high energies there is a bigger isotropic part. For comparison, in Fig. 2 the dashed curves are the experimental angular distributions of protons from photodisintegration of the deuteron at photon energies of 55 Mev[16] and 105 Mev,[17] normalized to the area under the histogram.

The angular distribution of the deuterons (Fig. 4) is close to isotropic in both the photon energy intervals $h\nu = 25.9 - 75$ and $76 - 170$ Mev. In Fig. 5 we give the angular distributions of the protons in the laboratory system for approximately the same intervals of photon energy, as constructed from 495 proton tracks. In constructing these curves, we used all cases where the proton track had a projected length ≥ 53 mm. We see from Fig. 5 that the proton angular distribution for $E_p \geq 21$ Mev is in satisfactory agreement with the calculations of Dedrick[18] on the quasideuteron model.

C. Correlation between Particles

To clarify the question of the existence of correlations in the emission of particles from the (γ, pnd) reaction, we constructed distributions of the relative energies of proton and neutron (Fig. 6) and proton and deuteron (Fig. 7), computed in units of the maximum relative energy. In the absence of correlation we should expect the distributions to have the form

$$\mathrm{const}\,[1 - E_{ij} / E_0]^{1/2}\,(E_{ij} / E_0)^{1/2},$$

where E_{ij} is the relative energy of proton and

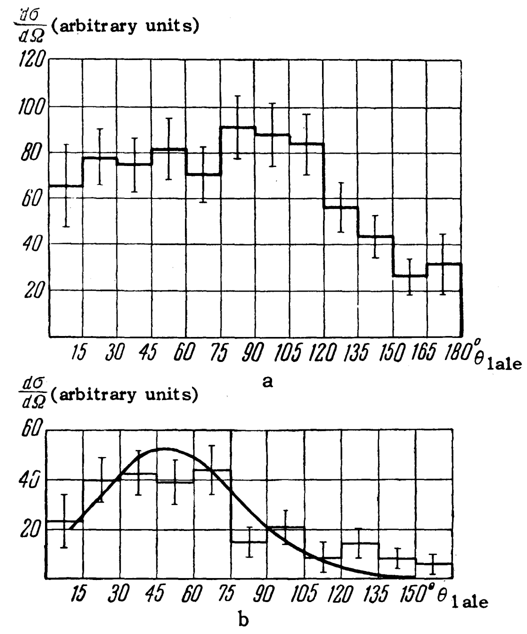

FIG. 5. Angular distribution of protons with energies: a) $E_p \leq 21$ Mev, b) $E_p \geq 21$ Mev, emitted from the He^4 (γ, pn) D reaction, in the laboratory coordinate system. The solid curve is calculated for quasideuteron absorption, from data given in the paper of Dedrick[18] (normalized at $\theta = 30°$).

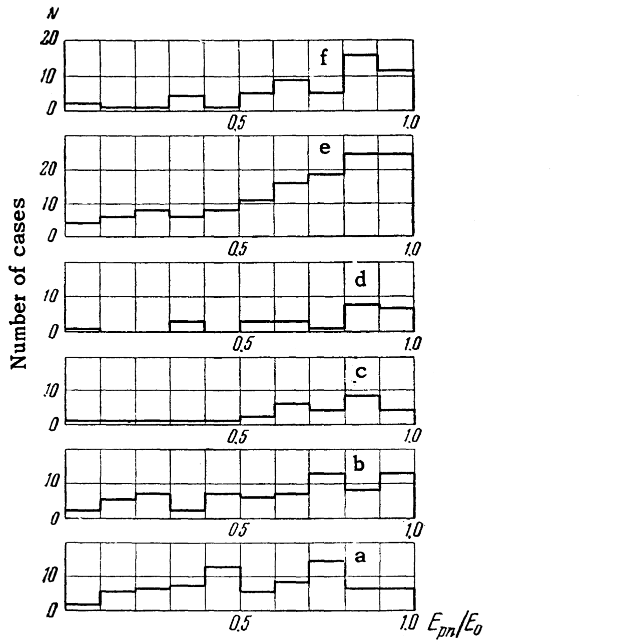

FIG. 6. Distribution of numbers of cases of the He^4 (γ, pn) D reaction as a function of the relative energy (in the c.m.s.) of proton and neutron, for various photon energies: a) $h\nu = 25.9 - 50$, b) $h\nu = 50 - 75$, c) $h\nu = 75 - 100$, d) $h\nu = 100 - 150$, e) $h\nu = 50 - 150$, f) $h\nu = 75 - 150$ Mev.

neutron or of proton and deuteron.

As we see from the graphs, the distributions have approximately this dependence only for photon energies from 25.9 (the reaction threshold) to 50 Mev. In the energy range 50 — 75 Mev, a preponderance of large relative energies of proton and neutron is indicated. The distribution of relative energies of proton and deuteron remains practically the same in the 50 — 75 Mev interval as it was at low energies. For energies above 75 Mev, the preponderance of large relative energies of proton and neutron becomes completely apparent. At the same time a preponderance of small relative energies of proton and deuteron becomes noticeable.

Thus for photon energies greater than 75 Mev, the neutron and proton are emitted preferentially in almost opposite directions, taking away an appreciable part of the energy of the reaction, while the low energy deuteron has a slight preference for being dragged along in the direction of emission of the proton.

Similar conclusions can be drawn from a consideration of the angles between the directions of emission of the particles. For energies up to 75 Mev, all three particles behave equivalently, so that the average angles between them are approximately 120°, whereas for energies > 75 Mev the average angles are

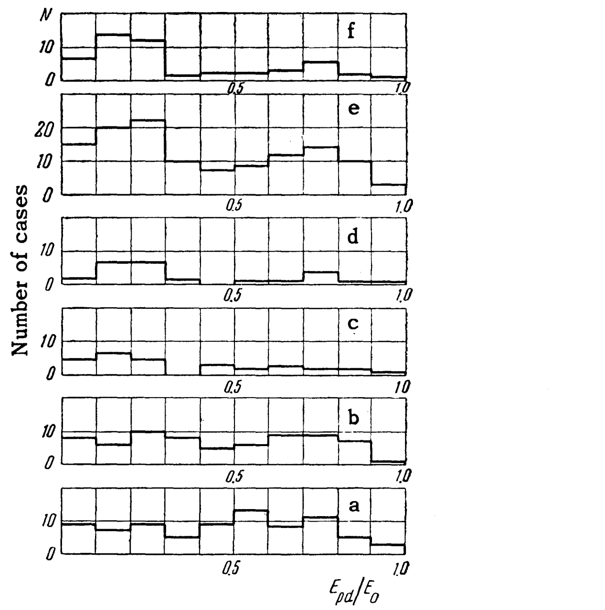

FIG. 7. Distribution of numbers of cases of the He^4 (γ, pn) D reaction as a function of the relative energy (in the c.m.s.) of proton and deuteron, for various photon energies: a) $h\nu = 25.9 - 50$, b) $h\nu = 50 - 75$, c) $h\nu = 75 - 100$, d) $h\nu = 100 - 150$, e) $h\nu = 50 - 150$, f) $h\nu = 75 - 150$ Mev.

$$\alpha_{pn} \sim 139, \quad \alpha_{pd} \sim 94, \quad \alpha_{dn} \sim 127°.$$

Table II gives the average momenta of the emitted particles in units of Mev/c.

TABLE II

Photon energy E_γ, Mev	Proton	Neutron	Deuteron
25.9—75	123	118	124
75—170	214	259	190

CONCLUSIONS

1. On the basis of results reported in papers I, II and III, we may suppose that the process responsible for the $He^4(\gamma, pn)D$ reaction is the quasideuteron absorption of photons, both in the low energy region and in the region above 75 Mev. This is indicated by the angular distributions of the particles and by the presence of correlation between proton and neutron which is clearly evident at high photon energies and is masked by the momentum distribution of the particles in the nucleus at low energies.

2. From comparison of the angular distributions of protons and neutrons from the $He^4(\gamma, p)H^3$ and $He^4(\gamma, n)He^3$ reactions with those from photodisintegration of the deuteron, we can assert that these processes occur as the result of direct single particle absorption of the photon, in which the main process is electric dipole absorption. At energies above 30 Mev, electric quadrupole absorption begins to be important. Its interference with the dipole absorption causes a marked shift of the maximum in the proton angular distribution, but gives no contribution to the yield of the (γ, n) reaction.

3. The relative importance of single-particle and two-particle absorption of photons changes with energy. As was stated above, the total contribution of two-particle absorption to the integral absorption cross section amounts to 12%, or to 14% if we include the $(\gamma, 2p\,2n)$ process which is also apparently related to two-particle absorption. However, in the region above 75 Mev, the contribution of two-particle absorption to the integral absorption cross section is at least 30%. Unfortunately, the poor statistics of the data at high photon energies do not allow us at present to draw conclusions concerning the importance of the two-particle mechanism of photon absorption in (γ, p) and (γ, n) processes for energies above 75 Mev.

4. The cross sections for the three main processes of photodisintegration of helium, (γ, p), (γ, n), and (γ, np) were measured as a function of photon energy. Comparison with the results of calculations of Flowers and Mandl,[19] Gunn and Irving[20] for electric dipole absorption with wave functions of various types (Gaussian, exponential, and the functions introduced by Irving[21]), for a pure central force, and with the calculations of Bransden et al.,[22] which include tensor forces, shows that it is not possible to choose the parameters of wave functions of this type so that one gets simultaneously the correct values of the binding energy and radius of He^4, the energy at which the cross section is a maximum, and the value of the maximum cross section.

5. From the measured values of cross sections for the main reactions in photodisintegration of helium, (γ, p), (γ, n), and (γ, np), we constructed a curve for the absorption cross section of photons in helium (Fig. 8). Using this curve and including

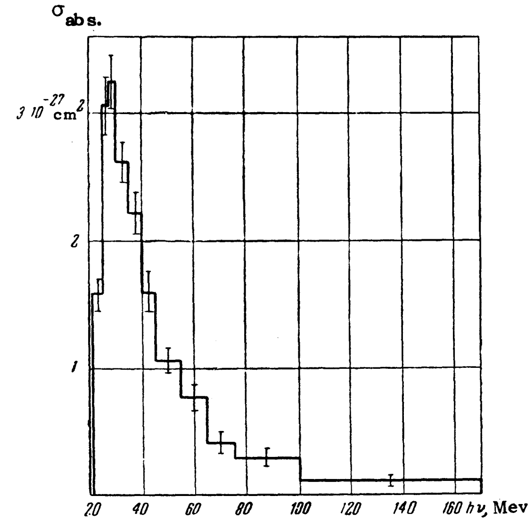

FIG. 8. Dependence of total cross section for absorption of photons by He^4 on photon energy. Only statistical errors are shown on the graph. Errors in absolute values are $\sim$ 6%.

the small contributions from the $He^4(\gamma, 2p\,2n)$ and $He^4(\gamma, 2d)$ reactions, we calculated the integral photon absorption cross section,*

$$\sigma_{int} = \int_{19.8}^{170} \sigma_{abs}(W)\,dW = 95 \pm 7 \text{ Mev}\cdot\text{mbarn}.$$

This result is in satisfactory agreement with the calculations of the integral cross section for electric dipole absorption of photons by He^4 which were done by Rustgi and Levinger[23] using sum rules. For central forces, with a 50% mixture of exchange force, these computations give σ_{int} = 89 Mev · mbarn.

*The value 95 ± 7 Mev · mbarn for the integral cross section is somewhat larger than the value σ_{int} = 88 ± 7 Mev mbarn given in I, although the difference is within the limits of error. The difference is due to the fact that in I we assumed $\sigma_{int}(\gamma, n) = \sigma_{int}(\gamma, p)$, while here we are using the independently determined value of $\sigma_{int}(\gamma, n)$ from II, and this value was somewhat larger than $\sigma_{int}(\gamma, p)$.

From the photon absorption curve we also calculated

$$\sigma_b = \int_{19.8}^{170} \frac{\sigma_{abs}(W)}{W} dW = 2.4 \pm 0.15 \text{ mbarn.}$$

It is known[24] that σ_b depends only on the mean square radius of the nuclear charge distribution, so that from the experimentally measured value of σ_b we can compute the mean square radius of the He^4 nucleus. We found the value

$$R = (1.57 \pm 0.06) \cdot 10^{-13} \text{ cm}$$
$$(\text{or } r_0 = (1.28 \pm 0.05) \cdot 10^{-13} \text{ cm})^*$$

in satisfactory agreement with the value $R = (1.61 \pm 0.08) \times 10^{-13}$ cm found from electron scattering experiments.[25] This value is markedly different from the values of the He^4 radius calculated using Irving's wave functions, as well as those found with wave functions of Gaussian or exponential type adjusted to give the correct binding energy of He^4.

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*For a model with a uniform charge distribution.

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